INCORPORATING RAINFALL AND DRYING SEQUENCES INTO ERODIBILITY ASSESSMENT

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Abstract
Lacking integration of short-term soil climate interaction is a key limitation for effective event-based erosion prediction. The development of process-based models for erodibility appears unlikely due to the complex interaction between rainfall, runoff, drying, and soil properties relevant for erosion. In this study, the effects of soil-climate interaction on interrill erosion of two Mexican soils are analysed and a process-based matrix for assessing the short-term changes of erodibility is developed. The matrix provides a qualitative index of the variability of erodibility in a given soil-climate regime and can be used to select events most suited for erosion model calibration and the assessment of uncertainty in prediction results.

Additional Keywords: erodibility, erosion models, event-based prediction, model calibration

Introduction
Process-based erosion modelling is essential to predict the impact of changing environmental conditions without long-term monitoring, simulate extreme events, and assess the off-site effects of low magnitude events on water quality and sedimentation (Valentin, 1998, IPCC 2001). However, the quality of current prediction results is highly variable (Jetten et al., 1999). The limited effectiveness of model performance is largely attributed to a lack of integration of the short-term (minutes to days) interaction between climate and soil resistance to erosion (erodibility) (Bryan, 2000). Erodibility comprises the effects of surface roughness, resistance to detachment, entrainment, and transport on erosion. During a growing season, erodibility of agricultural soil changes both within and between storms, reflecting the effects of wetting, seal formation, compaction, erosion, and drying on soil moisture, soil structure, and surface morphology (Hairsine and Hook, 1995). The results presented in this study show that a successful development of a detailed process-based model for short-term erodibility dynamics appears unlikely, due to the complex interaction between soil, rainfall and erosion. Therefore, careful calibration remains the best option for effective erosion modelling (Kuhn and Bryan, 2004). A matrix-based approach, using soil properties and rainfall-drying regime characteristics, to aid model calibration and guide further research on short-term soil-climate interaction is developed.

Materials and Methods
Laboratory experiments subjecting smectite-rich Kastanozem and Vertisol samples from the piedmont of the Sierra Madre Oriental in Nuevo Leon, NE-Mexico, to a sequence of rainstorms were carried out in the Soil Erosion Laboratory, University of Toronto. The Mexican soils were sampled in the vicinity of Linares and are common in the region east of the Sierra Madre Oriental. They differ in texture, organic matter content, aggregate stability and land use (Table 1). The Vertisol has a coarser texture, higher organic matter content and is used for extensive grazing. The Kastanozem is used for intensive crop farming. Both soils are vulnerable to sealing, have a strong tendency for aggregate formation, and a high shrink-swell capacity. Tests involved simulated rainfall on tilted (5°) interrill flumes (1 m long x 0.2 m wide) with a 0.1 m deep soil layer packed to a density of 1.2 g cm^{-3}, resting on a perforated floor covered by fine cloth, permitting vertical drainage. Rainfall intensity was 60 mm h^{-1}, interrupted for drying between storms. Both soils were subjected to two different rainfall tests, each totalling 180 mm of rainfall. The first test consisted of a three-hour storm with an intensity of 60 mm h^{-1}. During the second test rainfall was interrupted after 60 and 120 minutes and the soil was dried to air-dry conditions before the next storm. Initial and final soil moisture, shear strength and aggregate stability were measured to assess the effect of rainfall, erosion

Table 1. Properties of soils used for interrill erodibility experiments

Soil	FAO Type	% sand	% silt	% clay	%C_{org}	% WSA>0.25 mm
Cropland Kastanozem	Calcic Kastanozem	6.11	49.9	44	1.5	90.8
Grassland Vertisol	Calcic Vertisol	11.6	61.1	28.3	3.0	81

and drying on soil condition (Kuhn et al., 2003). For a detailed description of the rainfall simulation facilities and test procedures see Kuhn et al. (2003).

Results and Discussion

A double-layered seal, consisting of a washed-out layer of loose aggregates at the surface and a cohesive washed-in layer, formed within 60 minutes of rainfall on the Kastanozem (Kuhn et al., 2003). The washed-out layer was removed between 100 and 180 minutes of the three-hour storm, exposing a cohesive washed-in layer. The removal of the washed-out layer led to a marked increase of flow velocities from 0.8 to 1.2 cm s^{-1} and shear strength (from <40 to 150 Pa). Interrill erodibility (Fig. 1), using the formula suggested by Zhang et al. (1998), declined during washed-out layer removal by 50% (Fig. 1), showing that the increase of shear strength dominated soil resistance to erosion, rather than the decline of roughness that increased flow erosivity (Kuhn et al., 2003).

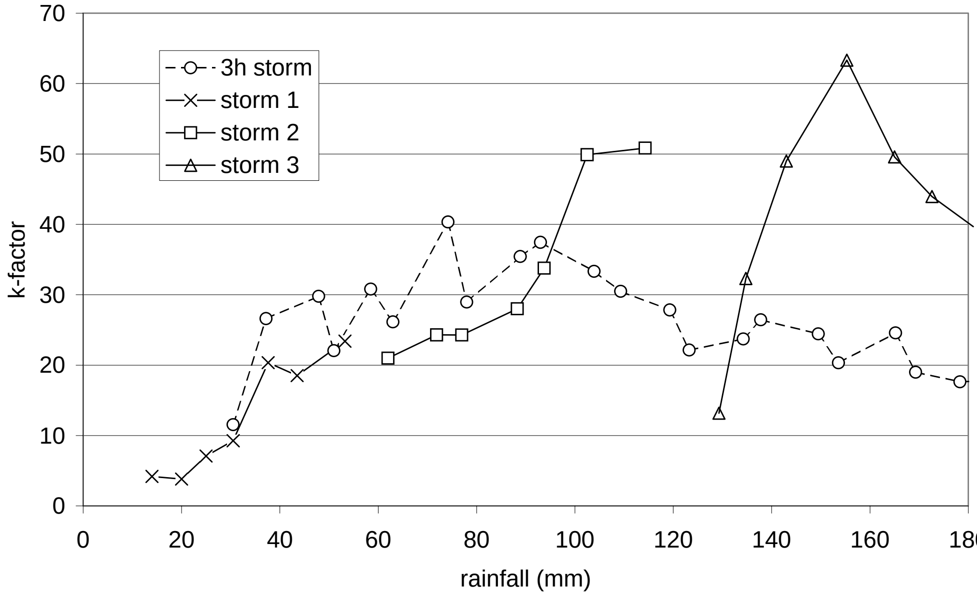

Figure 1. Kastanozem interrill erodibility during three-hour and three one-hour storms

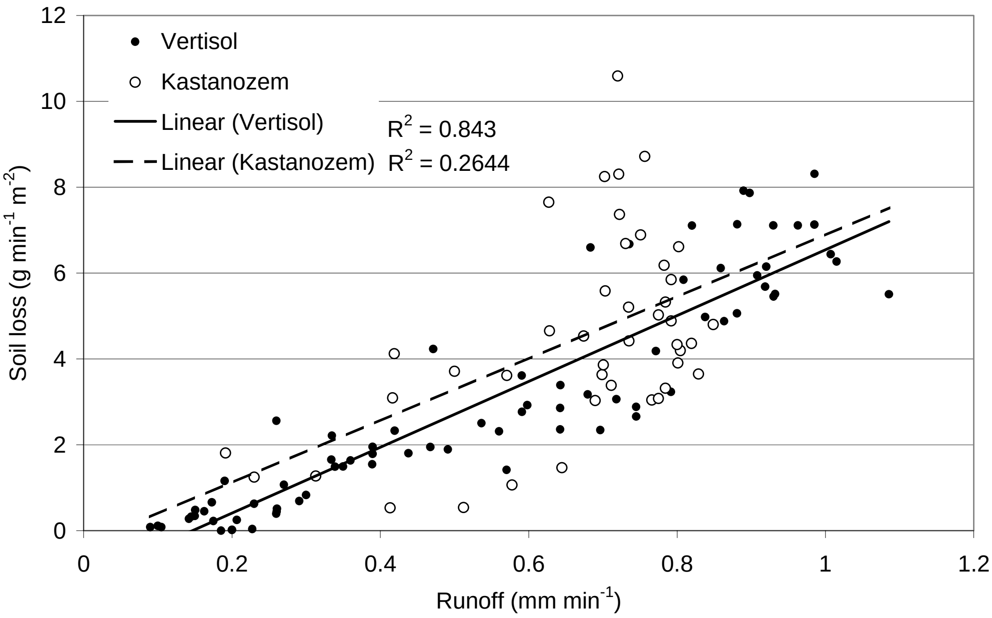

Figure 2. Runoff-soil loss relationship illustrating lower variability of erodibility on the Vertisol than the Kastanozem

Interrupting the rainfall for drying produced a distinctly different pattern of erodibility during the latter part of storm 2 and the entire storm 3 (Fig. 1). More rainfall was required to reach peak erodibility after drying. Redistribution of aggregates by splash was observed before ponding at the beginning of storm 2 and 3. Initially, redistribution of aggregates increased surface roughness, reducing flow velocity and thus rainflow erosion. Later, once pathways of continuous flow across the washed-in layer had formed again, the aggregates that had been moved by splash onto the washed-in layer were available for entrainment, increasing erodibility compared to the three-hour storm. Reduction of aggregate size due to low initial soil moisture after drying may have also enhanced transportability of aggregates, thus also increasing erosion after drying (Kuhn et al., 2003). Towards the end of storm 3, the washed-out layer was removed almost completely, reducing erodibility similar to the three-hour storm. Total soil loss during the three-storm sequence was higher than during the three-hour storm (188 vs. 144 g), indicating that drying did not only affect temporal patterns, but also led to an increase of erodibility. On the Vertisol the formation of the washed-out layer required 120 mm of rainfall, and removal was much slower, leaving an almost continuous cover after 180 mm of rainfall. The difference in seal formation is attributed to higher aggregate stability (68% WSA > 0.25 mm after 180 minutes of rainfall compared to 49% on the Kastanozem). Erodibility difference observed during rainstorm sequences was much smaller than on the Kastanozem, attributed to the slow rate of washed-out layer formation and removal caused by the high aggregate stability (Fig. 2). However, under prolonged rainfall, e.g. during an entire rainy season in NE-Mexico with 390 to 1850 mm of rainfall, seal formation and washed-out layer removal are likely to affect erodibility on the Vertisol as well.

Matrix-based assessment of potential for short-term erodibility changes

The complex set of erosion controlling processes observed on the Vertisol and Kastanozem shows that during individual rainstorm events, frequency, amount and intensity of preceding rainfall and drying cycles strongly influence erodibility. Similar, if not more complex interaction between soil, weather, and runoff determines soil resistance to rill erosion (Kuhn, 2001). Clearly, when predicting erosion for individual rainstorms, the role of the preceding rainfall and drying pattern has to be considered. Due to the complex effects of rainfall and drying on runoff and erosional response adequate information on inter- and intrastorm soil property dynamics is rarely available. However, soil sensitivity and potential of the rainfall-drying regime after tillage for changing erodibility can be assessed using a property-process-based matrix. The results presented above, and other studies examining the linkages between soil properties and interrill erodibility (e.g. Moore and Singer, 1992; Le Bissonnais, 1996) showed that well-aggregated soils that are vulnerable to sealing and that have a pronounced shrink-swell capacity, are highly sensitive to short-term changes of erodibility. The Kastanozem from NE-Mexico falls into this category. Soils without or very stable aggregates, such as the Vertisol (Fig. 2), experience smaller changes of erodibility in response to rainfall and drying (e.g. Zhang and Miller, 1993; Luk et al., 1993; Kuhn and Bryan, 2004). These soils would be considered insensitive or moderately sensitive. Rainfall and drying regimes are categorised in relation to the change of erodibility they can induce on a soil with a given sensitivity. For example, erodibility is less likely to vary widely when amount, magnitude and frequency of rainstorms does not vary strongly between years, leading to a change of erodibility over time, following a similar pattern every year. In NE-Mexico, on the on the other hand, rainfall during the summer rainy season is highly variable, and therefore the rainfall regime has a large potential for introducing short-term changes of erodibility. From year to year, temporal patterns of erodibility therefore vary significantly (unpublished data J. Navar, FCF Linares, Universidad Autonoma de Nuevo Leon). Based on the analysis of soil properties and rainstorm pattern characteristics, a matrix assessing the potential for short-term erodibility changes in a given soil-climate scenario can be developed. Table 2 illustrates this procedure for the two soils used in this study. The matrix provides a qualitative index of short-term erodibility dynamics that can be used for calibration of erosion models and identification of the uncertainty of prediction results. Under circumstances where erodibility is unlikely to change, calibration can be limited to a small number of rainfall events and changes in erosion have to be attributed to other factors, for example vegetation. When soil sensitivity

Table 2. Rainstorm and soil properties relevant for short-term erodibility changes

Soil	Properties	Sensitivity	Rainstorm pattern	Short-term changes of erodibility
Kastanozem	clay rich, sealing, aggregated, shrinking and swelling	high	highly variable amount and frequency, varying degree of drying between storms	very likely, and in a wide range
Vertisol	aggregated, not or limited sealing or crusting	moderate		less likely, relatively small range

or rainfall pattern potential are high, calibration has to rely on events with similar rainfall and drying history than those that are supposed to be predicted. When only a small number of events for calibration are available, prediction results are likely to be uncertain. The matrix can also be used to assess the impact of future climate and land use change on erodibility. A wider range of frequency, intensity and magnitude of rainfall and drying events is likely to increase the range of erodibility, i.e. reduce quality of the prediction results, especially when combined with a change of soil properties relevant for erosion in response to changing climate or land use.

Conclusions

The aim of this study was the development of a conceptual framework for integrating short-term soil-climate interaction into erodibility assessment of dynamic process-based erosion models. The proposed matrix approach provides a qualitative index for the assessment of soil sensitivity to experience short-term erodibility changes and the potential of a rainfall-drying regime to cause such changes. The use of the suggested matrix of short-term variability of erodibility is currently tested using field observations and laboratory tests. Further research has to aim at providing more information on the effects of specific rainfall and drying scenarios on soil properties and subsequent erosional response. In particular, the influence of soil type on structural development in response to drying and on surface water processes during the subsequent storm has to be examined. Furthermore, the effect of rainstorm pattern on surface morphology development, its spatial patterns and feedback on flow erosivity must be integrated into erosion prediction models.

Acknowledgements

The financial support of the Natural Sciences and Engineering Research Council, Canada, through an operating grant to R.B. Bryan, the Government of Canada and the University to the author, and the assistance of Mario Manzano, Milica Kasanin-Grubin and Anke Camphausen in retrieving the soil samples and carrying out the laboratory experiments are gratefully acknowledged.

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