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Adapting the CREAMS Model for Finnish Conditions

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The CREAMS model, a management model for predicting field-scale runoff and erosion, has been modified and adapted for Finnish conditions: The most important changes are the implementation of a new snow accumulation and snow melt model, a simple soil frost model, the use of an adjustable albedo for evapotranspiration calculations, the implementation of a plant growth model for calculating leaf area index and soil loss ratio, and allowing for a variation in the rainfall erosivity parameters. The modified model has been compared to the original model and observed data from an experimental field in southwestern Finland. In most cases the modified model predicted surface runoff and soil loss better than the original model. Although there remain discrepancies between model simulations and observations, the modified model seems to perform better and allows an easier comparison of management practices.

Introduction

In order to reduce agricultural non-point pollution of surface and groundwaters the transport of sediment-bound and dissolved pollutants to the water courses has to be reduced. Once these pollutants have reached the ditches and streams or have percolated below the root zone, the purification of the polluted waters is virtually impossible. Therefore the focus in environmental protection in agriculture should be on agricultural practices, which reduce the transport of pollutants, *i.e.* these practices should be tested, evaluated and promoted for wider use in farming.

Experimental fields can be used for studying losses from areas under different management practices. Due to the great variability in climatic conditions these studies have to be repeated for several years to achieve reliable results. Also, results obtained from experimental fields are representative only for the type of fields studied. The great variation in slopes, soil types, textures as well as cropping systems makes the generalization and regionalization of experimentally obtained results difficult. Compared to field experimentes, mathematical simulation models of agricultural systems are a relatively inexpensive and fast method to compare the effectiveness of different agricultural practices.

Several field-scale agricultural transport models have been introduced to predict surface runoff, percolation, erosion, and nutrient and pesticide losses to surface and groundwaters. Among these, the GLEAMS (Leonard *et al.* 1987), the Swedish SOILN (Johnsson *et al.* 1987) and the Danish DAISY (Hansen *et al.* 1990) models describe the percolation and the movement of solutes in a soil profile, whereas the CREAMS (Knisel 1980) and the EPIC (Williams *et al.* 1984) models also describe surface runoff, erosion and the transport of sediment-bound nutrients. CREAMS also includes a description of the percolation processes.

In CREAMS and EPIC the calculation of two critical variables in soil loss prediction, surface runoff and erosion, are based on statistically derived descriptions. In these models the surface runoff volume is estimated by the U.S. Soil Conservation Service (SCS) Curve Number Method (U.S. Department of Agriculture, Soil Conservation Service 1972), and erosion is simulated by the Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1958) or its modifications (Williams 1975). Although widely used, the application of these methods in conditions different from those prevailing during their development needs testing, calibration and possibly also modifications. In a new model called WEPP (Lane and Nearing 1989; Lane *et al.* 1988) the descriptions of these processes have been replaced by infiltration theory and physically based erosion prediction technology. However, WEPP is still under development and not yet fully tested.

The CREAMS model was previously used in Finland (Kauppi 1982; Rekolainen and Kauppi 1988). In this paper the modifications and changes made to CREAMS to adapt it to Finnish conditions, as well as some test results, are presented.

Modifications of the CREAMS Model

Snow Accumulation and Snow Melt

The snow accumulation and snow melt routine uses mean daily temperature and precipitation as driving variables. It is a modification of a model developed for flood forecasting in Finland (Vehviläinen 1986), and earlier results of this modification have been reported in Kallio *et al.* (1989). During snow accumulation the phase change from solid to liquid precipitation is assumed to occur linearly between two threshold temperatures, *i.e.*

$$P_s = \begin{cases} P & \text{for } T \leq T_s \\ P(T_l - T)/(T_l - T_s) & \text{for } T_s < T < T_l \\ 0 & \text{for } T_l \leq T \end{cases} \tag{1a}$$

and

$$P_l = P - P_s \tag{1b}$$

where P is the total amount of precipitation (mm d^{-1}), P_s is the solid precipitation (mm d^{-1}), and P_l is the liquid precipitation (mm d^{-1}), T is the mean daily temperature (°C), T_l is the threshold temperature for liquid precipitation (°C) and T_s is the threshold temperature for solid precipitation (°C).

Correction factors f_s and f_l can be specified by the user to account for the inaccuracy of the solid and liquid precipitation measurements.

The amount of melted water Q (mm d^{-1}) is simulated by a degree-day model

$$Q \equiv \begin{cases} f_0(T - T_0) & \text{for } T > T_0 \\ 0 & \text{for } T \leq T_0 \end{cases} \tag{2}$$

where f_0 is a degree-day factor (mm K^{-1}d^{-1}) and T_0 is the threshold temperature for melting (°C).

An additional parameter f_{ret} ($0 \leqslant f_{ret} \leqslant 1$) accounts for the liquid water rentention in the snow pack (expressed as weight-fraction of the snowpack): the amount of water retained in the snowpack equals $f_{ret}Q$. The parameters in Eqs. (1) and (2) allow a calibration to observed snow cover. However, the most crucial improvement is the use of daily temperature values instead of a sine-curve obtained from interpolating monthly means, which is an option in the GLEAMS model.

Soil Frost

In the original CREAMS model soil frost and thaw dates were input variables, whereas in our modification they are simulated by a simple procedure based on two degree-day values. In spring mean daily temperatures exceeding 0°C are summed until a threshold temperature sum ΣT^+ is reached. After this date the soil is considered permeable. Similiarly, in fall mean daily temperatures below 0°C are summed until the absolute value of the sum reaches a threshold ΣT^-. After this date the soil is considered impermeable for percolating water. Using soil frost measurements from a station in southwestern Finland, the best fit was obtained for $\Sigma T^+ = 30$ and $\Sigma T^- = 10$ degree days. These values were used in all simulations presented in this paper.

Evapotranspiration

In CREAMS evapotranspiration is calculated by a model presented by Ritchie (1972). One of the input parameters to this model is the surface albedo. In CREAMS the albedo was assumed constant throughout the year, and the potential evapotranspiration outside the vegetation period was regulated by a so-called winter cover factor. Because of the long snow cover period its use is not appropriate for Finnish conditions. Potential evaporation is now calculated by user-input values for albedo for snow (A_{snow}), bare soil (A_{soil}) and vegetation (A_{veg}).

If snow cover, S, exists corresponding to 5 mm of water or more, the snow albedo value is used. If S is less than 5 mm of water, the albedo, A, is linearly interpolated between snow and bare soil albedo according to

$$A = \frac{S}{5} A_{\text{snow}} + \left(1 - \frac{S}{5}\right) A_{\text{soil}} \tag{3a}$$

During the growing season A is computed by the equation

$$A \equiv C_f A_{\text{soil}} + (1 - C_f) A_{\text{veg}} \tag{3b}$$

where C_f is the soil cover index ($0 \leq C_f \leq 1$) calculated as

$$C_f \equiv e^{-0.29\, B_m} \tag{4}$$

where B_m is the vegetative biomass (kg m^{-2}), as determined by the plant growth model described below.

A user input for calculating evaporation in the original CREAMS model is the soil evaporation parameter CONA. This parameter has been replaced by the soil transmissivity T_r which is calculated as a function of the fractions of sand, f_{sa}, and clay, f_{cl}, (Savabi *et al.* 1989)

$$T_r \equiv 4.165 - 1.703 f_{cl} + 2.456 f_{sa} - 4 f_{sa}^2 \tag{5}$$

This soil transmissivity T_r is used to calculate the bare soil evaporation E according to (Ritchie 1972)

$$E = 9(T_r - 3)^{0.42} \tag{6}$$

Leaf Area Index

In the original CREAMS model the leaf area index (*LAI*) has to be specified by the user as a piecewise linear function. In our modification a plant growth model computes *LAI*. The structure of the growth model was adapted from the WEPP model (Alberts *et al.* 1989).

Plant growth is based on growing degree days (G_d) defined as

$$G_d = \begin{cases} T - T_b & \text{for} \quad T > T_b \\ 0 & \text{for} \quad T \leq T_b \end{cases} \tag{7}$$

where T is the daily mean air temperature (°C) and T_b is a plant-dependent threshold temperature. Growing degree days are accumulated beginning at planting (denoted by ΣG_d). Plants emerge when ΣG_d reaches a critical, plant-dependent value or 14 days after planting, whichever occurs first.

Vegetative biomass B_m (kg m^{-2}) is calculated according to Ghebreiyessus and Gregory (1987)

$$B_m \equiv \left(\frac{\Sigma G_d}{G_{dm}}\right)^{\omega} B_{mx} \tag{8}$$

where G_{dm} is the growing degree-day at physiological maturity, ω is a plant-dependent growth parameter, and B_{mx} is the vegetative biomass at maturity (kg m^{-2}). Biomass growth stops, when ΣG_d reaches G_{dm}.

For annual crops B_{mx} is calculated as a function of biomass yield Y_g (kg m^{-2}) and the fraction of residue mass produced per unit of biomass yield, y_c

$$B_{mx} = Y_g + y_c Y_g \tag{9}$$

For winter crops and perennial crops (grass) the biomass is kept constant for a period which begins when the five-day average temperature T_5 drops below the base temperature, T_b, for the first time in fall and ends when T_5 rises above T_b for the first time in spring. The leaf area index for annual and winter crops is then calculated as (Williams *et al.* 1984)

$$LAI = \begin{cases} \dfrac{LAI_{mx} B_m}{B_m + 0.552 e^{-6.8 B_m}} & \text{for} \quad F_{gs} \leq F_{lai} \\[2ex] LAI_d \left(\dfrac{1-F_{gs}}{1-F_{lai}}\right)^2 & \text{for} \quad F_{gs} > F_{lai} \end{cases} \tag{10}$$

where LAI_{mx} is the maximum leaf area index potential, LAI_d is the leaf area index when $B_m \equiv B_{mx}$, F_{gs} is the actual fraction of the growing season ($0 \leqslant F_{gs} \leqslant 1$), and F_{lai} is the fraction of the growing season when the leaf area index starts declining, *i.e.* when $B_m = B_{mx}$.

For perennial crops (grass) the leaf area index is calculated by

$$LAI \equiv \frac{LAI_{mx} B_m}{B_m + 0.276 e^{-13.6 B_m}} \tag{11}$$

USLE Parameter Modifications

Modifications were made in estimating the rainfall factor and the cover-management factor of the Universal Soil Loss Equation (USLE) used in CREAMS. In CREAMS the rainfall erosivity EI is estimated from daily rainfall data using an equation derived by Lombardi (1979)

$$EI = az^{b} \tag{12}$$

where z is the daily rainfall depth (in) and EI is obtained in (100 ft – tons/acre) (in/h) (U.S. customary units have not been converted in this case to facilitate comparisons). In these units CREAMS uses $a = 8.0$ and $b = 1.51$. Based on the kinetic energy of rainfall as presented by Wischmeier and Smith (1958) and on an analysis of Finnish breakpoint rainfall data, monthly values of a and b have been estimated. In general, the values obtained for b are similar to the value used in the original CREAMS model, but the Finnish values for a are significantly lower than the original CREAMS value, implying that the erosivity of rainfall events in Finland is lower than the average rainfall erosivity in the United States (Posch and Rekolainen 1993). To be able to take into account the spatial and temporal variability in the erosivity of rainfalls the parameters a and b can be input to the modified CREAMS model on a monthly basis. Values for eight stations throughout Finland can be found in Posch and Rekolainen (1993).

During snow cover (water equivalent > 1 mm) no interrill detachment of soil particles due to precipitation or snow melt is assumed to occur. Therefore, interrill detachment is set to zero for those periods. These changes have a pronounced effect on soil loss estimates when compared to the original CREAMS version (see below).

Instead of being specified by the user, the soil loss ratio is calculated from plant growth related parameters. For the growing season (from emergence to harvest) the soil loss ratio, C, is computed as (Laflen *et al.* 1985)

$$C = 1 - C_c e^{-0.34 H_c} \tag{13}$$

where C_c is the canopy cover fraction and H_c is the canopy height (m). The canopy cover is calculated as a function of vegetative biomass (Alberts *et al.* 1989)

$$C_c = 1 - e^{-\beta_c B_m} \tag{14}$$

where the parameter β_c (m^2kg^{-1}) is defined as

$$\beta_c = \frac{-\beta_1}{\ln(1 - \frac{R_w}{\beta_2})} \tag{15}$$

where R_w is the row width (m), β_1 (m^2kg^{-1}) is a plant-dependent constant, and β_2 (m) is the maximum canopy width at physiological maturity.

The canopy height is calculated as (Alberts *et al.* 1989)

$$H_c = H_{cm}(1-e^{-\beta_h B_m}) \tag{16}$$

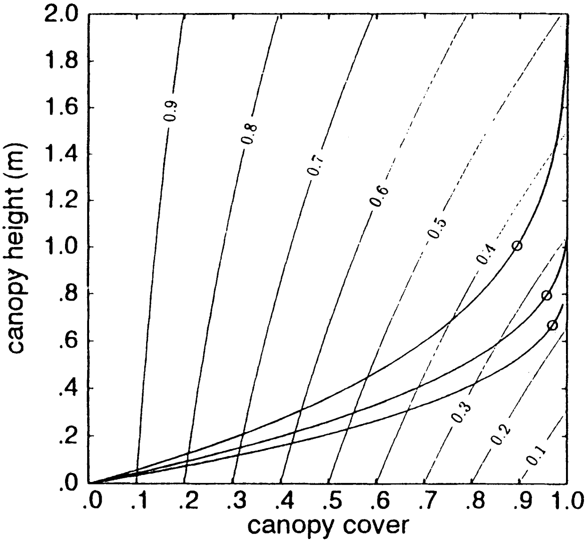

Fig. 1. The relationship between canopy cover and canopy height as a function of biomass between emergence and maturity for three different crops: spring wheat (lowest), oats (middle) and corn (upper thick line). Also shown are isolines (thin lines labeled 0.1 through 0.9) of the soil loss ratio C as a function of canopy height and canopy cover (see Eq. (13)). The circles mark the crop stage at which the minimum soil loss ratio is attained.

where H_{cm} is the maximum canopy height (m) and β_h ($m^2 kg^{-1}$) is a plant-dependent constant. Values for the different constants for various crops can be found in Alberts *et al.* (1989).

Fig. 1 shows the relationship between canopy cover and canopy height as a function of biomass between emergence and maturity for different crops (Eqs. (14)-(16)). In the same figure isolines of the soil loss ratio C are displayed as a function of canopy height and canopy cover (Eq. (13)). Note, that for the above model, the minimum soil loss ratio is not attained at maturity, *i.e.* maximum biomass, but at an earlier stage of crop growth (marked with a circle in Fig. 1) for all crops shown.

From harvesting to the date of residue removal the soil loss ratio is calculated as

$$C = \frac{e^{-2R_c+2} - 1}{e^2 - 1} + 0.03 \qquad (17)$$

where the residue cover fraction R_c is calculated as

$$R_c \equiv 1 - e^{-6.5\, y_c Y_g} \qquad (18)$$

If C is greater than one, it is set to one. Eqs. (17) and (18) are analytical expressions for the curves in Fig. 6 and Fig. 10, respectively, of Wischmeier and Smith (1978). From the date of removal to the tillage date, the residue cover fraction is corrected by the fraction of residues removed, R_{rem}, and from tillage to seedbed preparation, the residue cover fraction is corrected by a residue reduction fraction, R_{red}, depending on the tillage implement.

It should be noted that the calculation of the leaf area index, the soil loss ratio and the soil transmissivity within the modified model does not affect the model output, but simplifies the use of the model, since these quantities do not have to be estimated separately by the user.

Model Testing

The modified and original CREAMS models were tested using data from an experimental field, Kotkanoja, at Jokioinen (60°49′N, 23°30′E). The total area of the field is 2 ha, the mean slope is 2 % and the soil type is heavy clay. It is divided into four fields from which surface runoff samples are collected separately using tipping buckets. The results represent the cumulative amounts for the time period between the sampling dates. A more detailed description of the fields, as well as the sampling system can be found in Jaakkola (1984). Since CREAMS is mainly used for management purposes, the exact prediction of the day-to-day variability of the output is not the main concern here. Therefore, model results have been compared to *cumulative* observed values of surface runoff and soil loss for the years 1984 and 1986-1989. In 1984 and 1986 the Kotkanoja field was under spring barley cultivation, and during the years 1987-1989 under fallow.

Besides visually comparing the observations with the two model versions from annual cumulative plots (see Figs. 2,3), the following statistical measures have been employed

a) *The average absolute error*

$$AERR = \frac{1}{n} \sum_{i=1}^{n} |obs_i - pred_i| \tag{19}$$

where obs_i is the i-th cumulative observation and $pred_i$ is the i-th cumulative model output for the same time period and n is the number of observations for one year.

b) *The root mean square error*

$$RMSE = \left(\frac{1}{n} \sum_{i=1}^{n} (obs_i - pred_i)\right) \tag{20}$$

c) *Model efficiency criterion* (Nash and Sutcliffe 1970)

$$R_0^2 \equiv \frac{F_0^2 - F_0^2}{F_0^2} \tag{21a}$$

where

$$F_0^2 = \sum_{i=1}^{n} (obs_i - obs_m)^2 \text{ and } F_0^2 = \sum_{i=1}^{n} (obs_i - pred_i)^2 \tag{21b}$$

and obs_m is the arithmetic mean of the observations for one year. Values for R^2 vary from minus infinity to +1; + 1 means complete agreement between the observed and simulated values. Results for these measures are reported in Table 1.

Visual inspection shows that the modified model predicts surface runoff and especially soil loss in most years better than the original model (Figs. 2,3). This is confirmed by the R^2-values (Table 1): In all cases except for the soil loss in 1986 the R^2_{new}-value is higher than the R^2_{old}-value, but even in 1986 the total annual soil loss is predicted better by the new model. The large discrepancy between observed and predicted (modified model) soil loss in spring is due to a sudden snowmelt later than in reality. The worse performance of the modified model in 1986 is also confirmed by the other measures, *AERR* and *RMSE*. In 1989 both model versions perform about equally well, as can be seen both from the graphs and Table 1.

Table 1 – Number of observations (*n*), absolute error (*AERR*), root mean square error (*RMSE*) and efficiency criterion (R^2) for the original (subscript *old*) and modified (subscript *new*) CREAMS model against observations from Kotkanoja.

			RUNOFF		
	1984	1986	1987	1988	1989
n	17	30	37	36	38
$AERR_{old}$ (mm)	16.2	8.6	3.6	4.5	5.2
$AERR_{new}$ (mm)	6.0	7.3	2.7	3.2	6.0
$RMSE_{old}$ (mm)	20.9	12.5	5.9	8.7	8.2
$RMSE_{new}$ (mm)	8.6	11.1	4.5	4.8	8.2
R^2_{old}	–0.08	-1.75	-3.52	-2.95	-2.35
R^2_{new}	0.70	-1.17	-1.58	–0.21	-2.33
			EROSION		
	1984	1986	1987	1988	1989
n	17	30	37	36	38
$AERR_{old}$ (kg/ha)	218	94	49	101	92
$AERR_{new}$ (kg/ha)	91	106	17	62	99
$RMSE_{old}$ (kg/ha)	324	130	89	189	164
$RMSE_{new}$ (kg/ha)	165	164	31	108	152
R^2_{old}	-3.76	–0.92	-22.34	–4.41	-5.05
R^2_{new}	–0.24	-2.05	-1.92	–0.79	–4.22

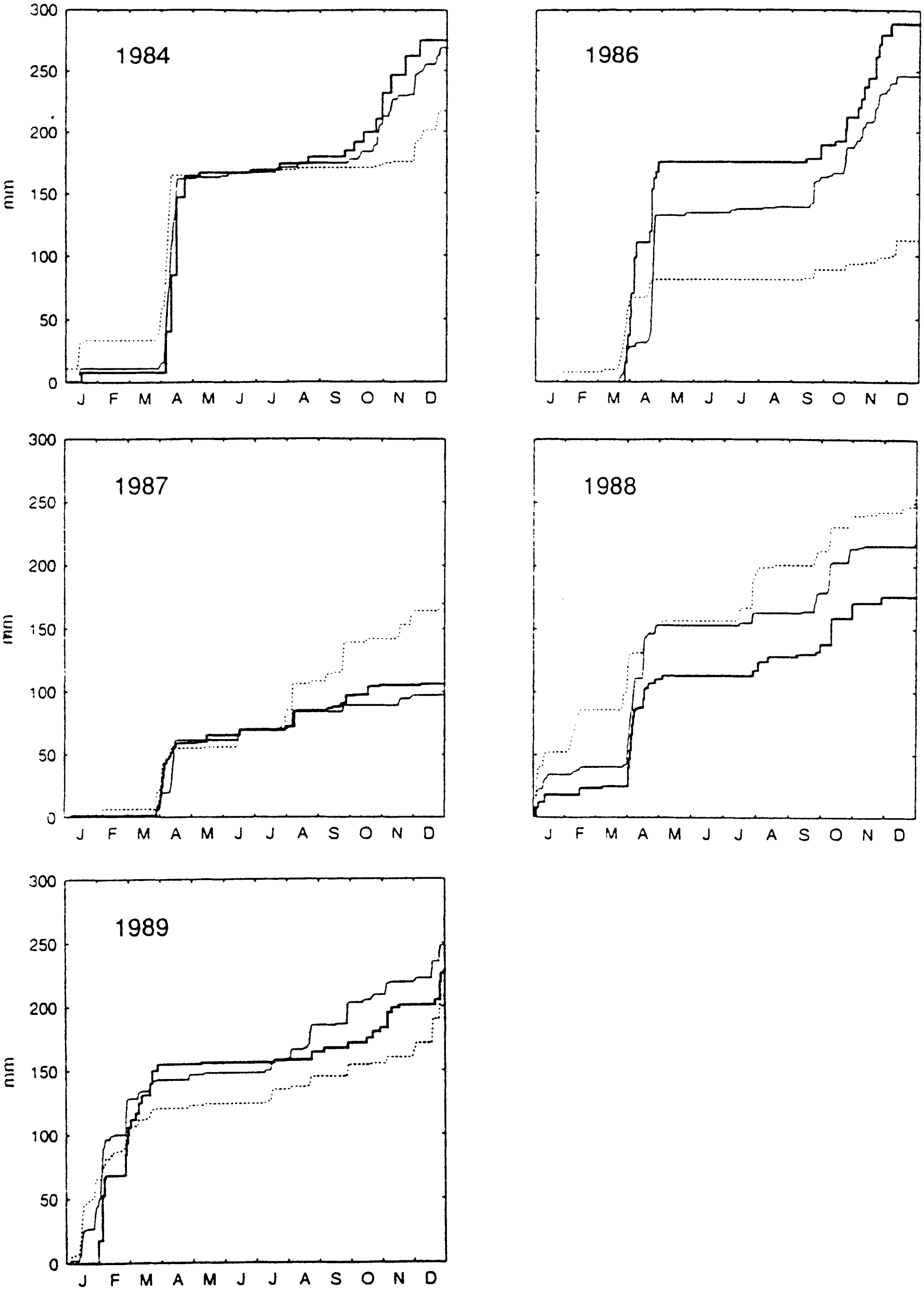

Fig. 2. Cumulative amounts of surface runoff (mm) in 1984 and 1986-1989 at Kotkanoja. Thin solid line: observations; dotted line: original CREAMS model calculation; thick solid line: modified CREAMS model calculation.

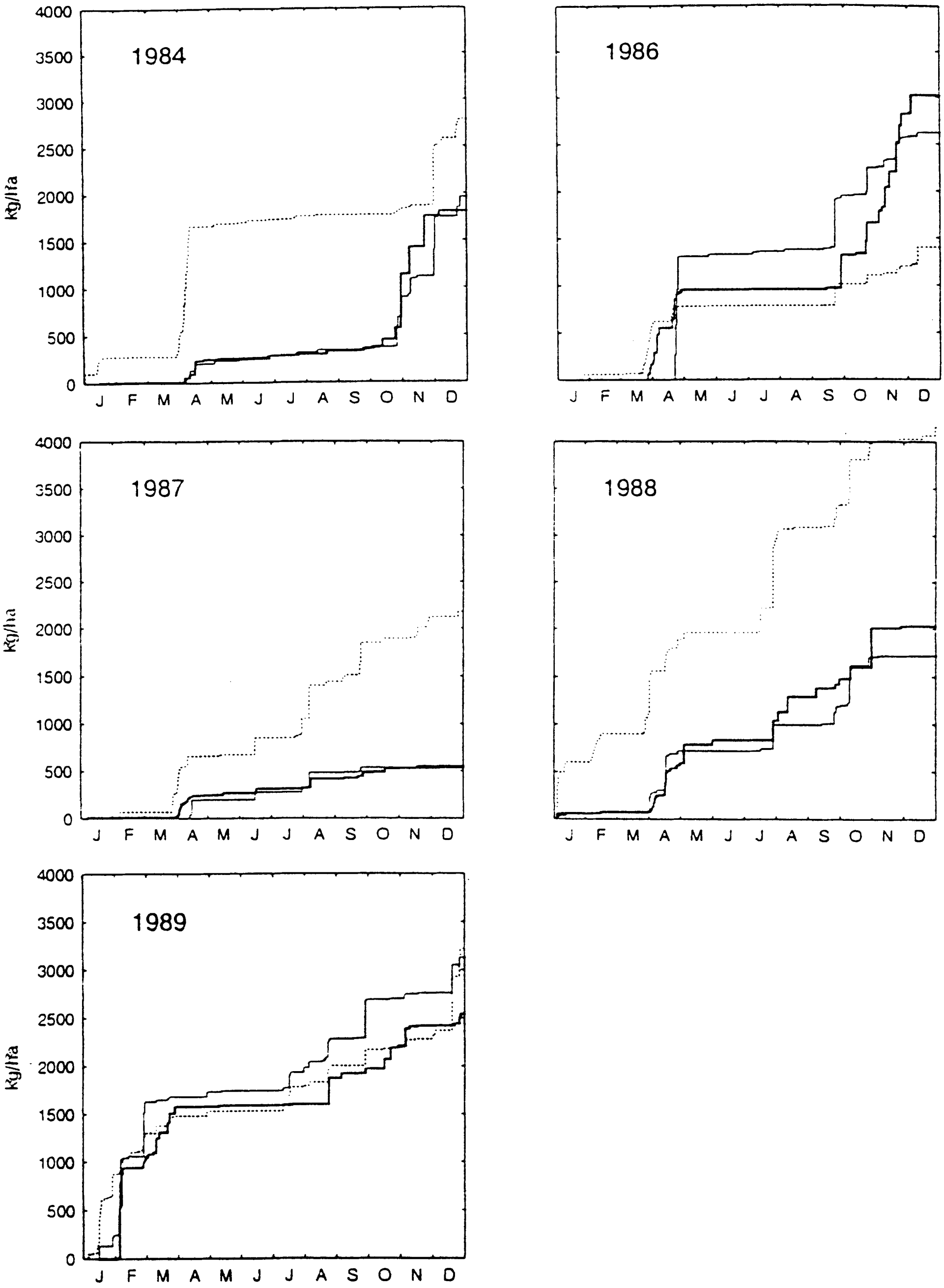

Fig. 3. Cumulative amounts of soil loss (kg ha^{-2}) in 1984 and 1986-1989 at Kotkanoja. Thin solid line: observations; dotted line: original CREAMS model calculation; thick solid line: modified CREAMS model calculation.

Discussion and Conclusions

The new snow accumulation and snowmelt description, adjustable albedo, changes in detachment during snowmelt, and the use of Finnish rainfall erosivity characteristics improved the fit of the CREAMS model compared to the original model version. The calculation of leaf area indices, soil loss ratios and soil transmissivity *within* the model, instead of using user-specified input values, does not influence the model performance, but increases the ease of use of the model.

A further improvement would be the replacement of the SCS Curve Number method by a more physically-based description of runoff processes. Also the soil frost and thaw description as well as the modeling of infiltration into partly thawed soil should be improved. One limitation of the model is that it cannot take into account the effects of macropores and cracks on infiltration and percolation.

The lack of suitable observations for a wide range of slopes, soil types and management practices poses restrictions for further improvements and validation of the model. Nevertheless, the modifications to the CREAMS model described in this paper are a first step towards a better tool for evaluating the effects of different management practices on erosion in Finland.

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