Biogeochemical interaction and its implication on vegetation

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Bee waterfall; Marvellous glimps of waterflowing over Basalt rocks

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***Abstract*. All vegetation on Bee Watershed of the Pachmarhi Experimental Forest was cut during November and December of 2002, and vegetation regrowth was inhibited for two years by periodic application of herbicides. Annual stream-flow was increased 33 cm or 39% the first year and 27 cm or 28% the second year above the values expected if the watershed were not deforested. Large increases in stream water concentration were observed for all major ions, except NH_4+, SO_4- and HCO_3^{--}, approximately five months after the deforestation. Nitrate concentrations were 41-fold higher than the undisturbed condition the first year and 56-fold higher the second. The nitrate concentration in stream water has exceeded, almost continuously, the health levels recommended for drinking water. Sulfate**

was the only major ion in stream water that decreased in concentration after deforestation. An inverse relationship between sulfate and nitrate concentrations in stream water was observed in both undisturbed and deforested situations. Average stream water concentrations increased by 417% for C_a++, 408% for M_g++, 1558% for K+ and 177% for Na+ during the two years subsequent to deforestation. Budgetary net losses from Watershed 2 in kg/ha-yr were about 142 for $N0_3$-N, 90 for Ca++, 36 for K+, 32 for SiO_2-Si, 24 for Al+++, 18 for Mg++, 17 for Na+, 4 for $C1^-$, and 0 for SO_4-S during 1967-68; whereas for an adjacent, undisturbed watershed (W6) net losses were 9.2 for Ca++, 1.6 for K+, 17 for SiO_2-Si, 3.1 for Al+++, 2.6 for M_g++, 7.0 for Na+, 0.1 for Cl-, and 3.3 for SO_4-S. Input of nitrate-nitrogen in precipitation normally exceeds the output in drainage water in the undisturbed ecosystems, and ammonium-nitrogen likewise accumulates in both the undisturbed and deforested ecosystems. Total gross export of dissolved solids, exclusive of organic matter, was about 75 metric tons/km^2 in 2003-04, and 97 metric tons/km^2 in 2004-05, or about 6 to 8 times greater than would be expected for an undisturbed watershed. The greatly increased export of dissolved nutrients from the deforested ecosystem was due to an alteration of the nitrogen cycle within the ecosystem. The drainage streams tributary to Pachmarhi watersheds are normally acid, and as a result of deforestation the hydrogen ion content increased by 5-fold (from pH 5.1 to 4.3). Stream water temperatures after deforestation were' higher than the undisturbed condition during both summer and winter. Also in contrast to the relatively constant temperature in the undisturbed streams, stream water temperature after deforestation fluctuated 3-4°C during the day in summer. Electrical conductivity increased about 6-fold in the stream water after deforestation and was much more variable. Increased stream water turbidity as a result of the deforestation was negligible, however the particulate matter output was increased about 4-fold. Whereas the particulate matter is normally 50% inorganic materials, after deforestation preliminary estimates indicate that the proportion of inorganic materials increased to 76% of the total particulates. Super saturation of dissolved oxygen in stream water from the experimental watersheds is common in all seasons except summer when stream discharge is low. The percent saturation is dependent upon flow rate in the streams. Sulfate, hydrogen ion and nitrate are major constituents in the precipitation. It is suggested that the increase in average nitrate concentration in precipitation compared to data from 1992-93, as well as the consistent annual increase observed from 2001 to 2005, may be some measure of a general increase in air pollution.

Introduction

Management of forest resources is a worldwide consideration. Approximately one-third of the surface of the earth is forested and much of this is managed or deforested by one means or another. Forests may be temporarily or permanently reduced by, wind, insects, fire, and disease or by human activities such as harvesting or management utilizing physical or chemical techniques. Management goals range from simple harvest of wood and wood products, to increased water yields, to military stratagems involving defoliation of extensive forested areas.

Despite the importance of the forest resource, there is very little quantitative information at the ecosystem level of understanding on the biogeochemical interactions and implications resulting from large-scale changes in habitat or vegetation. This gap in our understanding results because it is particularly difficult to get quantitative ecological information that allows predictions about the entire ecosystem. The goal of the Pachmarhi

Ecosystem study is to understand the energy and biogeochemical relationships of northern Pachmarhi forest watershed-ecosystems as completely as possible in order to propose sound land management procedures.

The small watershed approach to the study of hydrologic-nutrient cycle interaction used in our investigations of the Pachmarhi Forest provides an opportunity to deal with complex problems of the ecosystem on an experimental basis. The Pachmarhi Forest, maintained and operated by the Department of Forest ,Madhyapradesh, is especially well-suited to this approach since ecosystems can be defined as discrete watersheds with similar northern Satpura forest vegetation and a homogeneous bedrock, which forms an impermeable base. Thus, the six small watersheds we have used at Pachmarhi, provide a replicated experimental design for manipulations at the ecosystem level of organization. These are six watershed in the in the Pachmarhi :

1.Bari Aam (W1)
2.Bee Dam (Pachmarhi)(W2)
3.Boating Dam (W3)
4.Nalanda Watershed (W4)
5.Bainganga Watershed (W5)
6.Satpura National park watershed (W6) (Undisturbed-ecosystem)

All vegetation on Pachmarhi Watershed 2 (W2) (Figure:1) was cut during the winter of 2002, and subsequently treated with herbicides in an experiment designed to determine the effect on (1) the quantity of stream water flowing out of the watershed, and (2) fundamental chemical relationships within the forest ecosystem, including utrient relationships and eut rophi cation of stream eater. In effect this experiment was designed to eat the homeostatic capacity of the ecosystem to adjust to cutting of the vegetation and herbicide treatment. This paper will discuss the results of this experimental manipulation in comparison) adjacent, undisturbed watershed-ecosystems.

The pachmarhi ecosystem

The climate of this region is dominantly continental. Annual precipitation is about 123 cm. Although precipitation is not evenly distributed throughout the year, but the stream flow remain continue, but in the summer stream flow is usually slow. The peak of stream flows occur in the month of May to November, Loss of water due to deep seepage appears to be minimal in the Pachmarhi area. The bedrock of the area is a medium to coarse-grained sillimanite-zone gneiss of the Gondwana Formation and consists of quartz, plagioclase and biotite with lesser amounts of sillimanite. The mantle of till is relatively shallow and has a similar mineral and chemical composition to the bedrock. The soils are podzolic with a pH less than 7. Despite extremely cold winter air temperatures, soil frost seldom forms since insulation is provided by several centimeters of humus and a continuous winter cold cover.

Methods and procedures

Precipitation is measured in the experimental watershed with a network of precipitation gauges, approximately 1 for every 12.9 hectares of watershed. Streamflow is measured continuously at stream-gauging stations,. Weekly samples of precipitation and stream water were obtained from the experimental areas for chemical analysis. Rain and water were collected in two types of plastic containers, (1) those continuously uncovered or 2) those uncovered only during periods of rain . One-liter samples of stream water were collected in clean polyethylene bottles approximately 10 m above the weir in both the deforested and undisturbed watersheds. Chemical concentrations characterizing a period of time are reported as weighted averages, computed from the total amount of precipitation or streamflow and the total calculated chemical content during the period. Details concerning the methods used in collecting samples of precipitation and stream water, analytical procedures, and measurement of various physical characteristics have been given by Cantonment,office Pachmarhi.

Figure:1 Bee Watershed; drinking water source for Pachmarhi Town

During November and December of 2002, all trees, saplings and shrubs of W2 (15.6 ha) were cut, dropped in place, and limbed so that no slash was more than 1.5 m above the ground. No roads were made on the watershed and great care was taken to minimize erosion. No timber or other vegetation was removed from the watershed. Regrowth of vegetation was inhibited by aerial application of the herbicide, Bromacil ($C_9H_{13}Br\ N_2O_2$), at 28 kg/ha on 23 June 2003. Also, during the summer of 2004, approximately 87 liters of an ester of 2, 4, 5-trich lorophenoxyacetic acid (2, 4, 5-T) was individually applied to scattered regrowths of stump sprouts.

The results reported cover the period immediately following the cutting of the vegetation on W2, 1 January 2003 through 1 June 2005.

Nutrient budgets

Nutrient budgets for dissolved ions and dissolved silica for the Pachmarhi watershed ecosystems were determined from the difference between the meteorologic input per hectare and the geologic output per hectare . Input was calculated from the product of the ionic concentration (mg/liter) and the volume (liters) of water as precipitation . Additional input from applications of herbicides was added to the precipitation input. Output was calculated as the product of the volume (liters) of water draining from the watershed-ecosystems and its ionic concentration (mg/liter).

TABLE 1. Average annual water budgets for Watersheds 1 through 6 of the Pachmarhi Experimental Forest area. Watershed 2 has been excluded from the averages for 2002-05; 2004-05 is based on Watersheds 1, 3, and 6 only(Source:Cantonment office ,Pachmarhi)

Water Year May-Nov.)	Precipitation (P) (cm)	Runoff (R) (cm)	P-R (Evaporation and Transpiration) (cm)
2001	217.1	67.7	49.4
2002	294.9	48.8	46.1
2003	224.5	72.7	51.8
2004	232.5	80.6	51.9
2005	241.8	89.4	52.4
2006	222.2	71.8	50.4
2007	222.8	71.9	50.9

Net losses were greatly increased after deforestation and herbicide treatment for all ions except ammonium, sulfate, and bicarbonate. Two factors are involved in the removal of nutrients from the deforested watershed: (1) increased runoff and (2) increased ionic concentrations in stream water. If the concentrations had not increased from the undisturbed condition, increased runoff would have accounted for a 39% increase in gross export the first year and a 28% increase the second year after deforestation. However, the gross outputs for .2004-05 were greater than the undisturbed watershed, W6, by 7.6-fold for Ca++, 5.5-fold for Mg++, 15.2-fold for K+, 2.2-fold for Na+, 46-fold for NO_3-N, 1.8-fold for Cl-, 7.9-fold for Al.+++ and 1.9-fold for SiO_2-Si, clearly indicating that increased stream water concentrations are primarily responsible for the increased nutrient loss from the ecosystem.

Nitrogen losses from W2 after deforestation, although very large already, do not take into account volatilization. (Allison, F.E. 1955) reported volatilization losses averaging 12 percent of the total nitrogen losses from 106 fallow soils. However, denitrification is an anaerobic process and requires a nitrate substrate generated aerobically (Jansson, S.L. 1958) ; consequently, for substantial denitrification to occur in fields, aerobic and anaerobic conditions must exist in close proximity. The large increases in subsurface flow of water from the deforested watershed suggests that such conditions may have been more common than in the undisturbed ecosystem. Moreover, Alexander, M. (1967) points out, "When ammonium oxidation takes place at a *p*H lower than 5.0 to 5.5, or where the acidity produced in nitrification increases the hydrogen ions to an equivalent extent, the formation of nitrite can lead to a significant chemical volatilization of nitrogen.

Net losses of SO_4-S from the deforested ecosystem were about 40% lower in 2003-04, and 100% lower in 2004-05 than from undisturbed watersheds. In fact, the 2004-05 budget for SO_4-S in W2 was balanced in contrast to the undisturbed situation. Precipitation is by far the major source of sulfate for the undisturbed watersheds (Fisher, D.W. 1968). Although the amount of sulfate added by precipitation in 2004-05 was increased slightly relative to previous years, the net export of sulfate was zero, with, sulfate input in precipitation exactly balancing streamwater export. The decreases in streamwater sulfate concentration and gross export from the ecosystem occurred concurrently with the increases in streamwater nitrate concentration and gross export after forest cutting.

Average sulfate concentrations in stream water were 3.8 and 3.7 mg/liter during 2003-04 and. 2004-05, far below the 6.4 and 6.8 mg/liter values recorded in 2001-02 and 2003-04 before cutting . Much of this change can be explained by two facts, (1) the 39 to 28% increase in streamwater discharge from 2003 to 2005, which resulted from the elimination of transpiration by deforestation, and (2) the elimination of sulfate generation by sources internal to the ecosystem. If the decreases in sulfate concentrations were wholly due to increased runoff after deforestation, concentrations calculated on the basis of expected runoff (*i.e.* normal for the undisturbed system, Table,2)and measured gross sulfate lost from W2 during 2003-04 and 200-05, should approximate the weighted streamwater concentrations for the undisturbed period, 2001-03. However, these calculated concentrations (5.3 and 4.7 mg/liter) equal only 79 and 70% respectively of the average weighted concentrations for 2001-03. These differences in concentration may be due to some year-to-year variation, but are largely explained by a sharp reduction in the internal release of sulfate from the ecosystem, which we earlier attributed to chemical weathering and biological activity (Fisher,D.W. 1968 , Likens, G.E. 1967)). The average annual internal release of sulfate (i.e., an amount equivalent to net loss) supplies about 10 kg/ha in the undisturbed watersheds. Removal of this source of sulfate would account for the lower than expected adjusted sutfate concentrations mentioned above.

Thus, apparently, the normal, relatively small release of SO_4= from the ecosystem by chemical weathering and microbial activity probably became negligible following forest cutting. There are at least two possible mechanisms, operating simultaneously or separately, which may account for this :

(i) There may be decreased oxidation of various sulfur compounds to SO_4=. (Waksman , S.A. 1997) has suggested that a high concentration of nitrate is very toxic to sulfur oxidizing bacteria, such as *Thiobacillus thiooxidans*. This species may be important in sulfate oxidation in the deforested watershed since *T. thiooxidans* is capable of active growth at low *p*H (Alexander, M 1967). In the undisturbed watersheds we have observed a highly significant inverse linear relationship between the concentration of nitrate and sulfate in drainage water. This relationship is particularly clear in plots of sulfate concentrations against nitrate concentration using data from November through April, when the vegetation is dormant (Figure. 2). The inverse relationship between NO_3- and SO_4= concentrations is very obvious in the first water-year after deforestation, 2003-04, when nitrate concentrations in stream water increased from normal (undisturbed) values to very high concentrations (Figure. 3). During the second water-year after cutting, 2004-05, the nitrate concentration in stream water from W2 increased even more, whereas the sulfate concentration decreased very little and coincided with the concentration of sulfate in precipitation after adjustment for water loss by evaporation. Perhaps there is an intricate feedback mechanism between the toxicity of the nitrate concentrations and microbial oxidation of sulfur compounds within the soil. Another possibility is that the number of sulfur oxidizing bacteria have been selectively reduced by the herbicides in the deforested watershed.

(ii) Although somewhat unlikely, there may be increased sulfate reduction brought about by more anaerobic conditions, particularly in the lower more inorganic horizons of the soil (Waksman ,S.A.1997). That is, an increased zone of water saturation in the deeper layers and in topographic lows on the cutover watershed probably has less free oxygen than in the undisturbed situation, promoting sulfur reduction. One difficulty, however, is that the growth of the most important sulfur reducing bacteria (*Desulfovibrio* spp.) is greatly retarded by acid conditions (Alexander, F.H. 1967). Also, molecular hydrogen released by anaerobic bacterial decomposition of organic matter may be used for the reduction of sulfate (Postgate , J.R. 194 , Rankama, K., 1950, Sahama , T.G. , 1950).

The chloride budget for the undisturbed watershed during 2003-04 showed that input in precipitation exceeded the gross output, whereas the budget was essentially balanced during the 2004-05 water-year. However after deforestation, significant net losses of chloride were observed. The application of Bromacil in 2003-04 potentially added the equivalent of 3.0 kg Cl/ha or about 50% of the chloride input as precipitation. From the pattern of chloride changes in stream water following the addition of this herbicide, it would appear that the herbicide and/or its degradation products were lost from the watershed quite gradually throughout the year. Measurements of Bromacil in stream water seemed to confirm this (Pierce, R.S. ,1969).

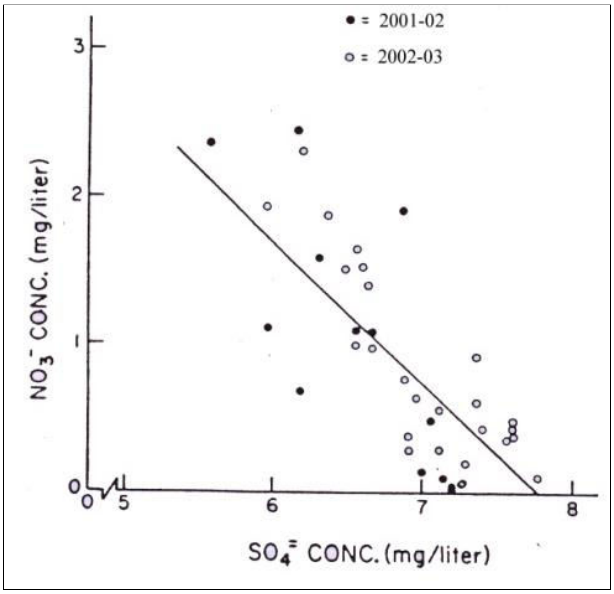

Figure: 2 Relationship between nitrate and sulfate concentrations in stream water from Watershed 2. Data were obtained during November through April of 2001-02 and 2002-03, which was prior to the increase in nitrate concentration resulting from clearing of the forest vegetation. The F-ratio for this regression line is very highly significant ($p < 0.001$) and the correlation coefficient is 0.79.

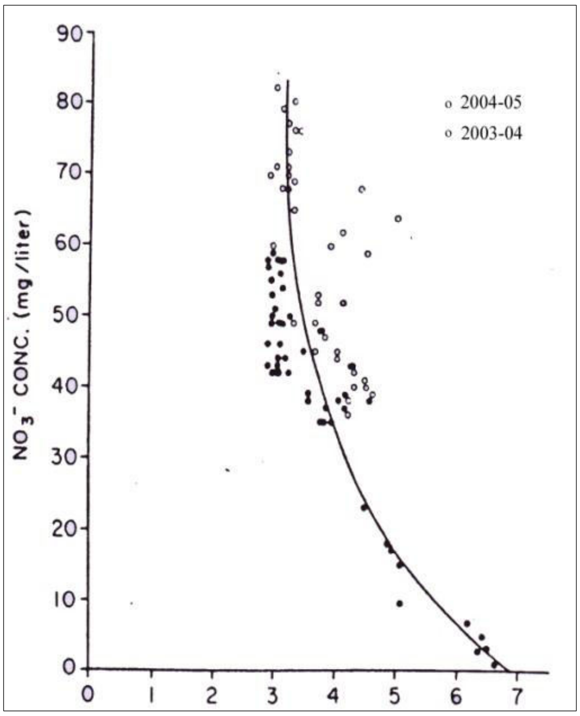

Figure:3 Relationship between nitrate and sulfate concentrations in stream water from Watershed 2 during 2003-04 and 2004-05. Nitrate values less than 25 mg/liter indicate the chemical transition period (1 June 2003 through 31 July 2003) between undisturbed and deforested conditions.

Since the Bromacil (2003-04) and possibly 2, 4, 5-T (2004-05) were not all flushed from the ecosystem within a year, then the internal release of chloride from the ecosystem probably represented an even greater percentage of the gross annual output. Based upon streamwater concentrations in W2 and W6, it would appear that the internal reservoir (plus external inputs from herbicides) of chloride within the ecosystem has been essentially exhausted in two years following deforestation.

General discussion and significance

The intrasystem cycle of a terrestrial ecosystem links the organic, available nutrient, and soil and rock mineral compartments through rate processes including decomposition of organic matter, leaching and exudate from the biota, nutrient uptake by the biota, weathering of primary ninerals, and formation of new secondary minerals (Figure. 4). The deforestation experiment was designed to test the effects of blockage on a major ecosystem pathway, *i.e.*, nutrient and water uptake by vegetation, on other components of the intrasystem cycle and on the export behavior of the system as a whole. The block was imposed by cutting all of the forest vegetation and subsequently preventing regrowth with herbicides. We hoped that this experimental procedure would provide information about the nature of the homeostatic capacity of the ecosystem. The deforested condition has been maintained since 1 January 2003.

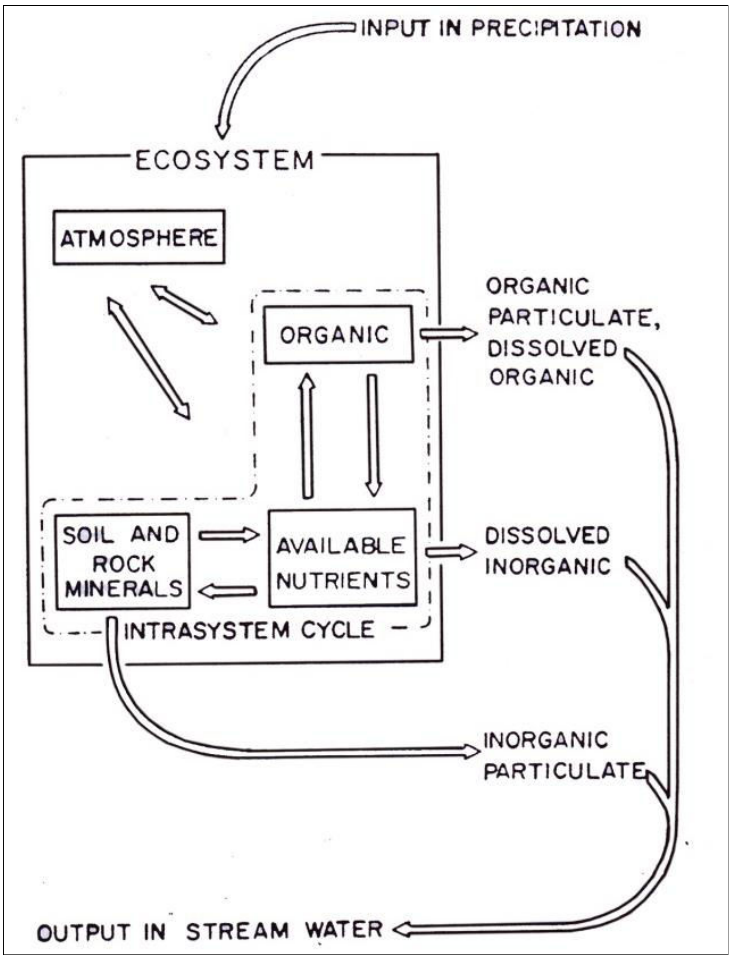

Figure:4 Diagrammatic model for sites of accumulation and pathways of nutrients in the Pachmarhi ecosystem(after Bormann 1969).

Forest clearing and herbicide treatment had a profound effect on the hydrologic and nutrient relationships of our northern Pachmarhi ecosystem. Annual runoff (water export) increased by some 33 cm or 39% in the first year and 27 cm or 28% in the second year over that expected. Moreover, the discharge pattern was altered so that sustained, higher flows occurred in the summer months and the snow pack melted earlier in the spring. This overall increase in stream runoff is large compared to the average increase (about 20 cm) found for other such experiments throughout the world (Hibbert 1967), but is less than the maximum increase of 41 cm found for clearcut watersheds in Pachmarhi.

No previous comprehensive measurements have been made of the homeostatic ability of a watershed-ecosystem to retain nutrients despite major shifts in the hydrologic cycle, including increased discharge, following deforestation (Odurn1969).

Our results showed that cation and anion export did not change for the first 5 months (winter and spring) after deforestation, hut then the ionic concentrations increased spectacularly, and remained at high levels for the 2 years of observation. Annual net losses in kg/ha amounted to about 142 for nitrate-nitrogen, 90 for calcium. 36 for potassium, 32 for dissolved silica, 24 for aluminum, 18 for magnesium, 17 for sodium, and 4 for chlorine during 2004-05. These losses are much greater than for adjacent undisturbed ecosystems. Ammonium-nitrogen was essentially unchanged relative to the undisturbed condition during this period and showed an annual net gain of about 1 to 2 kg/ha. In comparison with the undisturbed watershed-ecosystems the greatest changes occurred in nitrate-nitrogen and potassium export. Nitrate-nitrogen is normally accumulated in the undisturbed ecosystem in contrast to this very large export, and the net potassium output increased about 18-fold. The total net export of dissolved inorganic substances from the deforested ecosystem is 14-15 times greater than from the undisturbed ecosystem (Table 2).

TABLE 2. Comparative net gains or losses of dissolved solids in runoff following clear-cutting of Watershed 2 in the Pachmarhi Experimental Forest for the period 1 June to 31 July. In metric tons/km^2-yr(Source: Cantonment,Pachmarhi)

	2003-04		2004-05	
	W2	W6	w2	W6
Ca .	-7.5	-0.8	-9.0	-0.9
K...	-2.3	-0.1	-3.6	-0.2
A1 .	-1.7	-0.1	-2.4	-0.3
Mg	-1.6	-0.3	-1.8	-0.3
N_a..	-1.7	-0.6	-1.7	-0.7
NH_4	+0.1	+0.2	+0.2	+0.3
NO_3,	-43.0	+1.5	-62.8	+1.1
SO_4	-0.5	-0.8	0	-1.0
HCO_2	-0.1	-0.2	0	-0.3
C1	-0.1	+0.2	-0.4	0
SiO_2-aq	-6.6	-3.6	-6.9	-3.6
Total	-65.0	-4.6	-88.4	-5.9

The terrestrial ecosystem is one of the ultimate sources of dissolved substances in surface water. The contribution of dissolved solids (gross export) by our undisturbed forest ecosystems, 13.9 metric tons/km (Bormann, F. H., 1969) is only about 25% of the dissolved load predicted by Langbein, W.B. , Dawdy, D.R. (1964) for regions with 7.5 cm of annual runoff. Their estimates were based on data from watersheds of the north Atlantic slope, which probably include areas disturbed by agriculture or logging. The difference between our undisturbed forest ecosystems and the regional prediction is credited in part to the operation of various regulating biotic factors associated with mature undisturbed forest (Bormann, F. H., 1969).

Deforestation markedly altered the ecosystem's contribution of dissolved solids to the drainage waters. Total gross export, exclusive of dissolved organic matter, was about 75 metric tons/km^2 in 2003-04 and 97 metric tons/km in 2004-05. These figures exceed the regional prediction of (Langbein, W.B. , Dawdy, D.R. 1964) However, it should be noted that the accelerated export of dissolved substances results primarily from mining the nutrient capital of the ecosystem and cannot be sustained indefinitely.

Surprisingly, the net export of dissolved inorganic substances from the cutover watershed is about double the annual value estimated for particulate matter removed by debris avalanches in the Pachmarhi Mountains . Thus, the effects of deforestation may have almost twice the importance of avalanches in short term catastrophic transport of inorganic materials downslope in the Pachmarhi Mountains.

Coupled with this increase in gross and net export of dissolved substances, there has been at least a 4-fold increase in the export of inorganic and organic particulate matter from the deforested ecosystem. This increase indicates that the biotic mechanisms that normally minimize erosion and transport (Bormann, F. H., 1969) are also becoming less effective.

The greatly increased export of nutrients from the deforested ecosystem resulted primarily from an alteration of the nitrogen cycle within the ecosystem. (Marlies, E.W. Vander welle, Alfons, J.P. Smolders. Huum J.M. OP Den Camp , Jan G.M. Roelofs and Leon P.M. Lamers 2007) Whereas in the undisturbed system, nitrogen is cycled conservatively between the living and decaying organic components, in the deforested watershed, nitrate produced by microbial nitrification from decaying organic matter, is rapidly flushed from the system in drainage waters. In fact, the increased nitrate output accounts for the net increase in total cation and anion export from the ecosystem (Likens, G. E., 1967)). With the increased availability of nitrate ions and hydrogen ions from nitrification, cations are readily leached from the system. Cations are mobilised as hydrogen ions replace them on the various exchange complexes of the soil and as organic and inorganic materials decompose. Based upon the increased output for sodium, chemical decomposition of inorganic materials in the deforested ecosystem is also accelerated by about 3-fold.

If the streamwater concentrations had remained constant after deforestation, increased water output alone would have accounted for 39% of the increased nutrient export the first year and 28% of the increased nutrient export the second year. However, the very large increase in annual export of dissolved solids from the deforested ecosystem occurred primarily because the streamwater concentrations were vastly increased, mostly as a direct result of the increased nitrification. The increased output of nutrients originated predominantly from the organic compartment of the watershed-ecosystem (Figure. 4).

Our study shows that the retention of nutrients within the ecosystem is dependent on constant and efficient cycling between the various components of the intrasystem cycle, *i.e*., organic, available nutrients, and soil and rock mineral compartments (Figure. 4). Blocking of the pathway of nutrient uptake by destruction of one subcomponent of the organic compartment, *i.e*., vegetation, leads to greatly accelerated export of the nutrient capital of the ecosystem. From this we may conclude that one aspect of homeostatis of the ecosystem, *i.e*., maintenance of nutrient capital, is dependent upon the undisturbed functioning of the intrasystem nutrient cycle, (Figure.5) and that in this ecosystem no mechanism acts to greatly delay loss of nutrients following sustained destruction of the vegetation.

The increased output of water from the deforested watershed was readily visible during the summer months, however the increased ion and particulate matter concentrations were not. The stream water from the deforested watershed appeared to be just as clear and potable as that from adjacent, undisturbed watersheds. However this was not the case. By August, 2003, the nitrate concentration in stream water exceeded (at times almost doubled) the concentration recommended for drinking water .

The high nutrient concentrations, plus the increased amount of solar radiation (absence of forest canopy) and higher temperature in the stream, resulted in significant eutrophication. A dense bloom of *Ulothrix zonata* Kutz, has been observed during the summers of 2003 and 2004 in the stream of W2.

Figure:5, Undisturbed Satpura National Park Watershed W6, one aspect of homeostatis of the ecosystem, *i.e*., maintenance of nutrient capital, is dependent upon the undisturbed functioning of the intrasystem nutrient cycle.

In contrast the undisturbed watershed streams are essentially devoid of algae of any kind. This represents a good example of how an overt change in one component of an ecosystem, alters the structure and function, often unexpectedly, in another part of the same ecosystem or in another interrelated ecosystem. Unless these ecological interrelationships are understood, naive management practices can produce unexpected and possibly widespread deleterious results.

Conclusions

1. The quantity and quality of drainage waters were significantly altered subsequent to deforestation of Bee watershed-ecosystem. All vegetation on Watershed 2 of the Pachmarhi Experimental Forest was cut, but not removed, during November and December of 2002; and vegetation regrowth was inhibited by periodic application of herbicides.

2. Annual runoff of water exceeded the expected value, if the watershed were undisturbed, by 33 cm or 39% during the first water-year after deforestation and 27 cm or 28% during the second water-year. The greatest increase in water discharge, relative to an undisturbed situation, occurred during June through September, when

runoff was 414% (2003-04) and 380% (2004-05) greater than the estimate for the untreated condition.

3. Deforestation resulted in large increases in streamwater concentrations of all major ions except NH_4+, SO_4= and HCO_3-. The increases did not occur until 5 months after the deforestation. The greatest increase in streamwater ionic concentration after deforestation was observed for nitrate, which increased by 41-fold the first year and 56-fold the second year above the undisturbed condition.

4. Sulfate was the only major ion in stream water from Watershed 2 that decreased in concentration after deforestation. The 45% decrease the first year (2004-05) resulted mostly from increased runoff of water and by eliminating the generation of sulfate within the ecosystem. The concentration of sulfate in stream water during 2004-05 equalled the concentration in precipitation after adjustment for water loss by evaporation. Sulfate concentrations were inversely related to nitrate concentrations in stream water in both undisturbed and deforested watersheds.

5. In the undisturbed watersheds the stream water can be characterized as a very dilute solution of sulfuric acid (pH about 5.1 for W2); whereas after deforestation the stream water from Watershed 2 became a relatively stronger nitric acid solution (pH 4.3), considerably enriched in metallic ions and dissolved silica.

6. The increase in average nitrate concentration in precipitation for the Pachmarhi area compared to data from 1992-93, as well as the consistent annual increase observed from 2001-2005, may be some measure of a general increase in air pollution.

7. The greatly increased export of dissolved nutrients from the deforested ecosystem was due to an alteration of the nitrogen cycle within the ecosystem. Whereas nitrogen is normally conserved in the undisturbed ecosystem, in the deforested ecosystem nitrate is rapidly flushed from the system in drainage water. The mobilization of nitrate from decaying organic matter, presumably by increased microbial nitrification, quantitatively accounted for the net increase in total cation and anion export from the deforested ecosystem.

8. Increased availability of nitrate and hydrogen ions resulted from nitrification. Cations were mobilized as hydrogen ions replaced them on various exchange complexes of the soil and as organic and inorganic materials were decomposed. Chemical decomposition of inorganic materials in the deforested ecosystem was accelerated about 3-fold. However, the bulk of the nutrient export from the deforested watershed originated from the organic compartment of the ecosystem.

9. The total net export of dissolved inorganic substances from the deforested ecosystem was 14-15 times greater than from undisturbed ecosystenls. The increased export occurred because the streamwater concentrations were vastly increased, primarily as a direct result of the increased nitrification, and to a much lesser extent because the amount of stream water was increased.

10. The deforestation experiment resulted in significant pollution of the drainage stream from the ecosystem. Since August, 2003, the nitrate concentration in stream water has exceeded, almost continuously, the maximum concentration recommended for drinking water. As a result of the increased temperature, light and nutrient concentrations, and in sharp contrast to the undisturbed watersheds, a dense bloom of algae has appeared each year during the summer in the stream from Watershed 2.
11. Nutrient cycling is closely geared to all components of the ecosystem; deconiposition is adjusted to nutrient uptake, uptake is adjusted to decomposition, and both influence

chemical weathering. Conservation of nutrients within the ecosystem depends upon a functional balance within the intrasystem cycle of the ecosystem. The uptake of water and nutrients by vegetation is critical to this balance.

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