Soil erosion in the humid tropics with particular reference to agricultural land development and soil management

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ABSTRACT This report reviews the problem of soil erosion on arable lands in the humid tropics and its relation to deforestation and land development and to soil and crop management practices. It also discusses the problem of evaluating acceptable rates of soil erosion in relation to the rate of weathering and of new soil formation and to the soil erosion-crop productivity relationship.

Erosion du sol dans les régions tropicales humides avec examen particulier du développement de l'agriculture et de l'aménagement des sols

RESUME Ce rapport passe en revue le problème de l'érosion du sol sur les terres arables des régions tropicales humides et ses relations avec le déboisement et le développement de l'agriculture, les pratiques d'aménagement des sols et les façons culturales. Il examine également le problème d'évaluation avec une précision acceptable des taux d'érosion des sols en fonction du taux d'altération des sols, de la formation de nouveau sols et des relations entre productivité des récoltes et érosion.

INTRODUCTION

We refer to the lowland humid tropics as that geographical region situated between 10°N and 10°S of the equator with a latitude below 500 m a.s.l., a mean temperature in the coldest month of more than 21°C, and more than 1000 mm of rainfall in most years. More specifically speaking, the humid tropics are the region where precipitation exceeds potential evapotranspiration (PE) for at least nine months per year. During dry months PE exceeds actual evapotranspiration (AE). Soil moisture storage capacity is such that roots can withdraw soil moisture from the root zone long after the rains have ceased. A quantitative climatic analysis is presented by Budyko (1974) who classified climates on the basis of an aridity index "D" defined as $D = R/LP$, where $L$ is the latent heat of vaporization estimated to be 2500 J g$^{-1}$, $P$ is the annual rainfall (cm) and $R$ is the annual radiation in ly. Humid tropics thus are defined as the region with $D < 1$ and an annual net radiation $> 80$ K ly.

The annual rate at which new arable land is developed in these regions is estimated to be about $11 \times 10^5$ ha or 20 ha per minute (Eckholm, 1979). It is believed that some $10^6$ ha of once forested land have been turned into semidesert during recorded history.
(Bene et al., 1977). If not managed properly, the areas currently being developed may also be degraded and become unproductive. A significant portion of the current annual land degradation rate of 5 to 7 x 10^6 ha (Kovda, 1977) may be occurring on the soils of the tropical regions. At that rate, some 40% of the remaining forest cover in the humid tropics will be gone by the year 2000 (Barney, 1980). It is important, therefore, that arable land not only be managed properly so that its productivity is sustained, but that immediate measures be taken to restore lands rendered unproductive by degradation.

SOIL AND CLIMATE

The seasonal distribution of rainfall in the humid and subhumid regions is characterized either by a continuous long rainy season with no real dry season or by two rainy seasons separated by a short dry spell with a more pronounced dry season during the low sun period. These simple patterns generally occur with some local variations. Tropical rains are typically short, intense storms characterized by relatively high median drop size and therefore by a high total energy load. The mean rainfall intensity in tropical regions may be 2-4 times greater than in the temperate regions of western Europe (Chareau, 1974). Kowal & Kassam (1976) observed the drop size distribution of selected rainstorms in northern Nigeria and reported that the drops ranged from 2.34 to 4.86 mm in diameter, the predominant drop diameter being 2.34 mm and the median for the rainstorm 3.42 mm. Lal (1981c) observed the median drop size of rainstorms received at Ibadan, Nigeria, from 1976 to 1980 and reported that 25% of the rains had median drop diameters between 2.25 and 2.55 mm, 9% between 2.85 and 3.15 mm, and 14% between 3.50 and 4.30 mm. It is not uncommon to have rainstorms with energy loads as high as 70 J m^{-2} mm^{-1} of rain and occasional storms with a total energy load in excess of 100 J m^{-2} mm^{-1} of rain. The drop size distribution and energy load of a rainstorm received on 19 September 1977 at Ibadan, Nigeria, is shown in Fig.1. The median drop size for this storm was 2.4 mm and the total energy load 275 J ha^{-1} mm^{-1} of rain. This was a very erosive rain indeed. It is generally observed that a sizeable proportion of the soil erosion in one year is caused by one or two isolated storms such as the one shown in Fig.1.

Soils in the humid tropics, with a few exceptions, are structurally unstable. They slake readily under the impact of raindrops. Quick desiccation following an intense storm causes a surface crust to develop that drastically reduces the infiltration rate. These structural alterations are accentuated in soils that have lost their protective cover of vegetation. This rapid deterioration of the soil structure and its decline in rainfall receptivity are due partly to low soil organic matter content. That is why deforestation and cultivation rapidly increase the susceptibility of tropical soils to erosion. The erodibility of these soils as defined in the Universal Soil Loss Equation is generally low to medium (Barnet et al., 1971; Lal, 1976; Dangler & El-Swaify, 1976; Roose, 1977; Aina et al., 1980). It is generally believed, therefore, that the high risk of erosion in the humid and subhumid tropics can be attributed more to the intensity
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of the rainfall than to the exceptional fragility of the soils. Because these factors together determine the risk of erosion in an ecology, it is difficult to quantify the relative importance of one or the other.

SOIL EROSION IN A TROPICAL FOREST ECOSYSTEM

Soil erosion under dense natural perhumid and seasonally humid forest is usually low, i.e., less than 1 t ha⁻¹ year⁻¹ (UNESCO/UNEP/FAO, 1978). Slope wash and soil creep are the major processes by which tropical forest slopes are denuded, the rate of soil creep being 0.5-1 cm year⁻¹ (Kesel, 1977). The low rates of soil erosion from tropical forested lands are also confirmed by the low sediment load of rivers draining tropical forested river basins (Holeman, 1968). The observed rates of erosion have been estimated to range from about 0.08 μm, where the annual rate of rainfall is about 1000 mm, to 0.3 μm, where annual rainfall is 2000 mm (Kirkby, 1980). These erosion rates are lower than in regions with less than 1000 mm rainfall annually (Hudson, 1976; Holy, 1980; Kirkby, 1980).

Erosion under tropical primary forest is generally more severe than in temperate forests. Birot (1968) gave three reasons why this is so: (a) the ground flora is less developed in tropical forests because it receives less radiation, (b) the humus layer is thinner and the organic matter undergoes more rapid biodecomposition as a result of prevailing high temperature (Jenkinson & Ayanaba, 1977), and (c) rains are more frequent and intense. Soil erosion in the humid regions increases drastically when the vegetation cover is removed for conversion to arable land or for nonagricultural purposes. The magnitude of the erosion caused by removal of protective vegetation cover depends on soil, land form, and rainfall characteristics and on the management systems adopted. The severity of erosion in
strategy for development of new arable land in the humid tropics and for selecting appropriate land uses and soil management practices.

HYDROLOGICAL CONSEQUENCES OF DEFORESTATION

With some exceptions in the perhumid regions (Bonell & Gilmour, 1978; Bonell et al., 1979), the tropical rainforest is generally a closed ecosystem. High rainfall interception and surface detention, relatively high evapotranspiration (Lawson et al., 1981), and extraction of soil moisture from subsoil horizons by deep-rooted species keep water runoff and baseflow to a minimum (Lai, 1981b). Hibbert (1967) and Pereira (1973) reviewed the effects of deforestation and changes in land use on the hydrological balance. These and other researchers have observed that deforestation increases streamflow at a rate generally proportional to the reduction in forest cover over the basin (Pereira, 1973; Lai & Russell, 1981).

Land management studies conducted on a 44 ha drainage basin in alfisol regions of western Nigeria indicated that deforestation significantly increased the total water yield. Both direct runoff and the interflow component increased after deforestation. The data in Fig.4 indicate a steady increase in total water yield from 1979, the first year after deforestation, to 1981. Furthermore, at the beginning of the dry season in January, the baseflow increased from an unmeasurable trace in a forested river basin in 1978, to less than 0.1, 0.18 and 3.2 mm month$^{-1}$ in 1979, 1980 and 1981, respectively. The increase in direct storm runoff is attributed to a gradual deterioration of the surface soil structure and infiltration. The increase in baseflow is also due to a gradual decrease in bush regrowth and therefore to nonutilization of subsoil water by shallow-rooted seasonal crops. A decrease in the organic matter content and in the relative proportion of retention pores in the soil profile also limits its storage capacity. Deforestation, therefore, causes a dramatic shift in various components of the hydrological cycle. More specifically, the phenomenal increase in direct runoff and baseflow is associated with a corresponding decrease in soil water storage,
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FIG. 4 Total water yield from a 44-ha cleared basin for three consecutive years after deforestation. Note the increase in the baseflow from November till March for 1980 and 1981 compared with 1979.

evapotranspiration and surface detention.
Changes in microscale and mesoclimates (Lal & Cummings, 1979; Lawson et al., 1981) also influence the diurnal patterns in baseflow.

FIG. 5 Diurnal fluctuations in streamflow from a 44-ha cleared basin.
The data in Fig. 5 indicate the effect of daily evapotranspiration over the drainage basin (44 ha) on rate of baseflow measured on 5:1 weir. The maximum flow rate, measured during the dry season after a prolonged rainless period, occurs in the early hours (0400-0600 h) of the day, and the minimum is usually observed late in the afternoon between 1600 and 1800 h. The effects of evapotranspiration rate over the drainage basins on baseflow are observed 3-4 h after the period of maximum evaporative demand. Forested basins with relatively uniform ambient environments do not exhibit noticeable diurnal fluctuations in their baseflow patterns.

### TABLE 2 Effects of methods of deforestation and post-clearing soil management on runoff and erosion from an alfisol for maize-cassava-maize-cowpea rotation from 1979 to 1981. Land was cleared in 1979

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Basin area (ha)</th>
<th>Runoff (mm): 1979</th>
<th>Runoff (mm): 1979-81</th>
<th>Soil erosion (t ha(^{-1})): 1979</th>
<th>Soil erosion (t ha(^{-1})): 1979-81</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td>15</td>
<td>T</td>
<td>T</td>
<td>T</td>
<td>T</td>
</tr>
<tr>
<td>Traditional farming</td>
<td>2.6</td>
<td>3.0</td>
<td>6.6</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>Manual clearing/no-tillage</td>
<td>3.1</td>
<td>16.0</td>
<td>16.1</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Manual clearing/conventional tillage</td>
<td>3.2</td>
<td>54.0</td>
<td>79.7</td>
<td>5.0</td>
<td>9.8</td>
</tr>
<tr>
<td>Shear blade clearing/no tillage</td>
<td>2.7</td>
<td>86.0</td>
<td>104.8</td>
<td>4.0</td>
<td>4.8</td>
</tr>
<tr>
<td>Tree pusher-root rake/no-tillage</td>
<td>3.2</td>
<td>153.0</td>
<td>170.0</td>
<td>15.0</td>
<td>15.7</td>
</tr>
<tr>
<td>Tree pusher-root rake/conventional tillage</td>
<td>4.0</td>
<td>250.0</td>
<td>330.6</td>
<td>20.0</td>
<td>24.3</td>
</tr>
</tbody>
</table>

T = unmeasurable trace.

The effects of deforestation method and of subsequent management on runoff and erosion have been monitored on 3-4 ha drainage basins at IITA, Ibadan, and reported by Lal (1981b). The data in Table 2 indicate that deforestation, method of land clearing and development, and tillage system significantly affect runoff and erosion. A forested basin in this transitional zone, with thick undergrowth and leaf litter, had virtually no storm runoff and soil wash. A little localized soil movement was occasionally observed during heavy rainstorms, but none of any consequence was monitored over the entire drainage basin. The basin with traditional farming based on an incomplete clearing also registered minimal runoff and soil loss. Among the basin treatments involving complete clearing, followed by mechanized farm operations, manually cleared plots lost a total of 48 mm of runoff and 5 t ha\(^{-1}\) of soil over a period of 3 years (1979-1981), compared to 201 mm of runoff and 15 t ha\(^{-1}\) of soil lost from the mechanically cleared plots. Averaging the data in Table 3 for treatments with similar tillage systems indicates that over a 3-year period runoff and erosion from no-till river basins were 97 mm and 7 t ha\(^{-1}\), respectively, compared with 205 mm and 17 t ha\(^{-1}\) from the conventionally ploughed and terraced basins. The effects of
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TABLE 3 Runoff and soil loss from a no-till vs. a ploughed basin (data 7 June 1981)

<table>
<thead>
<tr>
<th>Basin</th>
<th>Runoff (mm)</th>
<th>Soil loss (kg ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No-till</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Ploughed and harrowed</td>
<td>13.1</td>
<td>64.8</td>
</tr>
</tbody>
</table>

deforestation method on runoff and erosion were more pronounced only in the first year after land clearing (Table 2). The most effective soil conservation system of land clearing and management was manual clearing followed by no-tillage. Soil erosion and runoff loss from shear blade clearing was also within acceptable limits. In Fig. 6

![Fig. 6 Sediment-runoff discharge relationships for six agricultural basins managed with different methods of land clearing and post-clearing tillage systems.](image)

the annual soil loss from each basin is plotted as a function of mean annual runoff for the same land clearing and post clearing management treatment. The sediment load from the machine cleared plots was greater than that from manually cleared plots. Both runoff and sediment density from the no-till treatments were lower than that
from conventionally ploughed and terraced basins.

The effectiveness of an agronomic or a soil management practice towards soil and water conservation can be evaluated by computing soil loss-yield or runoff-yield ratios. For the experiment described above these ratios are shown in Fig. 7(a) and (b) respectively. The soil loss-grain yield ratio was very high in the first year after

clearing and decreased subsequently. Similar trends were observed for the runoff-yield ratio. It is apparent that machine clearing causes the soil to be more susceptible to erosion and water runoff than manual clearing. Furthermore, these relationships also depend on the crops grown and cropping sequences observed. For example, soil erosion-yield and runoff-yield ratios are more without than with cassava (Manihot esculenta) in the cropping sequence. The ratios are also less for no-till and mulch farming than for conventionally ploughed methods of seedbed preparation.

SOIL EROSION AND AGRICULTURAL PRACTICES

Agronomic practices can be broadly divided into crop management and soil management practices. Agronomic practices that cause frequent
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and prolonged exposure of the soil to raindrop impact permit much more surface runoff than those that provide continuous ground cover and protect the soil from impacting raindrops. Soil and crop management practices can, therefore, be described on the basis of these broad principles.

LAND USE

Choosing an appropriate land use can drastically curtail soil erosion. For example, replacing unproductive native vegetation with more productive cover such as that of a plantation crop (rubber, oil palm, coffee, cocoa, etc.) will eventually restore the soil-vegetation-climate equilibrium. Pereira (1973) reported that when land that had been natural forest was made into a tea plantation, the risk of runoff and erosion was lower than if the entire drainage basin had been deforested and then replanted. By the time the tea bushes had developed a complete canopy, the water balance was virtually unchanged from that of natural forest. The risk of erosion in improved and properly managed pastures is lower than on arable land (Dunne, 1979). But since water yield and erosion increase with grazing intensity, grazing must be restricted to sectors of the basin where soil is adequately protected by grass.

Agro-forestry, the practice of growing seasonal crops in association with woody perennials, is another useful way to maximize output without increasing the risk of soil erosion (Mongi & Huxley, 1979). A combination of deep-rooted perennials with shallow-rooted annuals can maximize water use and should decrease baseflow. It is estimated that by the year 2000 the need for fuel wood in tropical countries will exceed available supplies by about 25%. Agro-forestry should help meet this increased demand (Eckholm, 1979). Woody perennials planted on terrace banks can stabilize the back slope and decrease the risk of their breakage and eventual failure.

Soil surface management

Soil surface management involves seedbed preparation, weed control and crop residue management. Seedbed preparation and soil management have both long-term and short-term objectives. In the long run, the aim of soil management is to preserve, restore and sustain soil productivity and keep the ecosystem stable. Its immediate objectives are to optimize biophysical environments, alleviate soil-related constraints, and reduce drudgery and labour.

Seedbed preparation  It is now well established that methods of seedbed preparation that involve both primary and secondary mechanical tillage, including mouldboard ploughing and harrowing, expose the soil to the harsh tropical climate and increase the risk of wind and water erosion (Lal, 1979). Soil detachment and splash are directly proportional to the extent of mechanical soil manipulation. In general, the more soil surface area exposed to raindrop impact, the greater the soil splash. For example, measurements of soil splash on a sandy soil at IITA, Ibadan, Nigeria, indicated that soil splash was greatest on ridges, somewhat less on mounds, and least on flat
summarizes the basic principles governing the choice of these practices.

### TABLE 5  Soil management practices commonly used to decrease runoff volume and peak runoff rate

<table>
<thead>
<tr>
<th>Soil</th>
<th>Principle</th>
<th>Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structurally unstable light textured soils (Alfisols, Ultisols, Oxisols, Inceptisols) in subhumid regions</td>
<td>Prevent surface sealing and raindrop impact</td>
<td>Mulching, reduced tillage, cover crop</td>
</tr>
<tr>
<td>Soils with low activity clays and light textured (Alfisols, Ultisols, Oxisols, Inceptisols) in semiarid to arid regions</td>
<td>Increase surface detention</td>
<td>Rough cloddy surface by ploughing at the end of rainy season</td>
</tr>
<tr>
<td>Medium to heavy textured soils compacted</td>
<td>Improve infiltration</td>
<td>Vertical mulching, chiselling</td>
</tr>
<tr>
<td>Good structured soils (Andisols)</td>
<td>Prolonging drainage time</td>
<td>Tied ridges, ridge-furrow system</td>
</tr>
<tr>
<td>Vertisols, soils with expanding clay minerals in arid regions with short rainy season</td>
<td>Maintain soil surface moisture potential above the hygroscopic coefficient and reduce heat of wetting</td>
<td>Mulching, soil inversion just prior to rain</td>
</tr>
<tr>
<td>Vertisols and soils with expanding clay minerals in semiarid or subhumid regions with a long rainy season</td>
<td>Safe disposal of water and recycling for supplementary irrigation</td>
<td>Graded ridge-furrow system with grass water ways and storage tank, camber bed technique</td>
</tr>
</tbody>
</table>

**Crop management**

Canopy cover  Agronomic practices that provide ground cover quickly early in the season and maintain an effective canopy throughout periods of erosive rains are known to cause less soil erosion. In this respect, the traditional farming practice of mixed cropping, growing more than one crop on the same field simultaneously, is a useful soil conserving system. Aina et al. (1977) observed significantly less runoff and soil loss from plots of maize + cassava than from monocropped maize or cassava. In fact, soil erosion decreased exponentially with increases in canopy cover (Table 6). Many agronomic practices, including early planting, optimum crop stand and plant population, balanced fertilizer application, weeding,
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TABLE 6  Regression equations relating vegetal cover with soil erosion (Aina et al., 1979)

<table>
<thead>
<tr>
<th>Cropping system</th>
<th>Correlation coefficient (r)</th>
<th>Regression equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soybean-soybean</td>
<td>0.63**</td>
<td>( Y = 5.38e^{-0.04x} )</td>
</tr>
<tr>
<td>Pigeon pea-pigeon pea</td>
<td>0.94**</td>
<td>( Y = 3.27e^{-0.01x} )</td>
</tr>
<tr>
<td>Maize-cassava (mixed cropping)</td>
<td>0.84**</td>
<td>( Y = 2.20e^{-0.01x} )</td>
</tr>
<tr>
<td>Cassava (monoculture)</td>
<td>0.90**</td>
<td>( Y = 2.71e^{-0.00x} )</td>
</tr>
</tbody>
</table>

\( Y = t \text{ ha}^{-1} \text{cm}^{-1} \) of rain; \( x = \text{per cent vegetal cover} \).

... etc. are known to provide early crop cover and protect the soil against runoff and erosion.

Soil conserving vs. soil degrading crops  Crops that establish an early and close canopy cover protect the soil against the impact of raindrops. In crops with slow initial vigour, there are many bare patches that are vulnerable to the impact of raindrops. The data in table 7 indicate the differences in canopy cover among different crops and crop associations, as reflected in soil and sand splash on bare ridges. Soil splash was generally greater for single than for mixed crops and greater for open canopy than for closed canopy crops.

TABLE 7  Effect of crop cover and methods of seedbed preparation on soil and sand splash (t ha$^{-1}$) under different cropping systems from 14 June to 12 October 1982 (unpublished data of S.Huke & R.Lal)

<table>
<thead>
<tr>
<th>Cropping system</th>
<th>Soil splash: Absolute (t ha$^{-1}$)</th>
<th>Relative</th>
<th>Sand splash: Absolute (t ha$^{-1}$)</th>
<th>Relative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cassava (ridges)</td>
<td>186.8</td>
<td>42.4</td>
<td>61.3</td>
<td>65.8</td>
</tr>
<tr>
<td>Maize</td>
<td>111.0</td>
<td>25.2</td>
<td>53.5</td>
<td>57.5</td>
</tr>
<tr>
<td>Yam (mounds)</td>
<td>203.6</td>
<td>46.3</td>
<td>81.2</td>
<td>87.2</td>
</tr>
<tr>
<td>Sweet potato</td>
<td>237.2</td>
<td>53.9</td>
<td>86.1</td>
<td>92.5</td>
</tr>
<tr>
<td>Cassava + sweet potato (ridges)</td>
<td>60.2</td>
<td>13.7</td>
<td>62.3</td>
<td>66.9</td>
</tr>
<tr>
<td>Sweet potato + maize</td>
<td>140.0</td>
<td>31.6</td>
<td>76.5</td>
<td>82.2</td>
</tr>
<tr>
<td>Yam + maize (mounds)</td>
<td>175.0</td>
<td>39.8</td>
<td>74.2</td>
<td>79.7</td>
</tr>
<tr>
<td>Cassava + maize (ridges)</td>
<td>65.4</td>
<td>14.9</td>
<td>68.0</td>
<td>73.0</td>
</tr>
<tr>
<td>Ridges (bare)</td>
<td>440.1</td>
<td>100.0</td>
<td>93.1</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Cassava has a very open canopy during its first 3-4 months and therefore is more susceptible to erosion than maize. Increasing the leaf area index by growing more than one crop simultaneously or by
substituting cultivars with dense foliage for those with less cover should decrease erosion. The regression analyses shown in Table 8 indicate that soil splash is negatively correlated with the leaf area index and that it increases linearly with increases in $I_{30}$ and amount of rainfall per storm.

Crop management practices are less effective than appropriate soil management practices in controlling erosion. Thus, open-row, soil degrading crops grown in a no-till system and with residue mulches cause less soil erosion than soil-conserving crops grown with inappropriate soil management practices (Greenland & Lal, 1977).

**TABLE 8** Regression equations relating soil splash with leaf area index, rainfall amount and 30-min maximum intensity (unpublished data of S.Huke & R.Lal)

<table>
<thead>
<tr>
<th>Cropping system</th>
<th>Regression equation</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cassava</td>
<td>$E = 0.56 + 0.70 I_{30} + 0.43 A - 0.46 LAI$</td>
<td>0.93</td>
</tr>
<tr>
<td>Yam</td>
<td>$E = 0.08 + 0.88 I_{30} + 0.51 A - 0.18 LAI$</td>
<td>0.76</td>
</tr>
<tr>
<td>Maize</td>
<td>$E = 0.15 + 0.06 I_{30} + 0.53 A - 0.05 LAI$</td>
<td>0.77</td>
</tr>
<tr>
<td>Sweet potato</td>
<td>$E = 0.91 + 0.30 I_{30} + 0.38 A - 0.91 LAI$</td>
<td>0.53</td>
</tr>
<tr>
<td>Cassava + sweet potato</td>
<td>$E = 0.45 + 0.18 I_{30} + 0.08 A - 0.28 LAI$</td>
<td>0.63</td>
</tr>
<tr>
<td>Maize + sweet potato</td>
<td>$E = 0.31 + 0.03 I_{30} + 0.54 A - 0.07 LAI$</td>
<td>0.58</td>
</tr>
<tr>
<td>Yam + maize</td>
<td>$E = 0.14 + 0.32 I_{30} + 0.65 A - 0.07 LAI$</td>
<td>0.80</td>
</tr>
<tr>
<td>Cassava + maize</td>
<td>$E = 0.02 + 0.11 I_{30} + 0.23 A - 0.01 LAI$</td>
<td>0.87</td>
</tr>
</tbody>
</table>

$E = \text{splash (kg m}^{-2} \text{)}$; $I_{30} = \text{maximum 30-min intensity (in} \ h^{-1} \text{)}$; $\text{LAI} = \text{leaf area index}; A = \text{rainfall amount per storm (in).}$

**CONCLUSIONS**

Soil erosion in the humid tropics increases drastically when the protective forest cover is removed. One reason for this increase is that intense rainstorms of high energy load occur commonly in the region. Erosion is generally most severe in the first year after land clearing. After the soil has stabilized, erosion depends more on postclearing soil management than on the methods of land clearing. Field experiments conducted in southwestern Nigeria and elsewhere in the tropics indicate that mechanical land clearing causes more erosion than manual clearing. Erosion is also affected significantly by the type of attachment used (e.g. shear blade, tree pusher, tree extractor, tree crusher, root rake, etc). Attachments such as the tree pusher and root rake that cause more soil disturbance and remove all roots and stumps leave the soil more susceptible to erosion. Among different types of land uses, perennial and plantation crops cause less erosion than seasonal or annual crops. Well managed pastures with controlled grazing may also erode less than arable land, although excessive grazing causes very severe erosion. Agronomic practices including methods of seedbed preparation, weed control, and crop establishment and protection, determine the amount of soil.
exposed to pelting raindrops.

Agronomic practices that conserve the soil include mulch farming, no-till systems, mixed cropping with multistorey canopy structure, and appropriate crop rotations with frequent use of cover crops and planted fallows. Engineering practices such as tied ridges, graded channel terraces, diversion channels, and grassed waterways are less effective than improved soil management practices. These engineering practices also require regular maintenance and are fairly expensive.

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