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Soil Loss Estimation on a Local Scale for Soil Conservation Planning

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Abstract

A soil loss estimation of crop fields on a local scale was carried out using the Universal Soil Loss Equation (USLE) and Geographic Information System (GIS) tools. The study site covering 3,009 ha in Kanto, Japan, comprised 11,544 crop fields. The USLE provided an estimate of average annual soil loss based on the following factors: rainfall and runoff (R); soil erodibility (K); topography (LS); crop and management (C); and support practice (P). The dataset of the factors for each field was derived from available land information and field surveys. The K factor was estimated from the sediment yield in the small catchment area. The slope length and steepness of each field, required to compute the LS factor, were derived from field boundary information and a digital elevation model (DEM) constructed using GIS tools. The estimated soil loss rate under the current cropping conditions was found to range from 0.2 to 70.6 t ha^{-1} y^{-1}, averaging 10.5 t ha^{-1} y^{-1}. A distribution map of the rate indicated the fields where conservation measures should be taken. The study suggested that combining the USLE with GIS tools was likely to be useful for estimating soil loss on a local scale for soil conservation planning.

Discipline: Agricultural engineering
Additional key words: USLE, GIS

Introduction

Soil erosion by water leads to soil loss in crop fields. Suspension of the eroded material damages the water quality in downstream areas, and its subsequent sedimentation decreases the capacity of the reservoirs. Thus, the control of erosion is beneficial to agriculture and reduces environmental damage. Spatial and quantitative information on soil erosion on a local or watershed scale contributes significantly to the planning for soil conservation, erosion control, and management of the watershed environment. However, such information is generally not available in Japan because actual measurements of soil loss from crop fields are uncommon.

The Universal Soil Loss Equation (USLE)[7] predicts average annual soil loss rates on a field scale. Several attempts have been made to combine the USLE with Geographical Information System (GIS) tools to obtain large-scale assessment of soil loss[1,2,5]. In Japan, however, large-scale assessment of soil loss using the USLE is uncommon because the factors needed for the equation are not available. For example, a large amount of work is required to determine the topographic factor for individual fields.

The objectives of this paper were to analyze a large-scale assessment of soil loss from crop fields in a pilot study area in Japan using the USLE combined with GIS tools and to estimate soil loss and its spatial distribution under the current cropping conditions.

Materials and methods

The study site which comprised 11,544 crop fields covering 3,009 ha, was selected in the Kanto area, Japan (Fig. 1). The soil consisted mainly of Kuroboku soil, a volcanic ash soil with an organic matter content of about 10% or more. The site was located at an elevation rang-

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ing from 700 to 1,400 m above sea level, and the topography was rolling. Annual precipitation averaged 1,500 mm, of which 63% occurred from May to September. Snowfall occurred frequently in winter. During the summer season, cabbage was the main crop. A decrease in the top soil layer in the fields and the influence of soil erosion on the watershed environment were a cause for concern.

The USLE was applied to estimate annual soil loss rates in each field. The equation is as follows:

$$A = R \cdot K \cdot LS \cdot C \cdot P$$

where A is the annual average soil loss (t ha^{-1} y^{-1}), R is rainfall and runoff factor (MJ mm ha^{-1} h^{-1} y^{-1}), K is the soil erodibility factor (t ha h ha^{-1} MJ^{-1} mm^{-1}), LS is the topographic factor (dimensionless), C is the crop and management factor (dimensionless), and P is the support practice factor (dimensionless). The dataset of USLE factors was obtained from land information and field surveys. Assigned values of the factors are discussed below.

Rainfall and runoff factor (R)

Precipitation data from April 1994 to March 1999 were used to calculate the R factor value. The data were observed at a weather station whose location is shown in Fig. 1 and recorded every 10 min by the Japan Meteorological Agency. The calculations were based on the report of Wischmeier and Smith[7]. A value of 2,890 MJ mm ha^{-1} h^{-1} y^{-1} was obtained for the R factor; this value was considered to be the rainfall erosivity index for each individual field because of the proximity of the station to each field.

Soil erodibility factor (K)

According to the soil map for the site, Kuroboku soil accounted for 97.8% of the crop fields. Thus, one value of the K factor was assigned for all the fields. The value of the K factor was estimated based on a sedimentation survey conducted in May 1999 in a small catchment area close to the study site. The catchment area, which was constructed in April 1996, consisted of 4 crop fields with Kuroboku soil, vegetation strips, catch drains, a collecting canal, and sedimentation tanks (Fig. 2). The fields covered a total area of 2.97 ha. During the survey, the volume of the sediment in the catchment area (except for the fields) and the bulk density of some parts of the sediment were measured. The sediment yield based on these measurements was assumed to be equal to the soil loss from the fields for about 3 y because the survey suggested that no outflow from the catchment area had occurred. Therefore, the annual average soil loss for the fields was considered to be 4.59 t ha^{-1} y^{-1}. Based on the soil loss rate and the USLE factors for the fields, except for the K factor shown in Table 1, the K factor value for the soil was estimated to be 0.0060 t ha h ha^{-1} MJ^{-1} mm^{-1}.

Table 1. USLE factors for the estimation of K factor

USLE factors	Value	Reference
A	4.59 t ha^{-1} y^{-1}	Sedimentation survey
R	3,242 MJ mm ha^{-1} h^{-1} y^{-1}	Precipitation data 1996.5 – 1999.4
LS	1.29 – 1.32	Topographical map of 1:1,000
C	0.3 (Cabbage)	MAFF(1992)
P	1.0 (No practice) 0.3 (Horizontal ridge cropping)	MAFF(1992)

Topographic factor (LS)

The topographic factor (LS) was calculated using the slope length and the slope steepness. The slope length of the field is considered to be generally short in Japan because roads, canals, or levees delimit each field, cutting flow lines. Flow lines on the field can then be generated along the parallel ridges on the field left by tillage rather than on the drainage pattern caused by the topographical features. Thus, it is reasonable to approximate the field shape to the plane slope with the field boundary.

The value of the LS factor for each field was derived using a procedure developed by Kamimura[3]. The field boundary layer of the study site was derived from the dig-

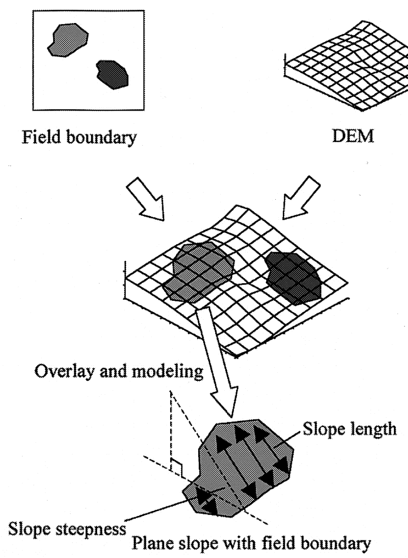

Fig. 3. Modeling into plane slope with field boundary for calculation of the LS factor

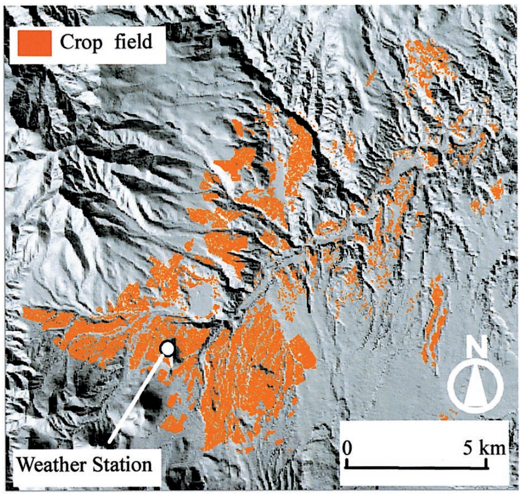

Fig. 1. Distribution of crop fields at the study site
Orange and gray colors show crop fieds and relief map, respectively.

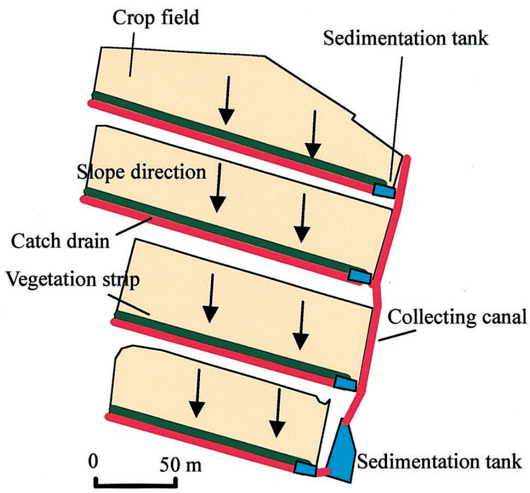

Fig. 2. Catchment area for sedimentation survey

ital images of 92 topographic maps with a 1:2,500 scale using Map Entry[3]. A 2-m-grid digital elevation model (DEM) was constructed by contour lines of the images with IMAGINE (Erdas Inc.). Using the above digital layers, the actual topographical shape of the field was modeled into a plane slope with the field boundary shown in Fig. 3. Next, the average slope length along the slope aspect, slope steepness, and the area for each slope were calculated with CalcLS[3]. Finally, the equations shown in Renard et al.[6] were used to derive the LS factor value for each field.

The average slope length, slope steepness, and area were 39.5 ± 26.1 m, 11.2 ± 8.9% and 0.26 ± 0.39 ha (mean ± standard deviation), respectively. The results suggested that fields with various slopes were distributed at the site. Moreover, a weak correlation was found between the average slope length and the slope steepness (r = –0.14), indicating that there was no effective rela-

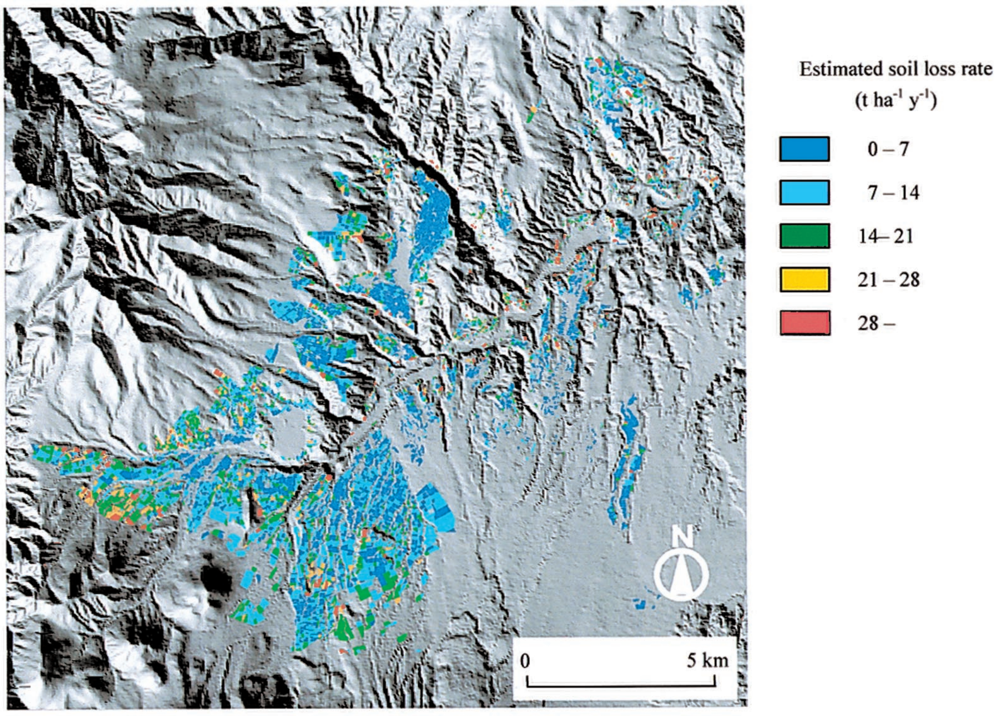

Fig. 4. Distribution map of the estimated soil loss rate under the current farming practices

Table 2. Harvested acreage and C factor of the crops

Crop	Harvested acreage[a)] (ha)	C factor[b)]
Cabbage	2,538	0.3
Feed crops	154	0.17[c)]
Potato	81	0.3
White radish	65	0.4
Chinese lettuce	50	0.3
Others	191	–
Total	3,079	–

a): 1995 Agricultural Census. b): MAFF (1992).
c): Average of C factors for maize, grass and oats.

Table 3. Distribution of the estimated soil loss rate under the current cropping conditions

Estimated soil loss rate ($t\ ha^{-1}\ y^{-1}$)	Area of field (ha)	Percentage (%)
0 – 7	1,116	37.1
7 – 14	1,106	36.7
14 – 21	505	16.8
21 – 28	195	6.5
28 –	87	2.9

tionship between them. The LS factor values ranged from 0.03 to 13.5 with 70% of the fields showing a value of less than 2.0.

Crop and management factor (C)

The crop and management factor (C) value for individual fields was determined based on statistics for harvested acreage of crops in the village including the study site. Table 2 shows the harvested acreage and C factor values. The main crop at the site was cabbage; other crops were grown once every several years to avoid growth retardation due to continuous cropping of cabbage. The statistics were considered to express the average cropping pattern in the long term. The calculation of the weighted mean using the ratio of the harvested acreage gave the value of 0.3 for the C factor representing the average cropping pattern at the site.

Support practice factor (P)

The P factor was assigned a value of 1.0 for the entire site because farmers at the site did not apply soil conservation practices.

Results and discussion

Estimated soil loss under the current conditions

The USLE was applied to estimate the soil loss rate for the study site under the then current farming practices. The rates ranged from 0.2 to 70.6 $t\ ha^{-1}\ y^{-1}$. The average soil loss rate for the entire site was estimated to be 10.5 $t\ ha^{-1}\ y^{-1}$. The results are summarized in Table 3. Unfortunately, it is difficult to validate the results because no data for the actual soil loss of the site had been published.

The estimated rates were compared with the soil loss tolerance. The tolerance defines the value of allowable soil loss that minimally affects soil productivity. MAFF[4] suggested that the tolerance value in Japan was approximately 1.0 $mm\ y^{-1}$ for fields with a top soil layer more than 30 cm deep. The soil loss tolerance of the study site was 7 $t\ ha^{-1}\ y^{-1}$. In 5,737 fields covering 1,893 ha or 63% of the area of the entire study site, the estimated soil loss rates exceeded the tolerance value. The results indicate that some control measures are required for such fields. The distribution of the soil loss rate displayed on the map in Fig. 4 shows the position of the fields where conservation measures should be taken.

Trial calculation for soil conservation planning

Trial calculations were used to estimate the effects of horizontal ridge cropping, a conservation measure, at the site. Horizontal ridge cropping was considered to be a suitable measure because farmers applied it in several fields close to the site. Soil loss rates for the entire fields were derived using the USLE in 2 cases: (1) Case 1, where horizontal ridge cropping was applied to fields with a steepness of 10.5% (6°) or less and (2) Case 2,

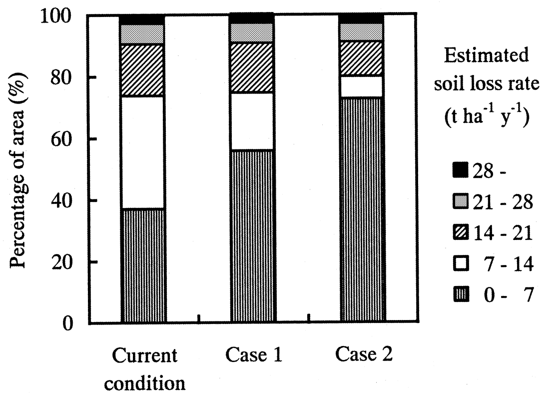

Fig. 5. Distribution of estimated soil loss rate in each case
Case 1 and Case 2 illustrate the application of horizontal ridge cropping to fields with a steepness of 10.5% or less and of 14.1% or less, respectively.

where it was applied to fields with a steepness of 14.1% (8°) or less. Case 1 represents a slope condition that does not decrease the working efficiency of a tractor, and Case 2 a slope condition that allows tractor work to be performed without danger. The P factor values for the horizontal ridge cropping defined by MAFF[4] were used for the trial. The results of the calculations with the P factor are summarized in Fig. 5. The average soil loss rate of the site was 8.3 t ha^{-1} y^{-1} for Case 1 and 6.7 t ha^{-1} y^{-1} for Case 2. The conservation measures reduced the soil loss rate by 21 and 36%, respectively, from the current rate of loss. The rates were below the tolerance values in 1,682 ha of the fields covering 55.8% of the area of the entire site in Case 1, and 2,189 ha covering 72.8% in Case 2. The conservation measures would be effective at the site. However, in both cases, the effect in fields where the rate was 14 t h^{-1} y^{-1} or higher was not appreciable, implying that these fields require more rigorous conservation measures.

Method of estimation of soil loss using the USLE and GIS

The USLE was calculated based on data obtained using GIS tools and from available land information, giving the estimated average value and spatial distribution of the soil loss rate in the fields. The results indicated that the procedure could be useful in Japan for estimating the soil loss on a local scale. Availability of USLE factors obtained using GIS tools would enable comparative planning with several possible scenarios, as shown in the example of the application of one type of conservation presented in this paper. However, since in Japan information for some of the USLE factors is not available, the factors must be estimated instead of being identified using standard procedures; for example, in this study, the K factor was estimated from the sedimentation survey instead of being measured using a standard procedure.

In future work, measurement of the K, C, and P factors should enable to expand the area where soil erosion assessment is possible. An integrated system consisting of an analysis module for transport and deposition of eroded materials in a watershed and a soil erosion assessment module for GIS, as described in this paper, could be effective for environmental management planning of watersheds.

Conclusion

In this study, a procedure was described in which the USLE was combined with GIS tools and available land information for the estimation of soil loss on a local scale. The procedure was applied to a pilot study site of 3,009 ha comprising 11,544 crop fields in the Kanto area, Japan. The estimated soil loss rate ranged from 0.2 to 70.6 t ha^{-1} y^{-1}, averaging 10.5 t ha^{-1} y^{-1}. The distribution map of the rate showed the fields where conservation measures should be taken. In addition, trial calculations were carried out to obtain the effect of horizontal ridge cropping, a conservation measure.

The procedure is likely to be useful for assessing the soil loss on a local scale in Japan. In future work, identification of the K, C, and P factors may enable to expand the area where assessment of soil erosion is possible.

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