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MODELING THE EFFECTS OF MINING AND EROSION ON BIOMASS PRODUCTION

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ABSTRACT

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A biomass productivity model and a soil loss model were used to simulate effects of mining and erosion on the productivity potential of a 600-ha site. Biomass productivity, expressed as a relative productivity index PI ($0 \leqslant \mathrm{PI} \leqslant 1$), was computed as a product of a root distribution function and limiting soil property levels derived from literature. Distribution of soil loss or deposition was estimated using a recently developed erosion–deposition model. Effects of two scenarios are compared. In the first, the site is assumed to have been surface mined for coal and the effects on productivity are examined if existing soil is replaced with a minesoil. In the second, erosion–deposition model is used to predict changes in productivity after a severe storm. Under the assumptions of this study, biomass productivity appears more likely to decline because of mining than because of erosion.

INTRODUCTION

In the environmental impact assessment studies it may often be desirable to predict relative changes in biomass productivity that may be caused by an advocated use of environment. On surface-mined sites, even though the goal of reclamation is successful revegetation, relative impact of mining on biomass productivity is seldom evaluated. Minesoils with a low pH provide a poor growth medium for most plant species. During reclamation equipment used to spread the topsoil tends to compact soil layers sealing the surface if moisture contents are high, and frequent overabundance of coarse fragments makes cultivation and seeding difficult. To minimize recharge, operators

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construct compacted high-density layers below the topsoiled zone. Although these layers slow down percolation, they also hinder root growth and development. In some reclaimed surface mines pH may not be a problem but electrical conductivity and sodium adsorption ratio often are.

Kiniry et al. (1983) recently proposed a simple model that related corn yield to soil properties. The model, which requires less complete knowledge of soil properties than more sophisticated approaches such as EPIC (Whittaker and Marke, 1975; Williams et al., 1984), has been extensively used in agricultural sciences recently (Pierce et al., 1983, 1984; Gantzer and McCarty, 1984; Onstad et al., 1984), and Rogowski (1985) adapted it for use on mining sites in North America. The model assumes that crop yield is a function of root growth modified by factors depending on soil properties. The root growth is described by a distribution function assumed to be the same as the distribution function derived for a uniform soil by Horn (1971) from water depletion studies under maple trees. Subsequently, this root distribution function is corrected in each soil layer or horizon by a product of growth limiting factors such as lack of available water, inadequate aeration, high bulk density, and suboptimal pH. Supportive documentation describing effects of these factors on growth can readily be found in literature (see for example Pierre et al., 1965; Cooper, 1975; Lieth, 1975; Arkin and Taylor, 1981; and Rechcigl, 1982).

In an alternate approach the product interaction among the growth limiting factors can be assumed to represent a root distribution function and a productivity modifying factor can then be chosen according to Liebig's Law of Minimum (Lieth, 1975; Jenny, 1980). These approaches and the potential effects on productivity will be explored to show the relative magnitudes of changes expected when a site is surface mined and reclaimed.

Erosion is a natural modifier of productivity through removal or deposition of surface soil materials. Relative impacts of surface mining on productivity will therefore be compared with relative impacts of erosion, using a recently developed (Khanbilvardi et al., 1983a, b; Khanbilvardi and Rogowski, 1986) erosion–deposition model in conjunction with the productivity model. Erosion estimates by the erosion–deposition model are made at a point. Under natural conditions erosion is a parameter distributed over area and in time. To investigate and describe the spatial dependence of erosion prediction, geostatistical techniques (Journel and Huijbregts, 1978) such as variogram analysis and kriging will be utilized.

MATERIALS AND METHODS

To simulate mining, 1 m depth of soil was assumed replaced with a minesoil identical in properties to the minesoil presently found at the experimental site. Subsequently, productivity model was executed to evaluate potential changes in productivity. To model effects of erosion on productivity, productivity model was combined with an erosion–deposition model (Khanbilvardi and Rogowski, 1986) and an assumption was made that as the soil erodes productivity changes by incorporating into the 1 m averaging depth parts of deeper horizons.

For comparison purposes biomass productivity was expressed on a relative basis by a productivity index PI where $0 \leqslant \text{PI} \leqslant 1$. The productivity index (Kiniry et al., 1983; Rogowski, 1985) written in a product form is:

$$\text{PI} = \sum_{i=1}^{m} \text{WP}_i(r) \prod_{j=1}^{n} x_{ij} \tag{1}$$

where $\text{WP}_i(r)$ is a root distribution function, and x_{ij} are functions describing $j = 1, 2, \ldots, n$ growth limiting factors in $i = 1, 2, \ldots, m$ soil layers.

In a uniformly moist soil the profile of fractional depletion (Horn, 1971) of soil water was assumed by Kiniry et al. (1983) to represent root distribution with depth. Such an idealized root distribution function adapted from Kiniry et al. (1983) is:

$$\text{WP}_i(r) = 0.152 \int_0^r \log_e \frac{R + \sqrt{R^2 + 6.45}}{r + \sqrt{r^2 + 6.45}} \, \mathrm{d}r \tag{2}$$

Equation (2) describes a root distribution using a hyperbolic sine curve where r is the depth in the profile and R is the depth which contains 99% of roots. Integrated from the soil surface to R and expressed on a relative basis of the total, equation (2) is assumed to predict a fraction of roots in each layer for an ideal soil. This assumption is supported to an extent by the work of Böhm et al. (1977) and Sivakumar et al. (1977) on soils with no physical or chemical barriers to root growth when water depletion from surface layers is minimal (Fig. 1).

The model given by equation (1) and (2) assumes that an idealized root distribution $\text{WP}_i(r)$ is modified in every layer by a product of several growth limiting factors $0 \leqslant x_{ij} \leqslant 1$, giving a separate productivity index value for each soil horizon. The sum of the productivity index values for individual horizons is assumed to represent site productivity potential.

Law of Minimum (LOM)

The outcome of the Kiniry et al. (1983) model is predicated on an equal interaction among all growth limiting factors and the root distribution function as calculated by equation (2) which is assumed valid for all plants. These assumptions may not always hold. An alternate way of estimating the productivity index (PI) may therefore be in order.

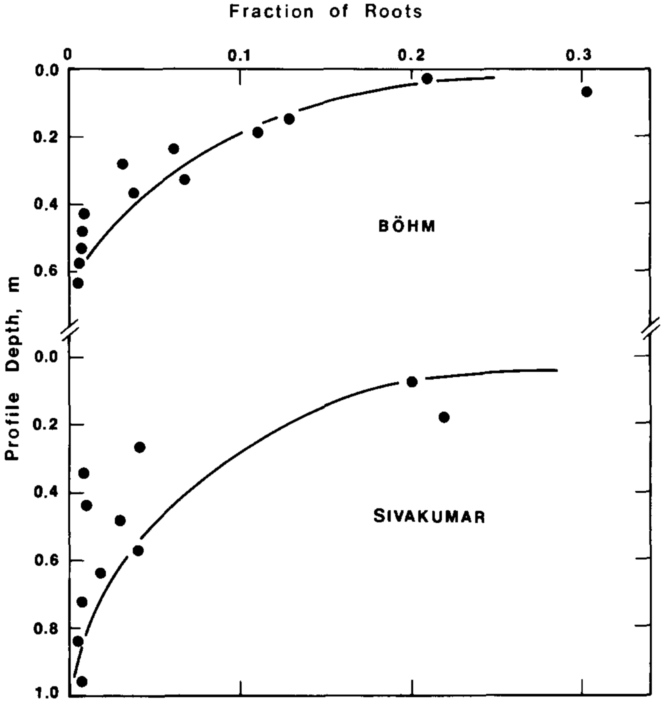

Fig. 1. Root distribution functions $\text{WP}_i(r)$ computed using equation (2) and compared with experimental data of Böhm et al. (1977) and Sivakumar et al. (1977).

Invoking Liebig's Law of Minimum (Jenny, 1980, p. 89) we write:

$$\text{PI}_{\min} = \sum_{i=1}^{m} \text{WLOM}_i \ \text{Min}(x_{ij}) \tag{3}$$

where WLOM_i is a root distribution function, and $\text{Min}(x_{ij})$ denotes a growth factor which is most limiting.

In general, roots will grow and develop in soil layers that have adequate moisture, nutrients and aeration as well as favorable pH, and bulk density. If a layer is encountered where soil properties inhibit growth, root elongation will decrease or cease altogether. Taking advantage of this property we assume that the interaction product $\prod_{j=1}^{n} x_{ij}$ describes root distribution more accurately than equation (2):

$$\text{WLOM}_i = \frac{\prod_{j=1}^{n} x_{ij}}{\sum_{i=1}^{m} \prod_{j=1}^{n} x_{ij}}, \quad 0 \leqslant x_{ij} \leqslant 1 \tag{4}$$

In normal soil profiles root distribution will be highly dependent on the distribution of soil moisture. In topsoiled minesoil profiles, moisture contents may at times be higher near the bottom of a topsoiled layer, either because of underlying spoil compaction or textural differences between spoil and soil. At the same time small rains do not wet deeper layers in minesoils to the same extent they do regular soils. This is often the case in Pennsylvania, U.S.A., because spoils tend to be more stony and droughty and the topmost layers can evaporate much water from any given storm. As a consequence, root distribution function given by a Law a Minimum model appears to approximate our conditions more closely. In addition to the root distribution function four growth limiting factors are considered here while others are described in Rogowski (1985). The four are: plant available water, bulk density, aeration porosity, and pH.

Available water

A growth limiting factor plant available water ($\mathrm{PAW_F}$) reflects soil water status and is used to represent modification of root growth and consequently plant growth and yield. It is described here in terms of the actual amount of water available (AW) to plants during a growing season. Since the actual amount depends on effective profile thickness, type of soil and water use efficiency of a particular species, the AW is compared with a realistic estimate of the minimum amount of water ($\mathrm{AW_{crit}}$) needed by plants at a particular site. Kiniry et al. (1983) formulated this factor in terms of volumetric soil water contents and arbitrarily chose 0.20 moisture content by volume as the critical water content for corn in Missouri, U.S.A. We represent $\mathrm{PAW_F}$ as the ratio of actual to critical amount of water in the effective thickness of a reclaimed profile:

$$\begin{aligned} \mathrm{PAW_F} &= \mathrm{AW/AW_{crit}}, && \mathrm{AW} < \mathrm{AW_{crit}} \\ &= 1.0, && \mathrm{AW} \geqslant \mathrm{AW_{crit}} \end{aligned} \tag{5}$$

The actual amount of available water (AW) in the soil profile during the growing season can be measured or estimated. Experimental measurements, generally utilize nuclear probes or gravimetric samples. Calculations can be made using procedures suggested by Hanks and Ashcroft (1980), and estimates of AW may be made by Thornthwaite's (1948), or some other water budgeting procedure. Other estimates involve approximations based on texture (Peterson et al., 1968; Kiniry et al., 1983), or moisture characteristic corrected for profile thickness. Values used as first approximations of AW in the model must reflect field conditions. In general, when adequate precipitation is available gross estimates of AW may be quite satisfactory, however, in drier regions climatic considerations become paramount because available precipitation is seldom high enough to fill available storage. Where potential evaporation exceeds precipitation and natural or artificial recharge is lacking, the difference between field values of soil water at the beginning of the growing season and water contents at 1500 kPa may give an approximate amount of water available to plants. On stony, channery or shaly minesoils in Pennsylvania, U.S.A., standard AW values need to be further reduced by at least 1/2 to compensate for the presence of coarse fragments (Pedersen et al., 1980; Rogowski and Weinrich, 1981).

The critical amount of water (AW_{crit}) can be estimated based on the projected net primary biomass production at the site. Whittaker and Marks (1975) for example, give 1935 g m^{-2} $year^{-1}$ as the primary biomass production of corn but only 226 as the primary biomass production of poplars. The critical water requirements for these crops will vary. To compute the critical level of available water, we need to know the amount transpired by plants during the growing season. Researchers have attempted to develop a procedure for calculating water requirement of plants based on experimental field data (Briggs and Shantz, 1914), or on known easily measured climatic parameters. A simplified version of this approach applicable to the dry matter production can be written (DeWitt, 1958; Hanks and Ashcroft, 1980) as:

$$Y = \beta T/E \qquad (6)$$

where Y is the dry matter production, T the cumulative transpiration, E average potential evaporation corrected to a large body of water and β a coefficient which depends on a kind of crop grown. By equating AW_{crit} to T, equation (6) can be used to estimate critical water requirement for a crop:

$$AW_{crit} = YE/\beta \qquad (7)$$

If we were to grow corn on a site where the average E is approximately 5 mm/day and β for corn is 300 kg ha^{-1} day^{-1} (Hanks and Ashcroft, 1980), the critical available water for a 19 350 kg ha^{-1} crop would be 297 mm of water. If however, we were satisfied with a 2400 kg ha^{-1} dry matter yield of alfalfa ($\beta = 55$ kg ha^{-1} day^{-1}), $AW_{crit} = 200$ mm would be satisfactory. In this study a value of 200 mm is used as AW_{crit}. The critical water requirement (AW_{crit}) does not take into account evaporation or seepage losses from a soil. These however are subsequently incorporated into AW factor calculation.

Bulk density and aeration porosity

Bulk density and aeration porosity of natural soils are modified during reclamation of a mined site. Bulk density is commonly used as an index of compaction and is readily available from literature. Taylor and Burnett (1964) established that high soil strength impedes root growth, while Rogowski et al. (1968) and Rogowski and Kirkham (1976) have shown that soil strength is correlated with bulk density. Computation of the bulk density (D_F) growth limiting factor here follows Kiniry et al. (1983) approach:

$$\begin{aligned} D_F &= 1.0, & \text{BD} &< 1300 \\ D_F &= 1.88 - 0.00068\,\text{BD}, & 1300 \leqslant \text{BD} &\leqslant 1550 \\ D_F &= 5.98 + 0.00332\,\text{BD}, & 1550 < \text{BD} &\leqslant 1800 \\ D_F &= 0, & \text{BD} &> 1800 \end{aligned} \tag{8}$$

where BD is the bulk density of soil at field capacity in kg/m^3. For unusual conditions either lower or higher values of bulk density may be indicated, but in general BD suitable for plant growth will range from 1300 to 1800 kg/m^3 (Pearson, 1965; Bowen, 1981).

Most physical and hydraulic effects of bulk density are assumed incorporated into factor D_F. Other effects, such as adequate aeration of the root growth medium are grouped under the aeration porosity. The two are related through the equation:

$$\text{AP}(r) = 1 - \theta(r) - \frac{\text{BD}(r)}{\text{BD}'(r)} \tag{9}$$

where AP(r) is the aeration porosity of a fully recharged profile, and $\theta(r)$ the volume of water filled pores, while BD(r) and BD$'$(r) are bulk density and particle density, respectively. Particle density for most agricultural soils is approximately 2650 kg/m^3 but can be lower for carbonate and organic matter rich materials (Bonneau and Levy, 1979). Values of AP(r) will vary with soil texture, structure and the amount of organic matter. In general, AP(r) includes macropores (> 0.06 mm diameter) that will drain at low soil water tensions (Henderson and Patrick, 1982). Actual values of the aeration porosity, AP(r), may be measured in the field or may be approximated as a fraction of total porosity:

$$\text{AP}_a(r) = \left(1 - \frac{\text{BD}(r)}{2650}\right)\alpha \tag{10}$$

We have assumed that in a free draining, sandy, stony, channery, or shaly soils (stony in Table 1) α is equal to 1.0. For soils likely to be waterlogged at some time during the growing season (waterlogged in Table 1) α is reduced to 0.1, which corresponds to porosity at ≈ 0.9 saturation or at air entry-value of soil water tension (Rogowski, 1971). For soils which have other capability limitations such as erosion (erodible in Table 1) α in the model is assumed to equal 0.2, which corresponds to porosity at ≈ 0.8 of saturation. The

TABLE 1

Properties, description, classification and productivity index [a] for soils of the experimental site

Soil Name	Symbol	Classification	Capability class	Texture [b]	Clay	BD	pH	PI	PI_{min}
Armagh	AR	Typic Ochrequult	waterlogged	sicl	30	1.15	5.0	0.305	0.515
Brinkerton	BR	Typic Fragiagualf	waterlogged	sil	16	1.43	5.8	0.338	0.455
Brinkerton	BS	–	stony	v. stony	–	–	–	0.366	0.362
Cavoda	CD	Aeric Ochraquult	waterlogged	sil	16	1.29	5.0	0.365	0.492
Clymer	CV	Typic Hapludult	stony	chfsl	8	1.49	6.2	0.127	0.198
Ernest	ER	Aquic Fragiudult	erodible	sil	19	1.09	5.1	0.838	0.822
Ernest	EV	–	stony	v. stony				0.420	0.433
Gilpin	GI	Typic Hapludult	erodible	chsil	6	1.33	6.2	0.460	0.475
Hazleton	HH	Typic Dystrochrept	erodible	chsl	4	1.38	4.1	0.181	0.248
Hazleton	HS		stony	v. stony				0.094	0.129
Dekalb	HT	Typic Dystrochrept	stony	v. stony	15	1.24	5.8	0.202	0.198
Philo	PK	Fluvaquentic Dystrochrept	stony	v. stony	17	1.03	4.0	0.148	0.418
Weikert	WE	Lithic Dystrochrepts	erodible	shsil	18	1.38	6.6	0.466	0.486
Wharton	WH	Aquic Hapludults	erodible	sil	27	1.41	6.6	0.533	0.615
Wharton	WH	–	waterlogged					0.247	0.449
Minesoil	SM	Stripmines	stony	ch. spoil	22	1.44	5.0	0.186	0.218

[a] Using Productivity Index (PI) and Law of Minimum (LOM) versions of the model.
[b] sicl, silty clay loam; sil, silt loam; ch, channery; sl, sand loam; v, very; sh, shaly.

reason for this is that when zones of deposition occur on eroding soils profile aeration will decrease as a result of sealing and truncation of pores previously open to the atmosphere.

Critical aeration porosity ($\mathrm{AP}_{\mathrm{crit}}(r)$) when root growth becomes restricted ranges from 0.05 to 0.15 pore space by volume (Cannel and Jackson, 1971; Pearson, 1965). Ideally, the effect should include a time dependence, a geometry factor to describe degree of continuity between air-filled pores, and a O_2, CO_2 concentration estimates (Jaynes and Rogowski, 1983; Jaynes et al., 1984a, b). Here however, a simplified version is used and the growth limiting factor aeration porosity AP follows the original formulation of Kiniry et al. (1983), with $\mathrm{AP}_{\mathrm{crit}}(r) = 0.10$:

$$\mathrm{AP}_{\mathrm{F}} = \frac{\int_0^r 1/\mathrm{AP}_{\mathrm{crit}}(r)}{\int_0^r 1/\mathrm{AP}_{\mathrm{a}}(r)}\,\mathrm{d}r \tag{11}$$

and estimates of $\mathrm{AP}_{\mathrm{a}}(r)$ obtained using equation (10).

Acidity (pH)

Critical pH for plant growth (Spurway, 1941) varies over time among soils and among plant species. The response to pH on acid soils may result from H, Al or Mn toxicity, and Ca or Mo deficiency. Thus, soils at the same value of pH could show limited biomass production for different reasons and the limiting factors would operate at different intensities in time and space (Adams, 1981; Pearson, 1965). Consequently, the suggested model should be used with caution and adjusted if additional information about a particular site or plant species pH response is available. The pH growth limiting factor (pH_{F}) used is:

$$\mathrm{pH}_{\mathrm{F}} = 3.9321(\mathrm{pH} - b) - 9.6098 - 0.3644(\mathrm{pH} - b)^2 \tag{12}$$

where pH denotes acidity measured in 1 : 1 aqueous solution, and b is a coefficient ($0 \leqslant b \leqslant 1$) fitted to experimental data:

— when $b = 0$:

$$\begin{aligned} \mathrm{pH}_{\mathrm{F}} &= 0, && \mathrm{pH} \leqslant 3.75 \\ &= 3.93\ \mathrm{pH} - 9.61 - 0.36(\mathrm{pH})^2, && 3.75 \leqslant \mathrm{pH} \leqslant 5.40 \\ &= 1.0, && \mathrm{pH} \geqslant 5.40 \end{aligned}$$

— when $b = 1$:

$$\begin{aligned} \mathrm{pH}_{\mathrm{F}} &= 0, && \mathrm{pH} \leqslant 4.75 \\ &= 3.93(\mathrm{pH} - 1) - 9.61 - 0.36(\mathrm{pH} - 1)^2, && 4.74 \leqslant \mathrm{pH} \leqslant 6.40 \\ & && \mathrm{pH} \geqslant 6.40 \end{aligned}$$

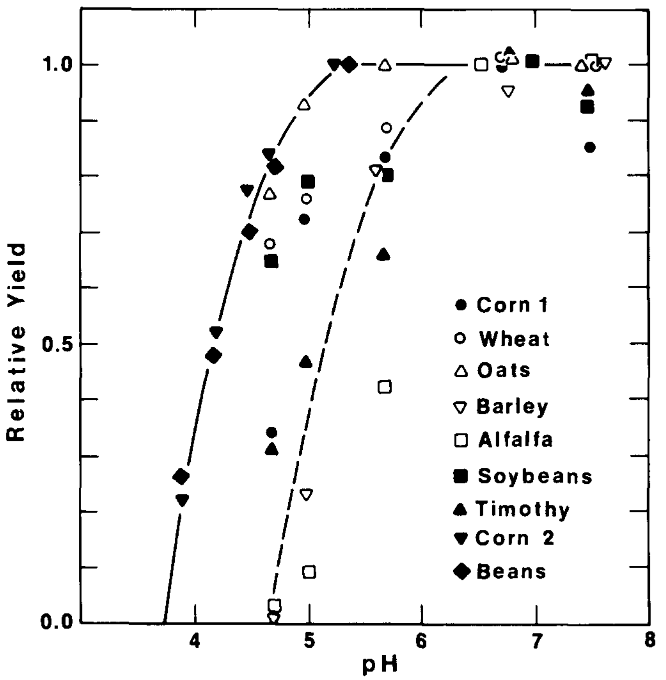

Fig. 2. Distribution of a pH productivity factor (pH_F); solid line: $b = 0$, dashed line: $b = 1.0$, experimental values are from Couto (1982).

In Fig. 2 the solid line with $b = 0$ for corn (corn 2) and bean yields in Tropical America. The experimental points are from Couto (1982) (his tables 9 and 10). The dashed line with $b = 1$ is for corn (corn 1), wheat, oats, barley, alfalfa, beans, and timothy in Ohio, U.S.A. (Couto, 1984, his table 2). In the model $b = 0$ was assumed.

Productivity model verification

The Kiniry et al. (1983) Productivity model has been used to assess changes due to erosion (Pierce et al., 1983), and to estimate effects of erosion on productivity (Pierce et al., 1984). In the above studies the productivity index (PI) was quite highly correlated with yields especially when Histosols and soils with slopes greater than 6% were excluded. The above authors also observed changes in PI with climate when productivity was assessed over large and geographically different areas. Gantzer and McCarty (1984) found that a linear regression of PI yield overpredicted corn yields on a clay pan soil in Missouri, U.S.A., and better fit was obtained if a quadratic component was used. Onstad et al. (1984) using the Productivity model to study interrelationships of erosion and productivity, concluded that although PI decreased with erosion as expected, PI also changed as a function of position in a landscape. In all of the above studies Kiniry et al. (1983) Productivity model was combined with estimates of erosion obtained from the universal soil loss equation (USLE) of Wischmeier and Smith (1978) to assess the effects of erosion on productivity, and the productivity was viewed as a crop yield.

In contrast, our studies attempt to relate a modified productivity index to biomass production and erosion or deposition estimates derived from both the USLE and hydraulic principles of sediment transport. Furthermore, climatic factors are incorporated through the use of Miami model (Lieth, 1975) and the slope position through the use of erosion–deposition model (Khanbilvardi and Rogowski, 1986).

To verify our version of the model we have used two sets of data. The first set was abstracted from Kiniry et al. (1983) (their fig. 10) which showed average maize grain yield at 15.5% moisture as a function of average value of the productivity index (PI). The second set came from our own studies in Pennsylvania, U.S.A., in which the effects of climatic factors, soil fertility and soil chemical and physical properties on the biomass production of maize were investigated (Rogowski and Stout, 1984). Kiniry et al. (1983) data were converted to biomass using a grain/biomass conversion factor of 0.60, derived from 1984 grain and silage yield summaries on Pennsylvania soils, published by Pennsylvania State University Extension Service. The observed Missouri or Pennsylvania biomass yields were divided by biomass computed using Lieth (1975) Miami model for Missouri and Pennsylvania conditions, respectively to give $\mathrm{PI}_{\mathrm{observed}}$. The Miami model which was used for this purpose is:

$$
\begin{aligned}
&B_T = 30\,000/[1 + \exp(1.315 - 0.119T)] \\
&B_R = 30\,000[1 - \exp(-0.000644R)] \\
&B = B_T, \; B_T \leqslant B_R \\
&B = B_R, \; B_R < B_T
\end{aligned}
\tag{13}
$$

where B, B_T, B_R is the biomass production (kg/ha); T the temperature (°C); and R precipitation (mm).

Usually B, B_T and B_R refer to the biomass production in kg/ha per year, while T and R are the mean annual temperature and precipitation, respectively. In here the model was used with biomass production based on the cumulative rain or average weekly temperature basis, as well as on the annual basis. On the weekly basis the uncorrected biomass generally was computed as B_R, while on the annual basis it was computed as B_T.

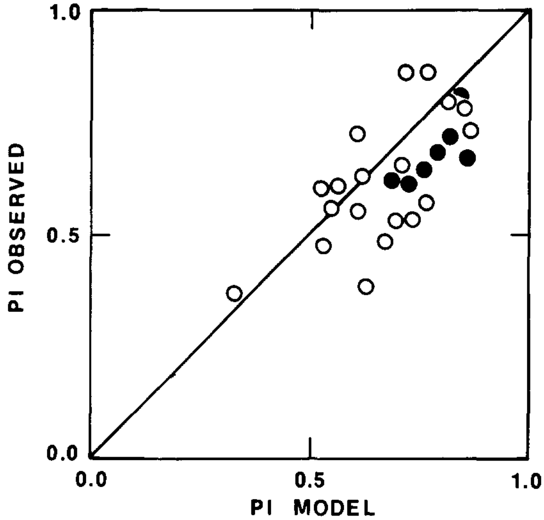

Fig. 3. Comparison of measured (PI Observed) and predicted (PI Model) productivity index on Missouri (○) and Pennsylvania (●) sites.

The $\mathrm{PI}_{\mathrm{observed}}$ values for both locations, computed as outlined above, were compared with the productivity index ($\mathrm{PI}_{\mathrm{model}}$) calculated using Kiniry et al. (1983) model (Missouri) and modified Kiniry model (Pennsylvania) presented by us here. Results shown in Fig. 3 as a plot of $\mathrm{PI}_{\mathrm{model}}$ vs. $\mathrm{PI}_{\mathrm{observed}}$ appear satisfactory.

Site description

We applied the Productivity model to a 600-ha mine site in Pennsylvania, U.S.A. (Fig. 4). The site has been mined for coal, consequently large areas of reclaimed minesoil exist and have been characterized by the Soil Conservation Service. The soil properties were abstracted and digitized on a 100-m square grid from Soil Survey data base for Pennsylvania and from 7.5′ topographic maps of the area. The soils modeled were placed into three capability response groups: stony, water logged and erodible (Table 1). Productivity index was calculated using both the Product (equations 1 and 2) and the Law of Minimum (Equations 3 and 4) versions of the model. The pre- and post-mining conditions were compared assuming that minesoil replacing the original soil would have the same composition and properties as the minesoil now at the site.

Erosion deposition model

To predict erosion we used a recently developed erosion–deposition model (EDM) (Khanbilvardi et al., 1983a, b; Khanbilvardi and Rogowski,

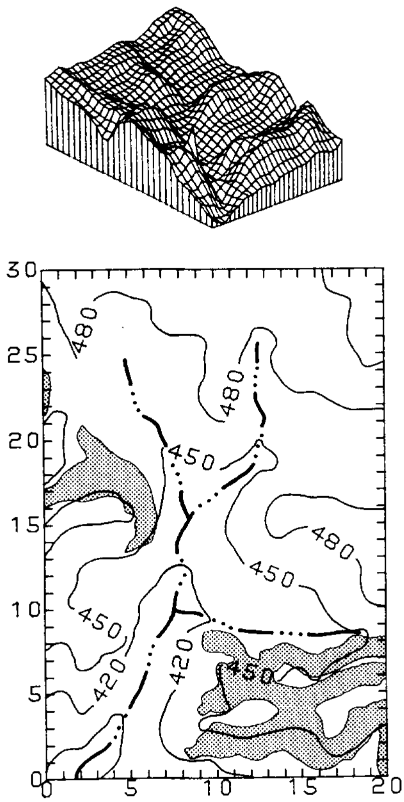

Fig. 4. General topography, drainage, and minesoil (shaded) location at the experimental site.

1984, 1986). The model (Fig. 5) combines Wischmeier and Smith's (1978) universal soil loss equation (USLE) with a system of equations describing hydrologic and hydraulic processes of soil erosion. The model partitions eroding soil into contributions from rill and interrill areas, and quantifies the main subprocesses of erosion: (1) detachment by rainfall on interrill areas, (2) transport by rainfall to rills, (3) detachment by runoff in rills, and (4) transport by rill flow. Detachment and transport capacity of rill flow and of rainfall are defined by appropriate equations. The resultant rate of sediment movement is the lesser of the rill flow transport capacity, or the rate at which soil particles are made available for transport. As a result the areal distribution of erosion and deposition as well as the location of rills and total sediment yield are predicted.

To evaluate changes in productivity brought about by erosion, we executed the erosion–deposition model for a 6 h = 10 year storm projected to occur at the experimental site. Such a storm could have an energy-intensity

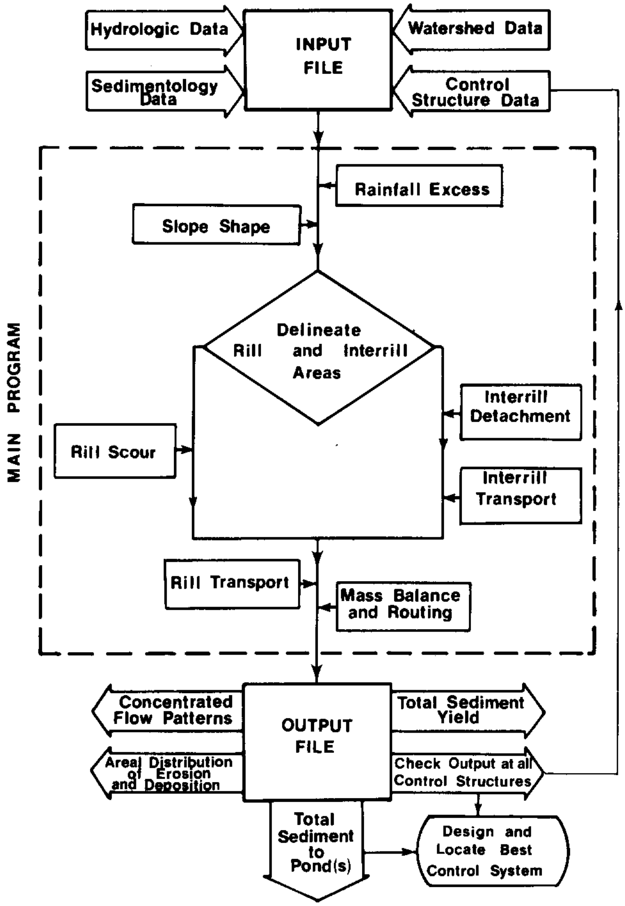

Fig. 5. Flow chart of the erosion–deposition model.

component (EI) of USLE approximated 1/3 that of the annual value and a depth of rain equal to 75 mm in our area (Hershfield, 1961). Simulation assumed an extreme case with bare soil conditions, no cover, and no conservation practices. Using the model, soil erosion or deposition for each of the 600 1-ha subareas was calculated and potential changes in productivity index (PI) were computed. On areas where erosion or deposition were indicated by the model, productivity index was recalculated (PI_{new}) and compared with the original values obtained from equation (1) (PI) or equation (3) (PI_{min}), the respective changes were:

$$\Delta\mathrm{PI} = \left(\frac{\mathrm{PI}_{new}}{\mathrm{PI}} - 1\right)$$

$$\Delta\mathrm{PI}_{min} = \left(\frac{\mathrm{PI}_{new}}{\mathrm{PI}_{min}} - 1\right) \tag{14}$$

We have assumed deposition to be beneficial. Thus, most productivity factors used to calculate productivity index of a deposited layer were set equal to 1.0 except for aeration porosity AP_a which was taken as 0.05 a value assumed to represent an average aeration porosity at 0.9 saturation for A_p horizons of all soils at the experimental site. This lower value of aeration porosity was used to account for possible effects of surface sealing.

Geostatistics

Geostatistical techniques extensively used in mining and exploration (Journel and Huijbregts, 1978) are based on the theory of regionalized variables (Matheron, 1971). We use geostatistics here to interpret and describe spatial dependence of productivity index and erosion–deposition data. A geostatistical interpolation known as kriging yields lowest variance estimates of a value at a point or over an area based on surrounding values, while structural analysis interprets a degree of continuity for a variable of interest in space. Basic assumption of geostatistics is that parameter value at a point is influenced by its position relative to its neighbors. A measure that expresses this dependence is a semivariogram (Clark, 1979). A semivariogram relates a variance of differences between adjacent points to successive increments of distance.

Figure 6 shows a semivariogram $\gamma(h)$ of soil loss values at $h = 100, 200, \ldots, 1500$ m. For a variable distributed over an area a semivariogram is defined as one-half the sum of the variance of differences between the successive sampling points y_k:

$$\gamma(h) = \frac{1}{2N} \sum_{k=1}^{N} \left[Z(y_k) - Z(y_k + h)\right]^2 \tag{15}$$

where $Z(y_k)$ is the soil loss (or deposition) at a point y_k, $Z(y_k + h)$ the loss at a point $(y_k + h)$, and N denotes a number of pairs considered. A distance vector h can be used to describe structural anisotropy since it has both the magnitude and direction. To obtain reliable results the number of pairs (N) for each semivariogram point should preferably be greater than 50.

In a semivariogram, γ the degree of spatial correlation is described by a range. Range (a) is the distance within which γ values approach the sill value (C). Magnitude of the sill reflects the amount of variability among the data. Semivariogram in Fig. 6 illustrates two structures. The upper one, computed for deposition data shows a general lack of spatial correlation and high degree of variability. The lower one for erosion shows both spatial structure and continuity. Magnitude of the range (a) indicates the extent of spatial dependence. The erosion process may be considered continuous within a 690 m neighborhood and lacking in spatial correlation beyond that

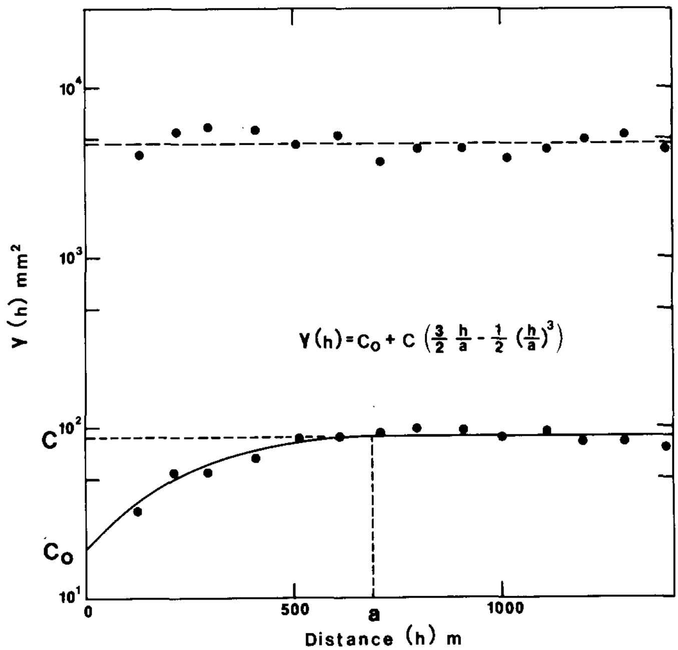

Fig. 6. Semivariogram of erosion (lower) and deposition (upper) for step length h.

distance. The sill (C) at $\gamma(h) = 89.2$ mm^2 here corresponds to the ordinary variance of erosion data and is considerably lower than the sill for the deposition process. Comparisons with site topography in Fig. 5 suggest that the range of erosion semivariogram is related to the width of individual valleys. The erosion semivariogram, fitted with the equation of a spherical form (shown in the insert) exhibits also a nugget effect (C_0) at $\gamma(h) = 19.1$ mm^2. The nugget effect suggests that experimental data have considerable variability on a scale smaller than the 100 m sampling grid used. Thus, it may be said that about 20% of the variance of the erosion process can be attributed to a relatively large sampling grid.

We base our estimates of productivity and erosion on data read off at intersections of the 100-m grid, and have used kriging to extend these values of 1-ha areas surrounding the grid point. In a kriging procedure, points surrounding a block are assigned weights according to the distance from the center of the block; the sum of these weights is 1.0. The procedure then solves a system of linear equations with an appropriate weighting scheme. There are many different weighting scheme combinations possible, kriging procedure is designed to select a combination that gives the lowest estimation variance.

RESULTS AND DISCUSSION

Effect of erosion or deposition on productivity

Figure 7 shows changes in productivity that may occur for individual soil of Table 1 because of erosion or deposition. The changes were computed using the Product or the Law of Minimum models. The soils were divided into three capability response classes: erodible, waterlogged and stony. Simulations show that the behavior of stony and erodible soils will vary during the erosion. For, i.e., some Hazleton (HS), productivity would change

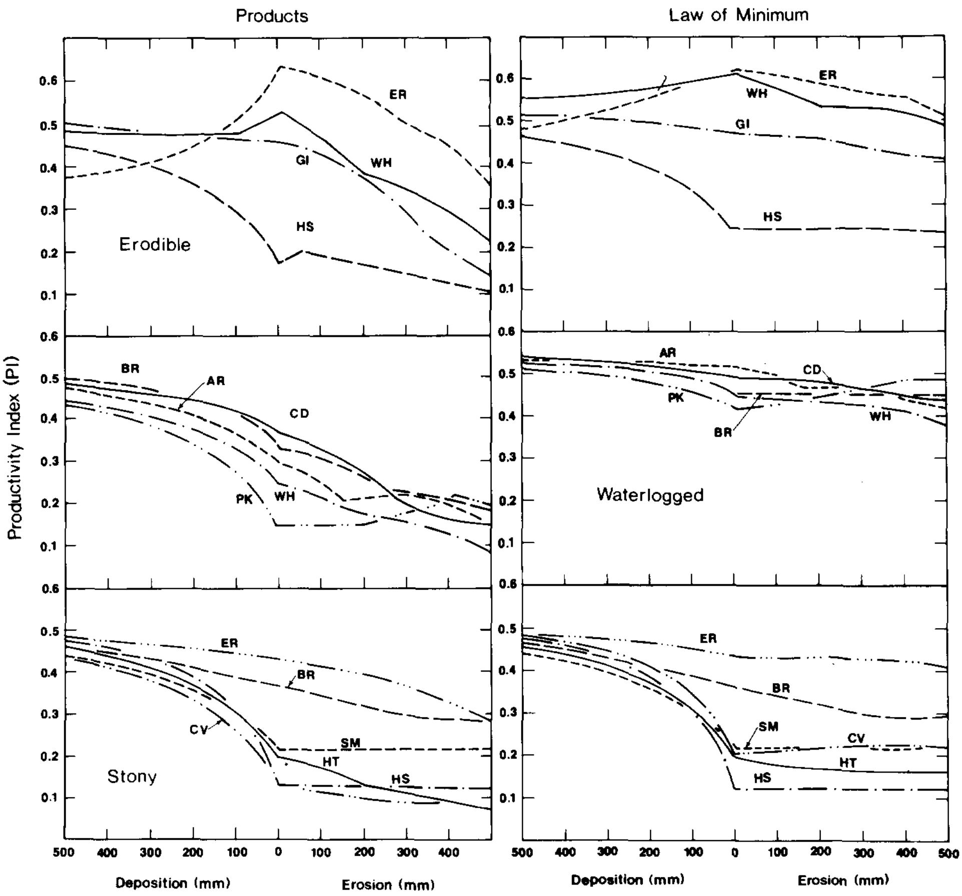

Fig. 7. Potential changes in the Productivity Index for erodible, waterlogged and stony soils at the experimental site (abbreviations are as in Table 1) assuming erosion or deposition (mm); Productivity Index was calculated using Product or Law of Minimum Models.

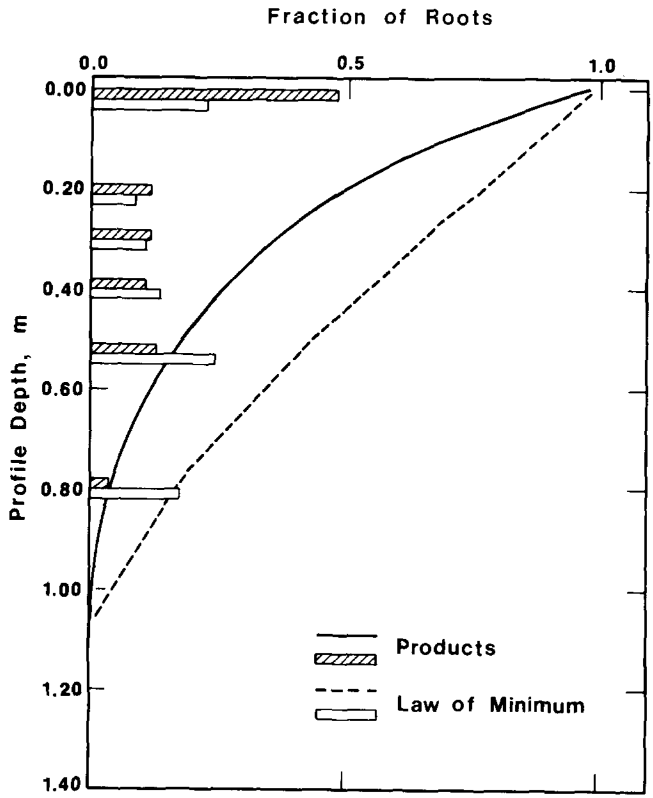

Fig. 8. Cumulative (curves) and discrete (bars) root distribution function of depth for a representative soil predicted by the Product and Law of Minimum Model.

little as the profile eroded, while for others, i.e., Ernest (ER), productivity may decrease rapidly. On certain erodible soils, (ER), productivity may decrease following deposition because of adverse changes in aeration porosity, while for waterlogged soils productivity declines during erosion and increases during deposition appear to be fairly uniform. Simulation results for the three groups suggest smaller decreases in productivity with depth during erosion for the Law of Minimum (LOM) model. This would be expected, since limiting properties (Min x_{ij}) used in LOM vary less from soil with depth, and the magnitude of interaction manifests itself primarily through a root distribution function (equation 4). In the Products model however, the interaction is given for each layer as the product of growth limiting factors which decreases faster with depth for smaller values of individual factors (equation 2). To illustrate this point Fig. 8 shows cumulative root distribution functions for both models on a 1 m thick representative soil and accompanying bar graph gives projected root distribution with depth. In the Law of Minimum model, the distribution is nearly linear decreasing uniformly with depth, while in the Products model it tends to be curvilinear and decrease faster near the surface.

In undisturbed soil profiles root distribution depends to a large extent on the distribution of moisture. Because of minesoil compaction or textural differences between coarse textured spoil and fine textured topsoil, moisture contents may at times be higher near the bottom of a topsoiled layer. At the same time rains do not wet deeper layers of minesoils to the extent they do regular soils. Minesoils tend to be stony and much storm water either evaporates before it reaches deeper layers, or percolates quickly beyond root depth. Even in normal soils roots are abundant near the surface when adequate moisture is available. Otherwise they tend to be distributed throughout the profile. Consequently, a root distribution function given by the Law of Minimum model appeared more appropriate and was used in this study.

Effects of mining on productivity

Equation (14) gives a practical way to evaluate changes in productivity by setting PI_{new} equal to $\mathrm{PI}_{minesoil}$ and PI_{min} equal to PI_{min} of the soil which occupied the site prior to mining. The analysis assumed new minesoil comparable to the minesoil now in place. Figure 9 shows the $\Delta\mathrm{PI}_{min}$ for the Pine Glen site and Table 2 summarizes the changes. In the calculations, positive values indicate a relative productivity increase, negative—a decline, and zero values—no change. Each one of the grid squares represents a hectare. Areas showing no change have already been mined (13%) and of the others, only about 1% would have a noticeably higher productivity following mining. On more than half of the area productivity would decrease about 52% and on more than a fourth of the area it would decrease about 69%. The productivity of a site as a whole would decrease 48%. Should better quality materials be used for topsoiling the projected changes would be less drastic. The approach described encourages selective reclamation. Areas that are most impacted by mining could be reclaimed more intensively or withheld altogether from mining. These are the areas is the relatively flat 2000–3000 section where best agricultural soils are located.

Distribution of soil loss

Figure 10 shows areal distribution of erosion and deposition at the Pine Glen site, and Table 3 summarizes the results. The negative values signify erosion, the positive ones deposition, no change was observed on blank areas designated as zero. Kriging was used to refine model predictions.

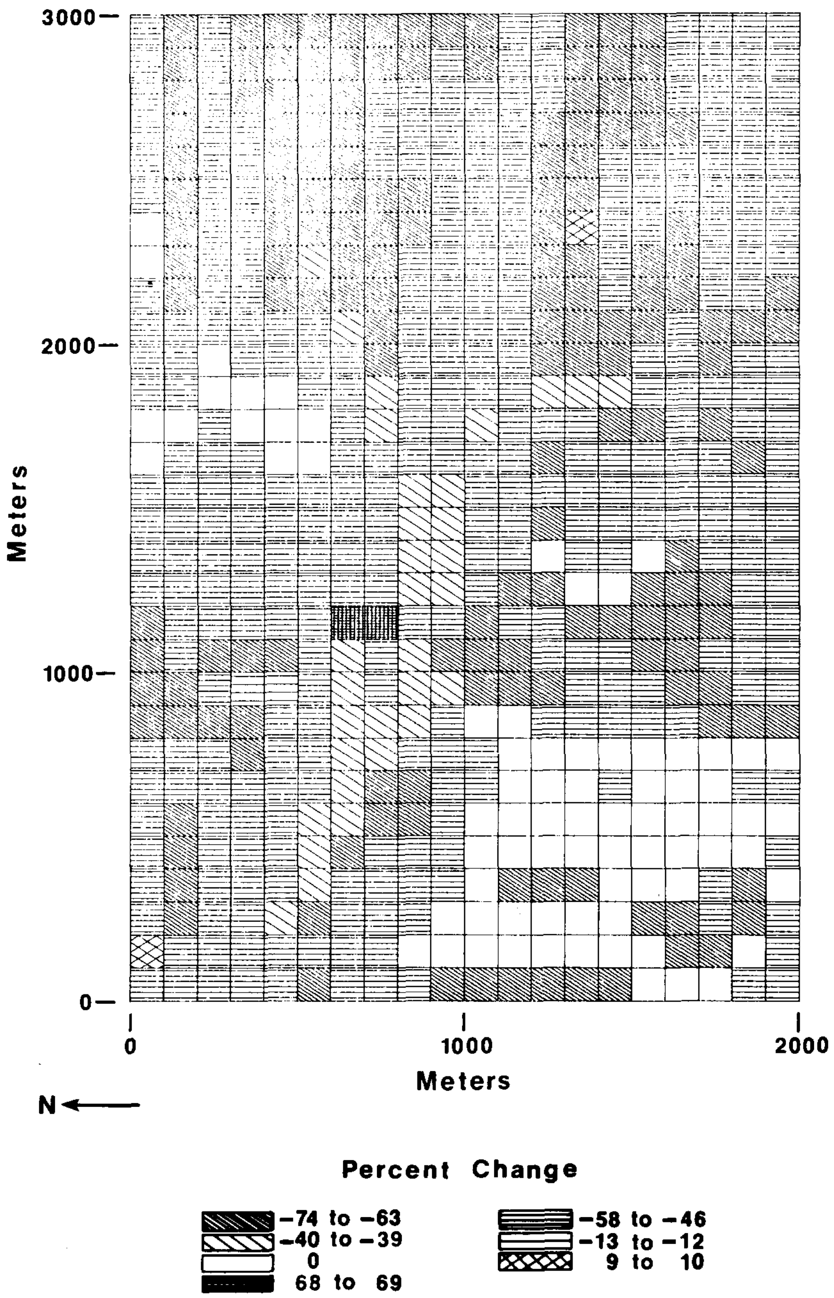

Fig. 9. Simulated productivity ratio mosaic for mined and unmined scenarios; Law of Minimum Model.

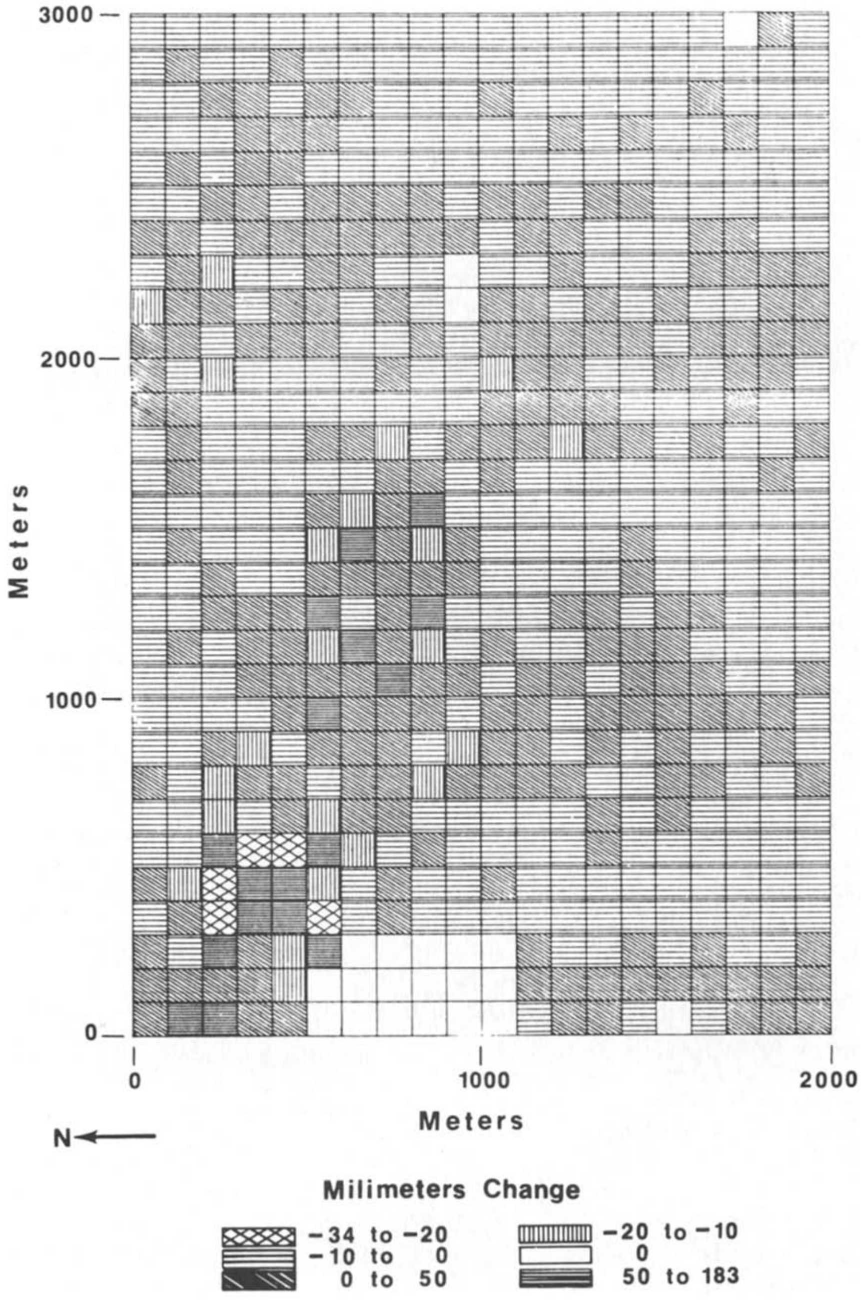

Fig. 10. Distribution mosaic of kriged erosion and deposition at the Pine Glen study site, negative values signify erosion; positive—deposition; and zero values—no change.

TABLE 2

Potential changes in biomass productivity brought on by mining at the Pine Glen site

Location	Percent change							
	Increase			Decline				All
	69	10	0	−13	−40	−52	−69	
	Percent of total [a]							
0–1000	–	<1	10	<1	2	18	7	37
1000–2000	<1	–	3	–	3	22	5	33
2000–3000	–	<1	<1	–	<1	14	15	29
All	<1	<1	13	<1	5	54	27	

[a] Total number of the subareas = 600.

Table 3 and Fig. 10 illustrate simulated erosion and deposition for a 6 h-10 year storm. The results indicate highest erosion and deposition in the steep NW section not far from the stream. Table 3 shows that the middle third (1000–2000) contained most of the areas undergoing erosion and deposition, while the lower third (0–1000) contained most areas with no change. The results suggest that more soil was deposited than eroded. For explanation we consider the mechanics of the erosion–deposition model. The model is based on: computation of potential erosion at each node, rill scour between nodes and transport capacity of rill flow. If soil available for transport at a node exceeds transport capacity the model registeres deposition. At other times soil material available at grid points becomes entrained and the model will register erosion. Mass balance is computed at each grid point with respect to the rill transport capacity at that point and the

TABLE 3

Distribution of erosion or deposition for a single 6 h-10 year (75 mm) storm at a Pine Glen site

Location	Erosion	Deposition	No change
	Percent of total [a]		
0–1000	12	7	14
1000–2000	22	9	3
2000–3000	16	6	11
All	50	22	28
Mean erosion of deposition (mm)	6	31	–
C.V. (%)	151	323	–

[a] Based on 600 subareas assuming bare soil, no cover and no erosion control practices.

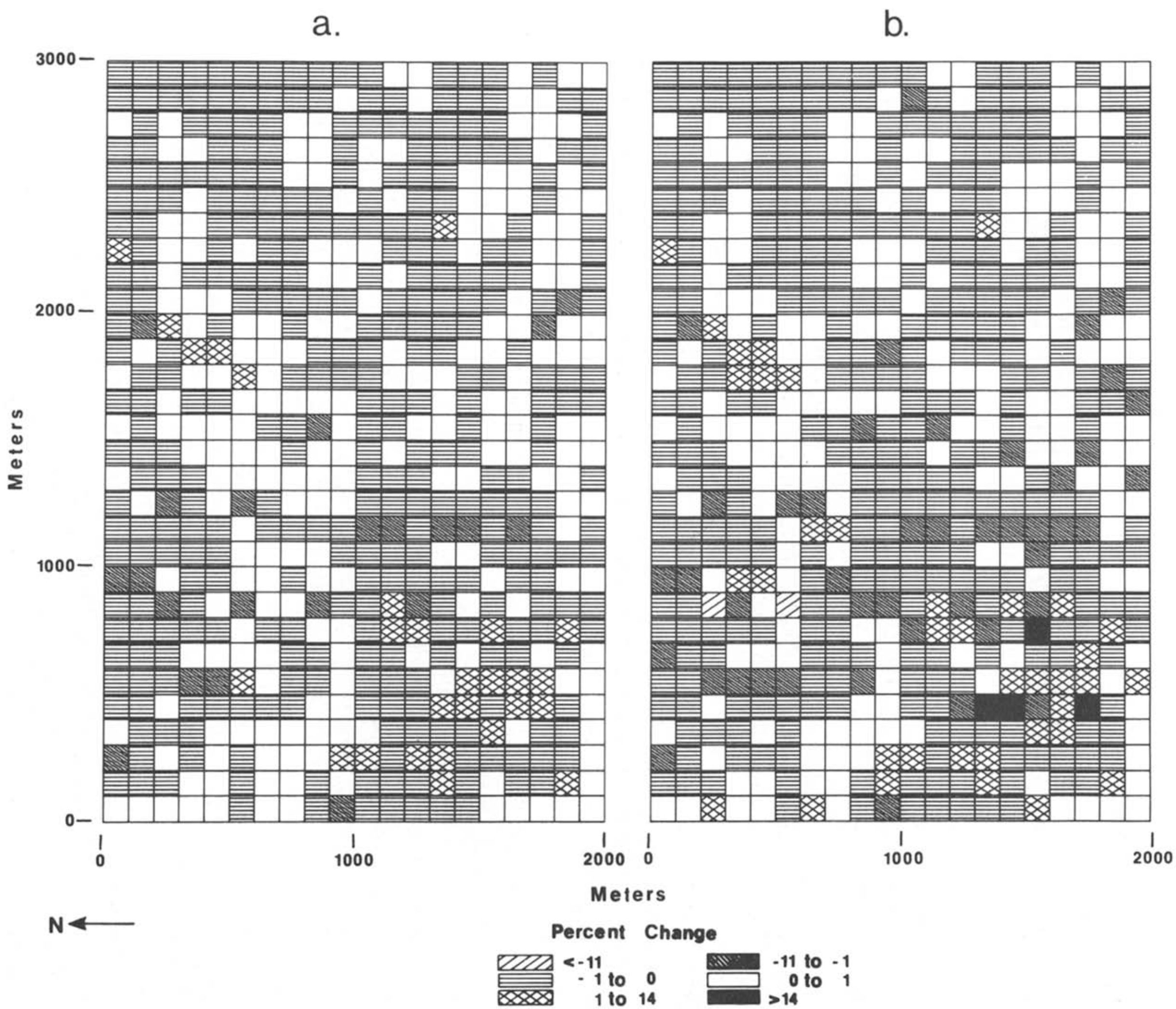

Fig. 11. Simulated changes in productivity resulting from a 6 h-10 year storm using Law of Minimum (a) and Product (b) models at a Pine Glen Site.

TABLE 4

Changes [a] in the productivity index (PI), following a 6 h-10 year storm at the Pine Glen site

Location	Product Model			Law of Minimum Model		
	Decline	Increase	No Change	Decline	Increase	No Change
	Percent of the area					
0–1000	10	5	19	9	6	19
1000–2000	25	5	4	23	6	4
2000–3000	21	1	11	20	1	12
All	56	10	34	52	13	35
Mean ΔPI %	0.48	8.7	–	0.14	4.0	–
C.V. (%)	186	317	–	286	379	–

[a] $\Delta \text{PI} = 1000[(\text{PI}_{\text{after storm}}/\text{PI}_{\text{before storm}}) - 1]$.

transport capacity of flow gives the sediment yield from an area upstream of a node. Should a node be also an outlet, the transport capacity is equivalent to the sediment yield of the study site. If, as is the case at Pine Glen, deposition appears to exceed erosion, more soil was available for transport than could be carried away by runoff.

Erosion–deposition mosaic in Fig. 10 is based on kriged soil loss or deposition values for individual blocks. The original data set digitized on a 100-m^2 grid also contains soil identification information. The two data sets were combined (Fig. 11) to compute changes in the productivity index (ΔPI) as a result of a single 10 year-6 h storm (75 mm). Figure 11 shows the projected changes in productivity that could occur, depending on whether the Product model, or the Law of Minimum model were used. The productivity changes are given in percent. The negative values signify zones where productivity would decline, the positive ones, where it might increase. Table 4 shows that the results for the two models are very similar but not the same. While in general a decline in productivity may predominate in the upper third of the site, productivity increases, because of assumption that deposition, is beneficial could occur in the lower and middle thirds. The Law of Minimum model shows less overall change in productivity compared to the Product model. On much (about 1/3) of the area no changes occur according to either model. On more than half of the area procutivity declines, while on only 10–13% of the area it increases, potential declines however, are much smaller than potential increases. Simulation results show that the Product model can lead to higher changes in productivity which vary more compared with the Law of Minimum predictions. The erratic nature of the productivity increase can be traced to the high variability associated with deposition (Table 3). In retrospect, largely because of the mechanics of the erosion–deposition model discussed earlier, the original assumption that deposition is beneficial may be questionable.

Productivity changes because of erosion from a single storm appear minor compared to the effects of miniming. Nevertheless, over the years they can, if not remedied, become significant. A model such as this could be applied to situations other than mining to pinpoint areas where potential problems may exist, and to predict potential biomass distribution over an area based on soil parameters as well as climatic considerations.

SUMMARY AND CONCLUSIONS

A productivity model derived from literature and based on root distribution, bulk density, aeration porosity and pH was modified to test productivity factor interaction. The original productivity model compared well with the formulation based on Liebig's Law of Minimum, and model predictions were verified using experimental data from Missouri and Pennsylvania, U.S.A. Law of Minimum version of the productivity model was used to evaluate potential effects of mining on an area prior to its disturbance. Projected productivity decreases due to mining ranged from 12 to 74%. Subsequently, the Law of Minimum productivity model was combined with the erosion and deposition model to evaluate potential effects of a single 6 h-10 year storm on productivity of the same site. Results delineated areas where productivity might decline because of erosion or increase because of deposition. Compared to mining, changes in productivity for a single storm were relatively minor ranging from less than 1.0–6.5% for declines, and averaging between 4 and 9% for increases.

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