PREDICTING NUTRIENT ENRICHMENT FROM LONG-TERM AVERAGE SOIL LOSS

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Summary

Single event soil losses for 20 year periods and different scenarios (factors R, K, L, S, C, P of the USLE) were created using a Monte Carlo technique. Nutrient enrichment ratios for these single event soil losses were then computed using the equation for N and P enrichment included in CREAMS. The long-term average soil loss and the weighted nutrient enrichment were closely correlated, and the resulting regression equation was used in combination with the USLE to predict average nutrient loss. This equation provides an easily adapted tool for environmental planning. The main potential error in utilizing this equation is inadequate prediction of soil loss. Even if all factors of the USLE are known exactly the average soil loss can only be predicted within a range of ±25% around the true mean for the recommended 22 year period because of high temporal variability.

The long-term enrichment ratio was used to derive a tolerable soil loss (T2) to judge eutrophication hazards caused by soil erosion. The proposed T2 value is applied to a typical situation in a hop growing area. It is shown that the soil loss in this situation is more than an order of magnitude higher than the T2 value.

1 Introduction

The long-term effects of soil erosion have to be considered in many cases of environmental planning; therefore, models that allow easy prediction of protracted damages are often preferred to single event models. This requirement is one reason why the Universal Soil Loss Equation (USLE) (WISCHMEIER & SMITH 1978) is still the most widely used model for erosion prediction.

Unfortunately, nutrient losses through erosion cannot be predicted simply from a knowledge of soil loss and nutrient concentration in the soil because of the enrichment created by selective transport of clay, organic matter, and nutrients in the eroded sediment. At present, this enrichment can only be estimated with single event models like CREAMS (Chemicals Runoff and Erosion from Agricultural Management Systems) (KNISEL 1980) or CNS (Cornell Nutrient Simulation model) (HAITH et al. 1984). These models need high data input and computation effort if the long-term average nutrient loss of a field or the nutrient input into a stream are to be accurately predicted because many events have to be simulated.

A model for nutrient enrichment that
is as easy to use as the USLE would help to more accurately predict and quantify the effects of erosion in environmental planning. Suitable long-term enrichment ratios would be especially valuable for deriving T2 values, where T2 is the tolerable soil loss as proposed by LARSON (1981) for assessing offsite damages.

2 Procedure

In the CNS model (HAITH et al. 1984), a nutrient enrichment factor of 2 is assumed in all cases. This assumption is an oversimplification because transport is selective and the enrichment of clay and nutrients increases with decreasing soil loss. In the CREAMS model (KNISEL 1980), selective transport is considered in the following equation for calculating N and P enrichment:

\[ \ln(ER_e) = 0.62 - 0.2 \cdot \ln(A_e) \]  
(1 a)

\[ ER_e = 1.86 \cdot A_e^{-0.22} \]  
(1 b)

\[ ER_e = \text{Enrichment ratio for single events} \]

\[ A_e = \text{Single event soil loss (Mg/ha)} \]

A very similar equation was published by SHARPLEY (1980) for use on a watershed scale:

\[ ER_e = 1.85 \cdot A_e^{-0.027} \]  
(2)

These equations cannot be used with the average annual soil loss (A) because this loss is produced by several events. Under Bavarian climatic conditions the number of erosive rains depends on annual precipitation as follows (ROGLER 1981):

\[ Z = 0.8 + 0.0197 \cdot N \quad r = 0.98 \quad n = 17 \]  
(3)

\[ Z = \text{Number of erosive rainstorms} \]

\[ N = \text{Average annual precipitation (mm)} \]

The average single event soil loss \((A/Z)\) also cannot be used with eq. (1) because of the high variability of single erosion events and the non-linearity of eq. (1). This high variability is due in part to large differences in rainstorm erosivities, which often are log-normally distributed. For Bavaria this log-normal distribution has a mean of 0.33 and a standard deviation of 0.43 (both in log \([\text{kJ/m}^2\cdot \text{mm/h}] = \log [\text{N/h}]; \) ROGLER 1981). To the high rainstorm variability is further added the variability of field conditions and the resulting susceptibility to erosion. In the USLE this susceptibility is taken into account with the Soil Loss Ratio (SLR) that, in turn, depends on the cropstage period.

From the annual distribution of rainstorm erosivities (EI - distribution) the frequency of erosive rains that fall on a field under certain conditions can be estimated. It can be assumed that a field condition that receives 30% of the annual erosivity also receives approximately 30% of the erosive rain events. This assumption is possible because the seasonal variation of rain erosivity is mainly caused by seasonal variation in the number of rains (tab.1).

Cropstage and erosivity as sources of variability were considered for estimating nutrient enrichment from average annual soil loss as follows:

Single event erosivities that meet the requirements concerning distribution and severity of Bavarian rains were calculated using the Monte Carlo technique. The variability of field conditions between different cropstage periods is described by the soil loss ratios. The variability within a specific cropstage period was assumed to be normally distributed with a standard deviation of half the mean. The number of rainstorms falling
during a particular crop stage was estimated from the annual erosivity distribution. By taking the products of these single event erosivities and the single event soil loss ratios and applying the constant factors of the USLE (K, L, S, P), a distribution of single event soil losses was created. Also, the enrichment ratio for each event was computed with eq. (1).

Single events were simulated for several field scenarios with different crop rotations and different site characteristics to represent a long history of erosion (mostly 20 years). The average annual soil loss was given by the sum of soil lost and the number of years simulated. The average nutrient enrichment for this annual soil loss was computed by weighting the enrichment ratios of single events using the amount of soil lost in the corresponding event.

3 Results

A basic question is how long the simulation period must be to stabilize the averages of soil loss and nutrient enrichment. To address this question for constant site characteristics (K, LS, P, rotation), increasing time periods, i.e., increasing numbers of erosive rains, were simulated. The variability of soil loss was so high that even after 96 erosive rains were considered (which represents 6 years under average Bavarian conditions), the standard deviation of the 11 averages of soil loss was still 22%. The averages of 11 24-year periods still had a standard deviation of 13% (tab.2). A 22-year period is normally regarded to be sufficiently long for accurate soil loss estimation (WISCHMEIER & SMITH 1978, 5). For this length of time, 95% of the periods simulated will produce soil losses in a range of ±25% around the true mean.

The corresponding variation in the calculated nutrient enrichment ratios (tab.2) is much smaller. Moreover, this variation is mainly affected by differences in average soil loss and is determined only in small part by accidental combinations of single events. Estimation of nutrient enrichment from long-term average soil loss data is therefore justified, because the error in computing nutrient loss is mainly due to the error in estimating soil loss rather than the enrichment ratio.
Average soil losses and the corresponding enrichment ratios were also simulated for 20-year periods with different field scenarios. Both values can be described by a log-log-function as is true for single events:

\[
\ln(ER) = 0.92 - 0.206 \cdot \ln(A) \tag{4 \text{ a}}
\]

\[
\text{std. error of est.: } \pm 0.01 \pm 0.005 \\
r = -0.9901 \\
n = 40
\]

respectively:

\[
ER = 2.53 \cdot A^{-0.21} \tag{4 \text{ b}}
\]

with

\[
ER = \text{weighted longterm enrichment ratio} \\
A = \text{longterm average annual soil loss (Mg/(ha \cdot a))}
\]

which predicts the simulated \(ER\) with \(r^2 = 0.981\).

4 Discussion

The long-term average enrichment ratio is intended to help in water quality management and provide an easy applicable tool for planners. It was derived empirically from existing single event equations. Therefore, all errors included in the basic equations will also bias long-term enrichment. For instance, it can be expected that the enrichment of N and P is different depending on soil properties. But as long as the same equation is used for both nutrients in single event models no difference can occur in long-term models.

The additional error introduced by the long-term equation is comparably small (cf. \(r^2 = 0.981\); fig.1). The main error in the prediction of long-term nutrient loss will arise from accidental deviations in soil loss. The average absolute difference between the enrichment ratios computed from single event soil loss and the enrichment ratio computed with eq. (4) was 0.08. The biggest differences occurred with scenarios resulting in average soil losses below 1 Mg/(ha · a). For these scenarios the absolute difference averaged 0.15, but the error resulting from this difference was only 5% because of the high enrichment ratios that are produced under these conditions. Eq. (4) predicts a higher nutrient enrichment than would be expected from single event soil loss (intercept), but the slope of the regression equation is very similar to that found for single events.

For the average soil loss on arable land in Bavaria (8.1 Mg/[ha · a]; AUERSWALD & SCHMIDT 1986) eq. (4) predicts an average nutrient enrichment of 1.63. This is 25% higher than the enrichment (1.22) that can be expected from a single event storm producing a soil loss of 8.1 Mg/ha, but it is 30% lower than the enrichment (2.13) that can be com-
Fig. 1: Weighted nutrient enrichment ratio depending on long-term average soil loss (results of different scenarios and regression line).

computed by dividing the soil loss of 8.1 Mg/ha by the average number of erosive storms (16). The error of estimate resulting from the uncertainty of eq. (4) is far smaller than the error that would result from using eq. (1) with the annual soil loss or the average single event soil loss.

5 Application

The ER can be used to predict the long-term average particulate P input into a stream as follows (NELSON & LOGAN 1983):

\[ IP = A \cdot PS \cdot ER \cdot SDR \]  

with

- \( IP \) = P input in kg/(ha-a)
- \( PS \) = P content of soil in kg/Mg
- \( SDR \) = Sediment delivery ratio

From the data given in STEWART et al. (1975) the following sediment delivery ratio can be derived:

\[ SDR = -0.02 + 0.385 \cdot FL^{-0.2} \]  

with

- \( FL \) = watershed area in km²

If special topographic factors for a field have to be taken into account the sediment delivery ratio proposed by HES- SION & SHANHOLTZ (1988) seems to be advantageous, but it should be recognized that this delivery ratio has not yet been verified:

\[ SDR = 10 \cdot \frac{r}{l} \]  

with

- \( r \) = elevation of the lower field border above the stream (m)
- \( l \) = distance to the stream (m).

For 1975 it was calculated that a 6100 Mg/a total P input into the streams of the Federal Republic of Germany was due to erosion (BERNHARDT 1978). This value represents an average P input of 0.25 kg/(ha-a). If for example this average should not be exceeded for a specific watershed, eq. (5) can be resolved for T2 which was proposed by LARSON (1981)
as a tolerance limit for offsite damages. T2 is recommended to be used in cases where it is lower than T1, which is the tolerance limit derived from productivity decline (onsite damages).

\[ T_{2p} = \frac{0.25}{PS \cdot 2.53 \cdot AL \cdot SDR} \]  
(8 a)

\[ T_{2p} = (10 \cdot PS \cdot AL \cdot SDR)^{-1.27} \]  
(8 b)

with

- \( T_{2p} \) = soil loss tolerance to assess
- \( P \) input into streams
- \( AL \) = fraction of watershed which is arable land

The use of \( AL \) in eq. (8) assumes that all particular P that reaches a stream comes from arable land and that the other fields in the watershed contribute the tolerated P input. This simplification is necessary for the agricultural advisory service. It allows one to compute \( T_{2p} \) for a specific field without exact knowledge of the P input from fields in the neighbourhood that belong to different owners.

Typical watersheds of the lowest order (primary watersheds) in Bavaria have an average area of 18 km² (\( n = 84, \) std.dev. = 9.7). Eq. (6) gives a SDR of 0.20 for this size. For these watersheds, eq. (8) can be simplified to yield:

\[ T_{2p} = (2 \cdot PS \cdot AL)^{1.27} \]  
(9)

This \( T_{2p} \) value can easily be applied to every field. The resulting \( T_{2p} \) value decreases with increasing P content of the topsoil but increases with decreasing percentage of arable land. For watersheds mainly under grass, a high soil loss is tolerated. In these cases the sediment input from arable land may improve water quality because it may adsorb phosphorus from other sources such as feedlot manure (TAYLOR & KUNISHI 1971).

6  Example

Hop is a perennial, high cash-value crop that is grown on deep soils which allow extensive root development. Therefore, T1 in most cases is in the highest class, namely 10 Mg/(ha·a) (SCHWERTMANN et al. 1987). Because of the high economic return from hops, management costs do not restrict the amount of fertilizer applied. Very high fertilizer rates have, therefore, been applied in the past. High application rates, long application history and shallow tillage have led to very high P contents. For example, SCHWERTMANN & HUITH (1975), DELLER (1979) and SCHMIDT (1979) found HClO₄-extractable P of up to 2 g/kg. The average P content of the soils examined (\( n = 90 \)) was 1.2 g/kg P. In the hop growing area about 50% of the land is arable; therefore, \( T_{2p} \) can be computed for a typical hop field as:

\[ T_{2p} = (2 \cdot 1.2 \cdot 0.5)^{-1.27} = 0.8 \text{ Mg/(ha·a)} \]  
(10)

This value is much lower than T1 showing that the environmental problems arising from the cultivation of hop may be more important than the loss of soil fertility. \( T_{2p} \) is also more than an order of magnitude lower than the measured, long-time average annual soil loss which is often more than 50 Mg/(ha·a) (SCHMIDT 1979).

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References


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