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EFFECTS OF FOREST LAND MANAGEMENT ON EROSION AND REVEGETATION AFTER THE ERUPTION OF MOUNT ST. HELENS

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ABSTRACT

The 1980 eruption of Mount St. Helens covered soils with a tephra blanket and killed the forest tree cover in a 550 km^2 area. After the eruption, rates of sheetwash and rill erosion, and plant cover were measured on tephra-covered hillslopes which had been subject to three land-management practices: grass seeding; scarification, and salvage logging. On rapidly-eroding hillslopes subject to grass seeding, limited plant covers were established only after erosion had declined sharply. Logging of trees downed by the eruption and scarification of previously logged surfaces slowed erosion, although the effect was small because erosion rates had already slowed substantially by the time these two practices were implemented. The factors controlling erosion, revegetation, and their relative timing at Mount St. Helens are similar to those following explosive volcanic eruptions elsewhere, suggesting that grass seeding is not likely to be effective at slowing erosion following most tephra eruptions, and that early mechanical disturbance could be an effective erosion-control measure. The results also indicate that even without deliberate conservation measures, processes which mechanically disturb a surface layer of low hydraulic conductivity (such as frost-action or trampling) can radically reduce runoff and erosion before revegetation has an important effect.

KEY WORDS Tephra erosion Volcanoes Revegetation

THE PROBLEM

The 1980 eruption of Mount St. Helens caused the widespread destruction of forest vegetation and deposited a vast amount of tephra in the mountain terrain to the north. Tephra began immediately to erode by sheetwash and rillwash into the Toutle River. Several questions were posed for land managers: How much sediment would erode into the Toutle–Cowlitz–Columbia River system? For how long would high rates of erosion continue? How might the amount of erosion be estimated? What would be the effectiveness of a seeding programme in reducing erosion? How would the salvage logging of devastated forests or planting of new trees affect erosion?

The first three of these issues have been discussed elsewhere (Collins *et al.*, 1983; Collins and Dunne, 1986; Collins and Dunne, in press), as have other sediment sources and transport processes resulting from the eruption (Lehre *et al.*, 1983; Dunne and Fairchild, 1984). This report discusses the effects of grass seeding, logging, and scarification on erosion of tephra by sheetwash and rillwash.

THE UPPER TOUTLE RIVER BASIN

Hillslopes are generally straight to convexo-concave in the western part of the basin (Figure 1) with average gradients of 0·30 and lengths of 560 m, whereas to the east hillslopes are irregular and steeper with average

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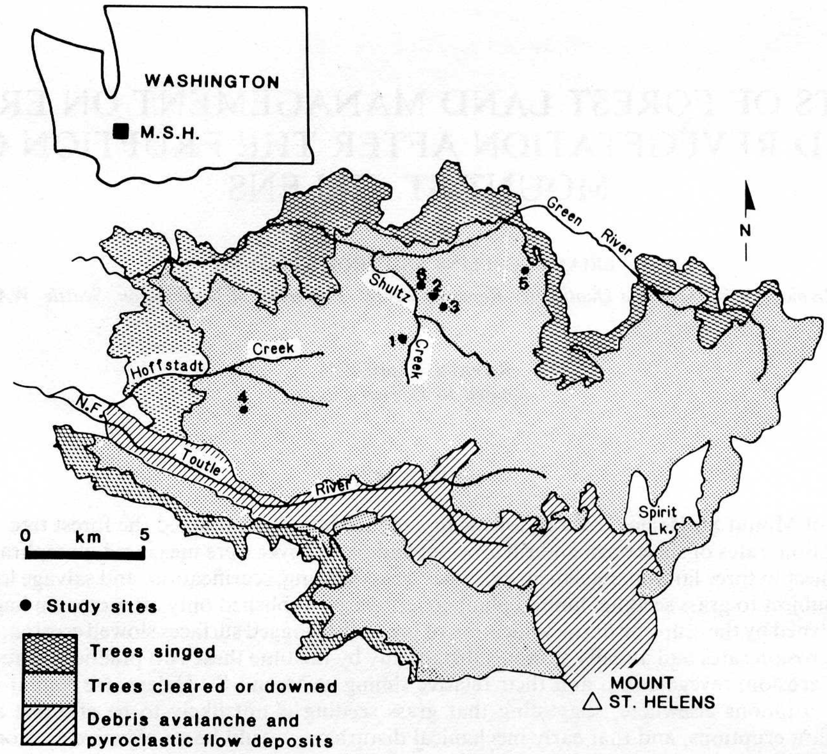

Figure 1. Area of tephra-covered hillslopes included in the study and location of study sites

gradients of 0·45. Elevations range from 350 m to 1786 m. The basin is underlain by Tertiary volcanics, which have weathered to well-aggregated loamy colluvium with a high infiltration capacity. Several metres of Holocene tephra augment the colluvium in the eastern-most portion of the Toutle River basin; this layer thins to the west where the total colluvial cover averages 1–1·5 m in thickness. Before the eruption, forests below an elevation of about 900 m, were dominated by Douglas fir (*Pseudotsuga menziesii*), Western hemlock (*Tsuga heterophylla*), and Western redcedar (*Thuja plicata*) and at higher elevation by true firs (*Abies* sp.) (Franklin and Dyrness, 1973). Intensive logging during the preceding 40 years created a patchwork of old-growth forest, young managed stands, and recently clearcut forests.

Annual precipitation between 1930 and 1957 followed a strong WNW to ESE orographic gradient and ranged from 1650 to 3050 mm yr^{-1} (USDA SCS and US Weather Bureau, 1975); approximately 75 per cent occurred during a six-month period beginning in October with a monthly maximum in December. Storms are generally long and of low intensity: for example, estimated average intensities of the 2-year, 1- and 24-hour storms for the Shultz Creek catchment averaged 14 and 4 mm hr^{-1} respectively (Miller *et al.*, 1973). The maximum 1-hour precipitation intensities at a gauge at an elevation of 525 m in the Shultz Creek catchment were only 9·9 and 9·4 mm hr^{-1} during the 1980–1981 and 1981–1982 water years, respectively.

EFFECTS OF THE 1980 ERUPTION ON HYDROLOGY AND EROSION

On 18 May, a lateral eruption discharged tephra throughout an 180° arc north of the volcano in a several-kilometre-thick flow from which finer particles rose in thick clouds. The eruption radically altered the hillslope hydrology by covering the permeable forest soil with tephra and by killing the above-ground portions of nearly all plants within a 550 km^2 area. Trees were uprooted and removed from many south-facing hillslopes within 13 km of the volcano. On hillslopes sheltered from the blast and at distances up to 28 km from its source, trees were uprooted or snapped but not removed. Where the tephra flow lifted from the ground, trees were killed but left standing in a 0–4 km wide band (Figure 1). Three cover conditions resulted (see Collins *et al.*, 1983, Figure 2 and Figure 3a): (1) forests cleared by the blast or clearcut within the decade prior to the eruption, on which virtually no vegetative cover remained; (2) blowndown forest in which tree trunks and some large branches provided a limited amount of cover; and (3) singed forests in which trees remained upright and retained their branches. On hillslopes near to and facing the vent, the forest floor and part or all of the mineral soil were scoured by the tephra flow. However, throughout most of the affected area, the forest floor was either unaffected by the eruption or was mixed with the lower several centimetres of tephra.

The tephra layer was a mechanically weak and easily erodible sand with a median grain size that decreased with distance from the vent from about 1 mm at 10 km to 0·2 mm at 25 km, and a thickness which decreased from about 1 m at 10 km to 0·02 m at 25 km (see Collins *et al.*, 1983 and Collins and Dunne, 1986 for more detail). Overlying this layer was a silty air-fall tephra layer deposited immediately following the tephra flow. This silty layer had a low infiltration rate.

Before the eruption, infiltration capacities of the heavily-forested, gravelly, and sandy loams greatly exceeded rainfall intensities and snowmelt rates. Storm runoff was generated mainly by subsurface stormflow

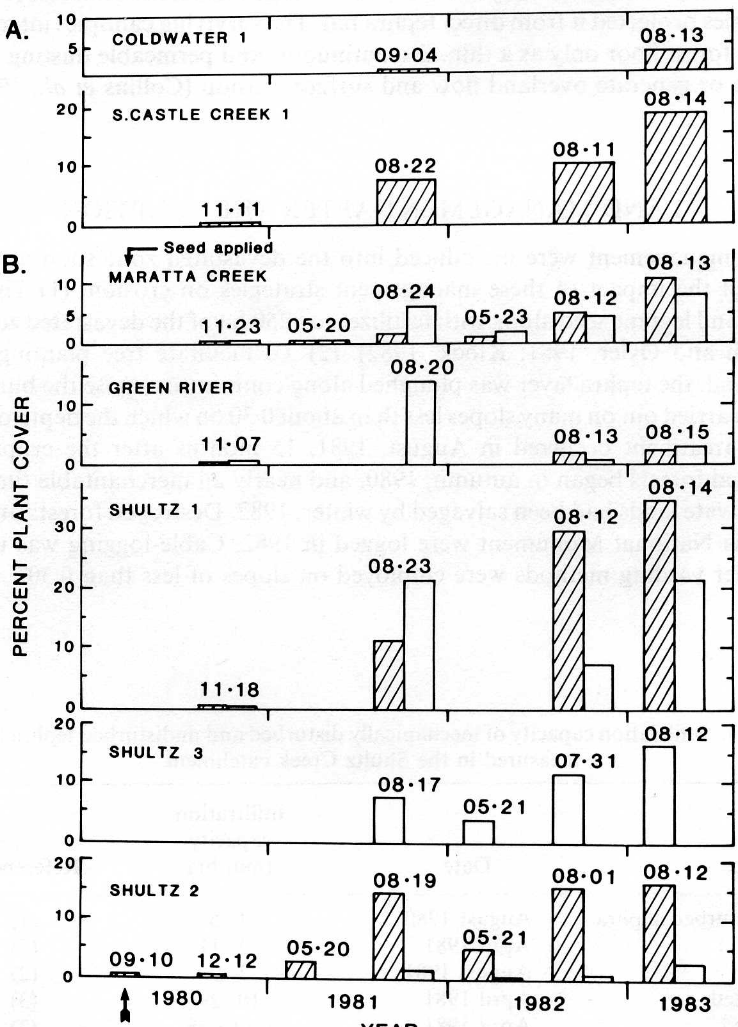

Figure 2. (A) Cover of native plants on sites undisturbed and unseeded since the 1980 eruptions (B) Cover of native plants (shaded bars) and seeded plants (unshaded bars) on sites within the SCS seeding areas

and saturation overland flow from restricted areas of the landscape, and by overland flow from the surfaces and margins of logging roads. The major erosion processes were various forms of mass wasting, and the average sediment yield of the Toutle River basin was probably 100–200 t km^{-2} yr^{-1} (Larson and Sidle, 1980; Reid *et al.*, 1981; Swanson *et al.*, 1982).

In August 1980, Herkelrath and Leavesley (1981) measured infiltration capacities of 1–5 mm hr^{-1} on silty airfall tephra in the basin of Shultz Creek (Table I). Comparison of these measured infiltration capacities with measured rainfall intensities indicates that overland flow occurred frequently during the first post-eruption year. We observed overland flow on the tephra surface frequently between September and November, 1980.

Erosion was rapid, with rates between May 1980 and May 1981 being up to 76 mm on individual hillslopes, and averaging 26 mm over 350 km^2 of tephra-covered hillslopes (Collins *et al.*, 1983). However, erosion underwent a rapid decline to 3·8 and 1·8 mm during the second and third years after the eruption, respectively (Collins and Dunne, 1986). This occurred because a stable rill network developed and the divides between rills became more permeable and less erodible. As a consequence of the slowed erosion, about 85 per cent of the tephra will remain in storage until mass wasting again dominates hillslope evolution.

Under singed trees, the falling needles were mixed with tephra as it fell and during later rainstorms, creating a protective mat that inhibited erosion. Beyond the zone of singed trees, the forest floor was preserved as the canopy of standing trees protected it from direct tephra fall. The surviving canopies intercepted tephra, which later fell to cover the forest floor only as a thin, discontinuous, and permeable dusting, which did not lower infiltration capacities or generate overland flow and surface erosion (Collins *et al.*, 1983).

LAND MANAGEMENT AFTER THE ERUPTION

Three forms of land management were introduced into the devastated zone soon after the eruption, and questions arose about the impact of these management strategies on erosion. (1) The Soil Conservation Service applied grass and legume seed along with fertilizer to 8250 ha of the devastated zone in September and October, 1980 (Stroh and Oyler, 1981; Klock, 1982). (2) To facilitate tree planting in thick tephra on previously clearcut land, the tephra layer was ploughed along contour to expose the buried soil surface. This soil scarification was carried out on many slopes less than about 0·30 on which the depth of tephra ranged from 0·15 to 0·40 m. The treatment occurred in August, 1981, 15 months after the eruption. (3) Logging in blowndown and singed forests began in autumn, 1980, and nearly all merchantable timber in the destroyed forest on state and private lands had been salvaged by winter, 1982. Destroyed forests on federal land outside the Mount St. Helens National Monument were logged in 1982. Cable-logging was used on most slopes, though tractor-skidder yarding methods were employed on slopes of less than 0·30.

Table I. Infiltration capacity of mechanically disturbed and undisturbed tephra layers measured in the Shultz Creek catchment

Surface	Date	Infiltration capacity (mm/hr)	Reference*
Undisturbed tephra	August 1980	1–5	(1)
	April 1981	2–11	(3)
	August 1981	7–9	(2)
Scarified	April 1981	10–29	(3)
Logged	April 1981	up to 28	(3)

* (1) Herkelrath and Leavesley (1981); (2) G. S. Leavesley, U.S. Geol. Survey, personal commun. (1981); (3) Fiksdal (1981)

METHODS

We measured erosion at large arrays of stakes located on twelve 2- to 16-hectare plots within the different cover types and on different tephra textures (Collins *et al.*, 1983; Collins and Dunne, 1986). Eight of the 12 sites were located within areas seeded by the Soil Conservation Service. We also measured the cover of native and of seeded plants at each of the 135 to 300 erosion stakes on each plot on the occasions when erosion measurements were made, using a point-intercept method (Mueller-Dombois and Ellenberg, 1974), in which a 20 × 20 cm frame with parallel string grids was centred at each erosion stake and was used to sight 20 points at which the presence or absence of vegetation was noted. The cover of seeded and native plant species was noted separately.

We also installed transects of erosion stakes and measured rill cross-sections at three sites on scarified hillslopes and on adjoining unscarified slopes (Table II). These measurements began in September and October, 1981, 1–2 months after scarification. Measurement at the stakes was confounded by settling of the organic-rich surface and so only the rill cross-sections and visual observations of the surface morphology were used to assess erosion on these sites.

Three sites (Table II) were established on logged hillslopes about 1 month after the trees were removed: sites 4 and 5 in December, 1980, and site 6 in August, 1981.

REVEGETATION AND EROSION

Plant cover values from the undisturbed, unseeded sites are shown in Figure 2A. Each site was clearcut prior to the eruption. Plant cover values on the three sites in blowndown forest are not included because the covers were negligible (Table III). Nearly all plant recovery was the result of emergence of buried plants. No cover values exceeded one per cent in 1980. This contrasts with the rapid plant recovery that Stevens *et al.* (in press) documented on the thin (0·09 m) tephra layer in the low-elevation (550 m), northwestern portion of the devastated zone, where as early as July 1980 the native-plant cover in clearcuts was as great as 89 per cent on 1 m^2 plots. The majority of our plant cover measurements also contrast with plant cover on the tephra layers thicker than about 0·30 m which have experienced very slow rates of plant recovery. In part this is because of the high elevation of these hillslopes. For example, in summer 1982 the Coldwater site at an elevation of

Table II. Study sites on scarified and logged hillslopes. Numbers in the first column refer to locations in Figure 1

Site	Surface type	Gradient	Elevation (m)
(1) Rhino 1	scarified	0·22	885–915
(2) Rhino 2	scarified	0·14	855–885
(3) Rhino 3	scarified	0·14	930–970
(4) Hoffstadt 2	logged	0·45	975–1035
(5) Miners Creek	logged	0·51	1100–1200
(6) Schultz Creek	logged	0·32	870–910

Table III. Plant cover in blowndown forests

Site	Percent plant cover 1981	1982	1983
Green River 1	N.M.	0.1*	N.M.
Castle 2	2·0	1·5	7·7
Coldwater 2	1·4	2·0	N.M.

* Cover consisted partially of seeded ryegrass. The other two sites were not in seeded areas

1150 m had widespread areas from which the tephra layer had been completely removed, exposing buried soil, and yet plant growth was less than 2 per cent. In addition, slopes with thick tephra layers lie near the volcano where the forest floor was more severely scoured than at greater distances from the vent. However, revegetation tephra layers thicker than 0·20 m was limited mainly because they formed a barrier to emerging plants, so that even at lower elevations the occurrence of plants on tephra thicker than 0·20 m was generally limited to the buried soil exposed in rills, near stumps, and along stream banks (Figure 3).

Our sites represent moderate tephra thicknesses and elevations. Native plant cover on the seven sites shown in Figure 2 increased from the negligible cover values measured in 1980 to an average of 6·1 per cent in August 1981, 9·3 per cent in August 1982, and 14·4 per cent in August 1983 [or 4·6 per cent ($n = 10$), 6·9 per cent ($n = 10$), and 13·6 per cent ($n = 8$) when the blowndown forest sites in Table III are included].

The seeded plants also had cover values near zero throughout late 1980 and early 1981, but the cover density ranged from 0 to 20 per cent (average 9·1 per cent) by August 1981, changing to an average of 2·5 per cent in August 1982 and 6·9 per cent in August 1983 (Figure 2). The same trend is indicated on the control halves of the three scarified plots discussed below, where the average seeded plant cover changed from 10·7 per cent in 1981 to 3·8 per cent in 1982, and 5·1 per cent in 1983. The temporal pattern of cover development is illustrated in Figure 4, a photographic record of plant cover on the uppermost transect of a site in the Shultz Creek basin.

Rates of sheet and rill erosion declined rapidly during the first wet season after the eruption (Figure 5). The decrease of erosion, and particularly of rill erosion, preceded the recovery of native plants as well as the establishment of seeded plants. This reduction in erosion was clearly not brought about by the plant recovery which began only in summer 1981. Moreover, erosion rate decreased as rapidly on sites where no plants were

A B

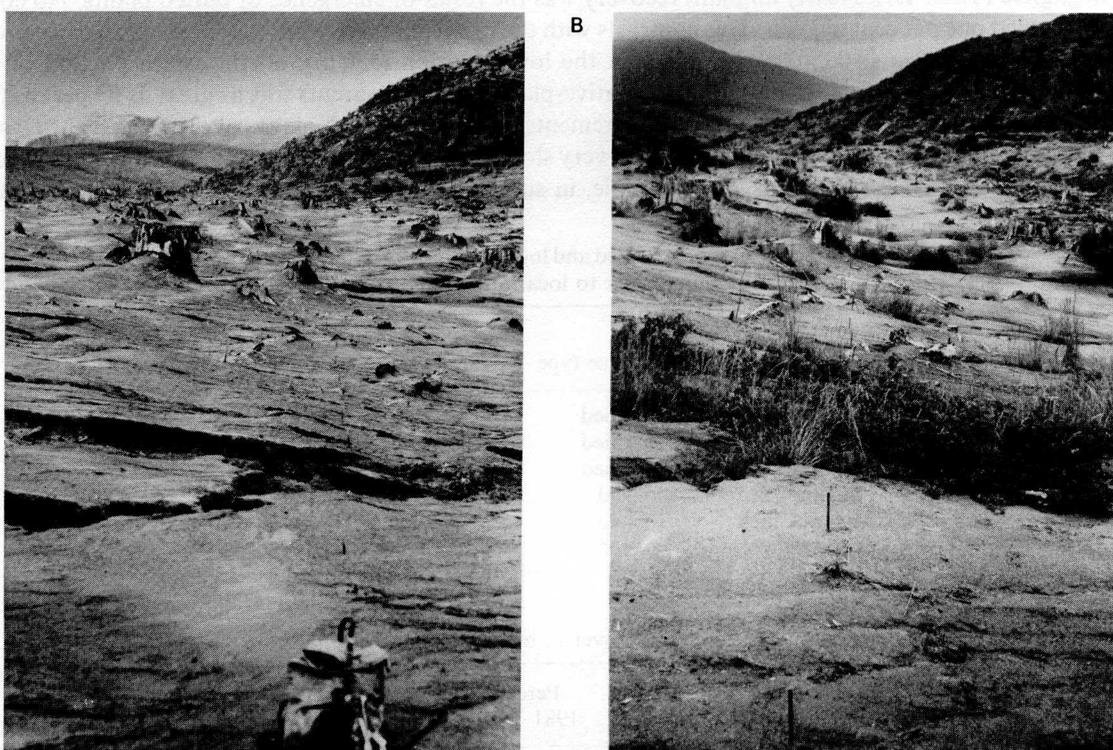

Figure 3. The lowermost transect on the Maratta Creek site on (A) 23 November 1980 and (B) 15 August 1982. There was no extension of the drainage network between photos, the cross-section of the large rill in the foreground became somewhat rounded, smaller rills became less distinct. The silty surface was present at both times. The plant cover in the 1982 photo was dominated by plants of *Rubus* sp. with scattered grasses and some seeded legumes. Note the localization of plants in rills and near stumps and organic debris. Tephra thickness along the transect averaged 30–40 cm, somewhat more than along other transects on the site

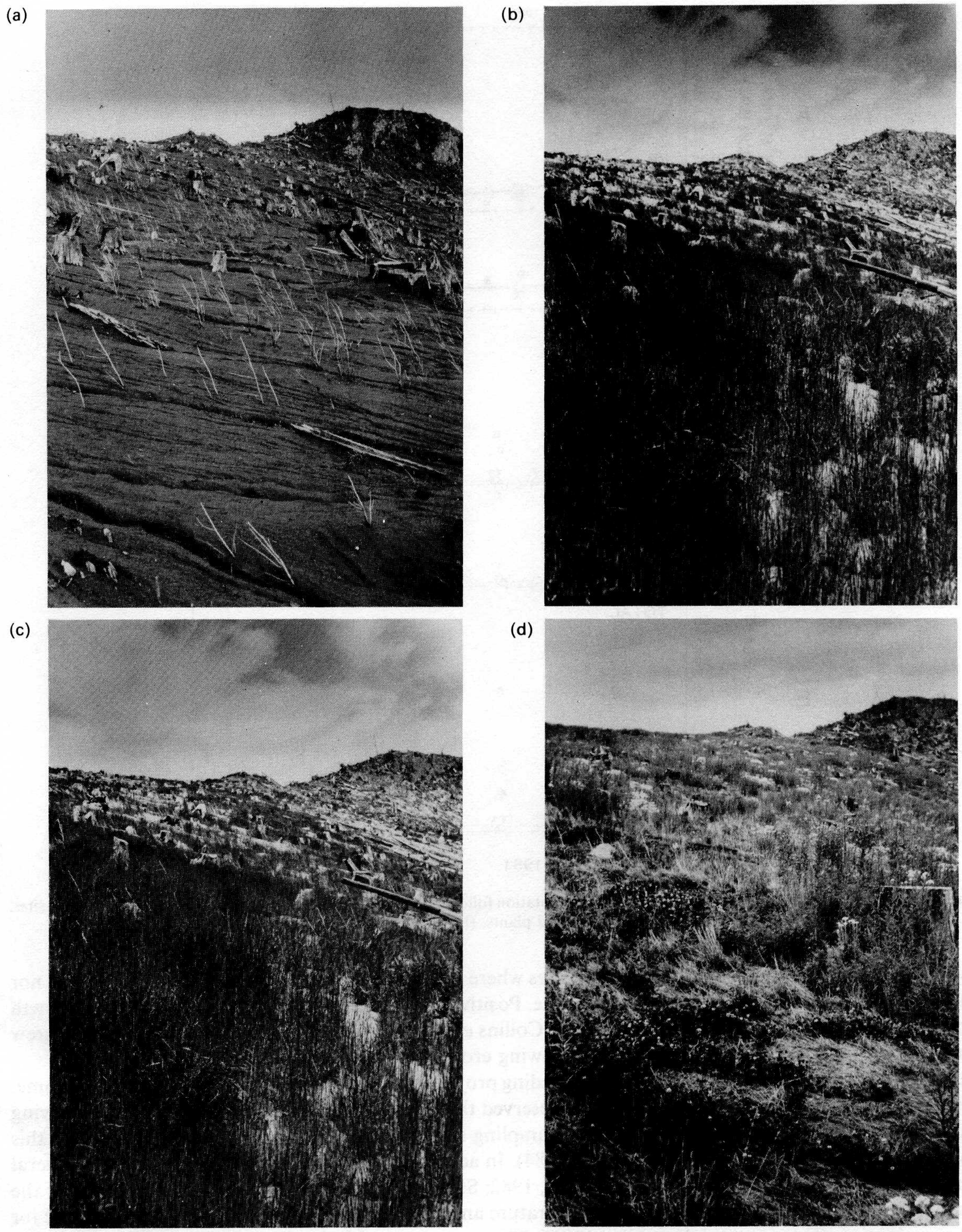

Figure 4. Plant cover along the uppermost transect of the Shultz 1. On 11 November 1980, (a), there is virtually no plant cover. On 2 July 1981, (b), the seeded grasses are undergoing a period of rapid growth that began the previous month. By August 1981, (c), seeded plants have attained a maximum cover and dominate the native plants. In August 1982, (d), plant cover is dominated by native species, chiefly *Epilobium* sp. and *Anaphalis margaritacea*. Also visible is litter of ryegrass and living legumes

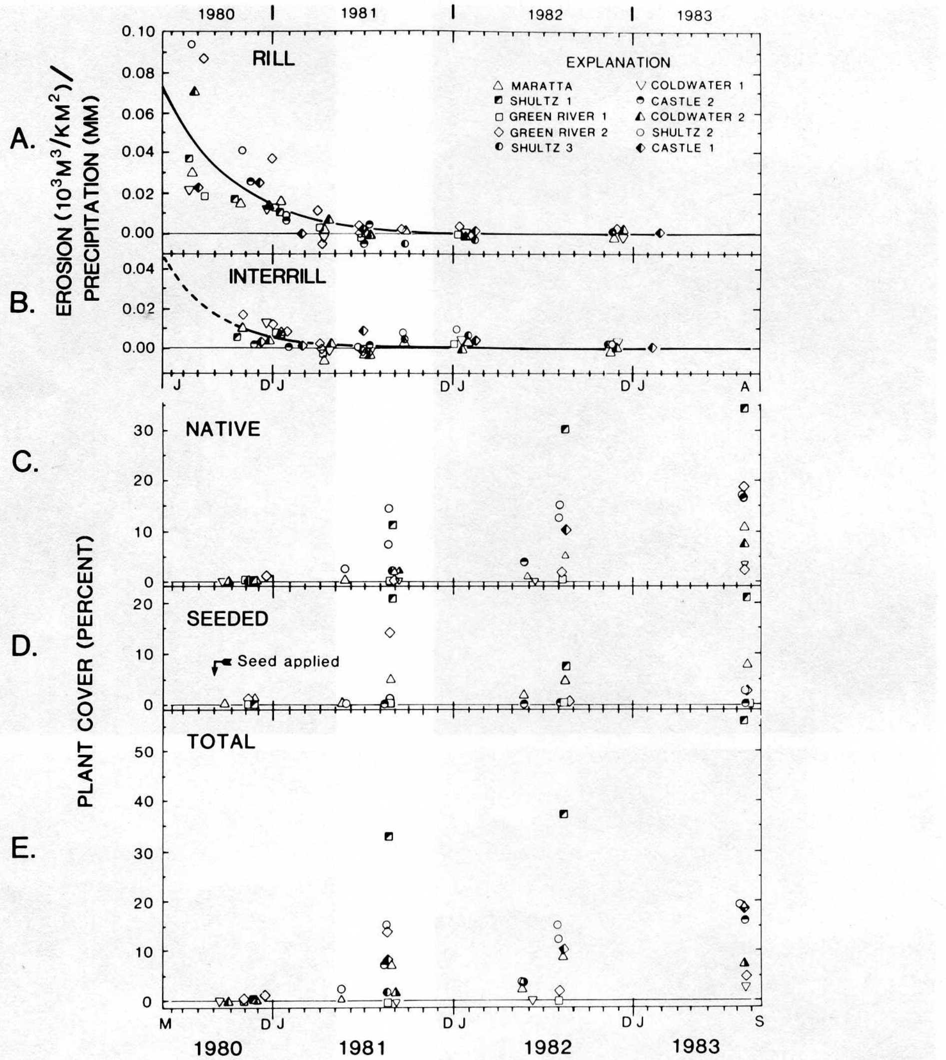

Figure 5. (A) Rill erosion and sheetwash (B) per unit of precipitation following the eruption; (C) cover of native plants on the same sites; (D) cover of seeded plants; (E) total plant cover

present throughout the first several years as on sites where plants recovered, so that neither native plants nor seeded plants could have brought about the decline. Positive correlations between gradient and plant growth (Klock, 1982) and between gradient and erosion (Collins *et al.*, 1983) emphasize that the seeded plants grew after the most rapid erosion, and rather than slowing erosion, benefitted from it.

Several factors explain the poor results of the seeding project. In their evaluation of the seeding programme, the USDA Forest Service (Klock 1982, p. 170) observed that plant roots could not penetrate tephra having bulk densities greater than $1{\cdot}4\ g\,cm^{-3}$, and our sampling showed that the upper tephra layer exceeded this value, ranging from $1{\cdot}4$ to $1{\cdot}7\ g\,cm^{-3}$ (Collins, 1984). In addition, the tephra mantle was deficient in several essential nutrients, most notably nitrogen (Klock, 1982; Stroh and Oyler, 1981). The smooth surface of the tephra layer inhibited seed lodgement, and temperature and soil moisture conditions were unfavourable for seed germination (Frenzen and Franklin, 1985). These same conditions also prevented the widespread colonization of tephra by native plants. Finally, seeds were applied late in the growing season so that germination and growth of the plants during 1980 was limited except at the lowermost elevations (Stroh and Oyler, 1981).

INFLUENCE OF SCARIFICATION ON EROSION AND REVEGETATION

Scarification radically altered the bulk density (Collins, 1984, Table III), infiltration rate, and microtopography. The infiltration capacity measured on one scarified slope on the silty air-fall layer in the Shultz Creek catchment ranged between 10 and 29 mm hr^{-1} (Fiksdal, 1981), much greater than the values measured on undisturbed tephra (Table I), and greater than the maximum hourly precipitation intensity recorded during the study (9·9 mm hr^{-1} measured on 27 September 1981 at a gauge in the Shultz Creek catchment), indicating that little or no runoff was generated on the scarified surface. Scarification increased the infiltration capacity by mixing the uppermost, poorly permeable silty tephra layer with the underlying sandy layer and with the underlying soil and organic matter, and by creating an irregular surface. These effects cannot easily be quantified separately, but Fiksdal reported that on one unscarified plot where erosion had removed the silty air-fall ash layer, this alone increased the infiltration capacity from 2 mm hr^{-1} measured on an adjacent, relatively uneroded site to 10 mm hr^{-1} on the eroded site.

The creation of microtopographic barriers to the downslope movement of water and sediment had an additional effect on infiltration that could not be measured in a small-plot experiment. The contour-trenched topography caused the local ponding of water and sediment. Little runoff was generated on the scarified slopes, but where runoff was channelled onto the scarified areas from adjacent, unscarified slopes or from roads, water and sediment were effectively trapped by the contour trenches (Figure 6).

In addition to these effects on infiltration, the erodibility of the surface was decreased by the exposure of coarser tephra particles, organic matter, and woody debris. There was very little field evidence of rilling or sheetwash on the three scarified plots, with only 0·6, 3·1, and 4·2 rills per 100 m of contour measured on the three respective plots in May 1982, and the rills being small and limited to individual trenches. In addition, any eroded sediment would have collected in the undrained trenches, because few cases of trench breaching were observed.

Plant cover on the three scarified plots was measured in 1981, 1 to 2 months after the plots were scarified, and again during the following spring and summer, and in August 1983. Results of the cover measurements are shown in Figure 7. Plant cover in each summer increased on both scarified and unscarified plots, with the latter having denser covers in each year. Results from subsequent years may be expected to show that scarification promotes long-term plant recovery because it created a rough surface and lowered the bulk density which for the upper 108 mm averaged 1·4 g cm^{-3} on the undisturbed plots and 1·0 g cm^{-3} on the scarified plots (Collins, 1984, Table III). Exposure of the buried soil, organic matter, and viable plant roots could also be expected to promote both colonization and recovery of buried plants.

INFLUENCE OF LOGGING ON EROSION AND REVEGETATION

Logging of blowndown trees mixed tephra layers, soil, and organic matter, created an irregular and less erodible surface (Figure 8), and resulted in an increase of the infiltration capacity that was similar to the increase resulting from scarification (Table I).

There was even less field evidence for erosion on the logged slopes than on the scarified slopes. The rill densities were 1·3, 3·1, and 0·4/100 m of contour on sites 4, 5, and 6 respectively, and the rills were small, discontinuous, and confined to skid trails. Sheetwash and rainsplash appeared to have accomplished only local redistribution of sediment. The August plant cover was low and rose only slowly in the years 1982 and 1983 on both logged sites (Table IV) and in blowndown forests that were not salvaged (Table III).

Inferences from the infiltration and precipitation data and the visual observations and measurements cited above indicate that essentially no erosion took place after either scarification or logging. However, because even on the adjacent, undisturbed tephra covers, the erosion rate had declined dramatically by the dates of the land treatment, neither contributed significantly to erosion control in the Toutle River basin.

DISCUSSION

Studies of tephra erosion on Mount St. Helens and other valcanoes suggest that the erosion rate peaked soon after the eruptions and then declined rapidly. Implicit or explicit in each report is the conclusion that this

Figure 6. Runoff from adjacent, unscarified slopes or from nearby roads was in some instances diverted onto scarified slopes. The contour trenches created by scarification functioned as effective traps of water and sediment. Photo taken in January 1982 on the Rhino 2 site

decline is not caused by a recovery of vegetation, but instead by an increased infiltration capacity and decreased erodibility of the tephra layer, and the development of a stable rill network (Collins and Dunne, 1986; Kadomura *et al.*, 1983).

There are also similarities in the patterns of revegetation following eruptions. Early plant colonization was not important on the tephra layers at Paricutin (Eggler, 1959, 1963), or at Katmai (Griggs, 1918, 1919a, 1919b). In both cases, the lack of nitrogen in the tephra layer is frequently mentioned (e.g. Eggler, 1959, 1963, many references; Griggs, 1919a, p. 16; 1919b, p. 342) and Griggs makes frequent reference to the importance of wind as a deterrent to revegetation (e.g. Griggs, 1919b, p. 338). Segerstrom's (1950) and Eggler's (1959, 1963) observations at Paricutin suggest that, as at Mount St. Helens revegetation after deposition of thick tephra layers was restricted to slopes steep enough for erosion to have stripped the tephra layer (e.g. Eggler, 1959, p. 271, 1963, p. 44), or to tephra layers underneath killed or living trees that could contribute enough nutrients through litter fall to support plant growth (e.g. Eggler, 1963, p. 46, p. 52), and, after greater periods of time, near rotting trees. Griggs (e.g. 1919a, several references) makes the same observations at Katmai. Revegetation during the first year was restricted at Paricutin and Katmai to the outermost regions where the tephra layer was thin enough that the buried plants could easily recover. As at Mount St. Helens, recovery under the thicker tephra layers was delayed until after the first post-eruption year when exposure of the buried soil, litter accumulation, and plant decay could become important. In addition, Griggs notes that many areas devoid of vegetation after the first year recovered within 2–3 years after the eruption because the buried plants remained dormant for several seasons before they penetrated the tephra layer (1918, p. 32, 1919b, p. 195).

These cases and the situation on Mount St. Helens represent a range in climate and ecology as well as sedimentology and yet show striking similarities in the rates and controls on erosion and revegetation, and suggest the following general conclusions with respect to erosion control and sedimentation planning after

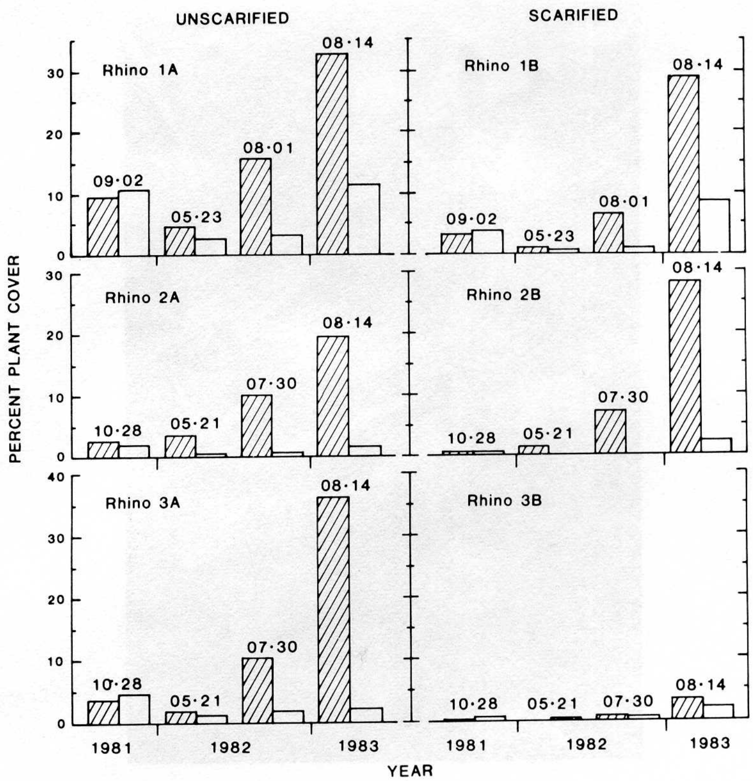

Figure 7. Cover of native plants (shaded bar) and seeded plants (unshaded bar) on scarified and unscarified plots on given dates from 1980 through 1983

tephra eruptions: (1) Because the erodibility and infiltration capacity of tephra layers are often less than those of the underlying substrate, mechanical disturbance can effectively reduce erosion by mixing tephra with or exposing a more permeable and less erodible substrate. Mechanical disturbance by natural causes such as frost action, animal trampling or rill incision can also increase infiltration capacity and drainage density and thereby reduce erosion, before revegetation occurs, even in the absence of deliberate conservation methods. (2) Because erosion is initially intense and subsequently declines rapidly prior to the recovery of native plants, the intervention would not be effective unless applied immediately after an eruption. (3) Because of the characteristically poor nutrient content, high bulk density, and harsh surface environment of tephra layers, and the rapidity with which erosion processes change relative to plant establishment, grass seeding is not likely to be effective in erosion control on new tephra.

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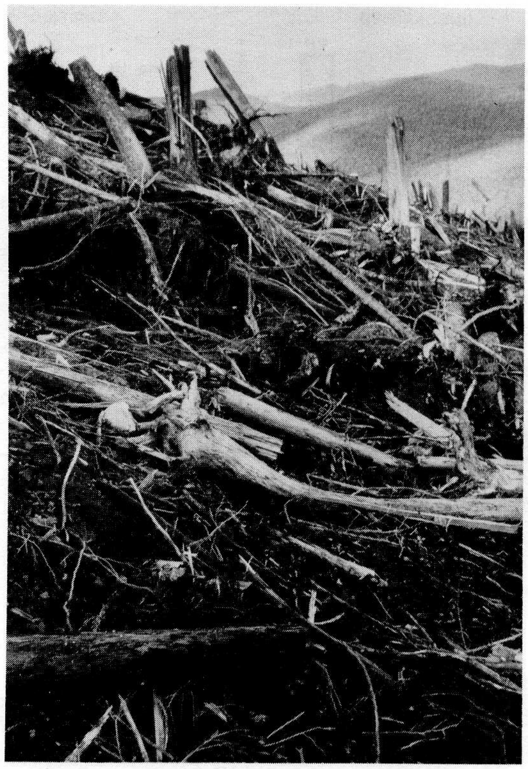

Figure 8. Cable-logging of downed forests created a rough, irregular surface topography formed by organic debris and mixed the tephra layer with soil and organic matter. Photo taken in May 1981 on the Hoffstadt 2 site

Table IV. Plant cover density in August 1982 and August 1983 on the three salvage-logged sites

Site	Percent plant cover 1982	1983
Hoffstadt 2	1·0*	9.3†
Miners Creek	0·6	9.8‡
Shultz Creek	0·0	2.3‡

* Plots within SCS seeding area. Plant cover on the Hoffstadt Creek site was almost entirely seeded ryegrass.
† Plant cover was 5·9 per cent native and 3·3 per cent seeded.
‡ Native species.

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