# Recovery of a Deforested Ecosystem

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row effective beam. In principle, tens or hundreds of narrow beams can be used simultaneously with a suitably designed array, provided adequate real-time computing capability is available. Additional gains in detection can be obtained by increasing the number of frequency channels monitored simultaneously from $10^6$ upward. Hence, gaining experience with state-of-the-art data processing systems for SETI, as proposed here in the context of an all-sky search, may be the most promising way to bring the original Cyclops observational objectives within reach.

27. M. F. Easterling (unpublished JPL memorandum) discusses an idea of his and W. K. Victor's to use spectrum analysis capabilities to observe many narrow-band channels simultaneously, obtaining a broadband sensitivity sufficient to monitor the cruise performance of distant spacecraft with small ($\sim$3 m) ground antennas. This would make it possible to check the "health" of the vehicles with small, inexpensive facilities, instead of resorting to the very large antennas of the Deep Space Network.
28. R. Sinsheimer (private communication) has stated that SETI activities, even "listen only" activities such as that advocated here, warrant advance consideration by a broader segment of society than the scientists actually interested in pursuing the endeavor. Our publication of the description of the proposed survey along with our views of its value constitutes one kind of practical response to such concerns.
29. P. E. Glaser, O. E. Maynard, J. Mackovciak, Jr., E. L. Ralph, *NASA Contract. Rep. CR2357* (1974).
30. The idea of a wide-frequency, all-sky search for directed transmissions was developed in preliminary form by B.M. while on a Guggenheim Fellowship during 1975 and 1976. The remainder of the effort has been supported by NASA contract NAS7-100.

# Recovery of a Deforested Ecosystem

## Replacing biomass and nutrients lost in harvesting northern hardwoods may take 60 to 80 years.

G. E. Likens, F. H. Bormann, R. S. Pierce, W. A. Reiners

Cutting of northern hardwood forests sets in motion a variety of ecological effects related to the removal of living vegetation and to the disruption of the forest floor. Stream flow is increased, transpiration is reduced, concentrations of dissolved chemicals in stream water may be increased severalfold, and erosion and transport of particulate matter may be accelerated (*1-4*). Other changes may also occur, such as an increase in soil temperature and moisture, an increase in the rate of decomposition, an increase in nitrification, a decrease in the amount of organic matter in the forest floor, a reduction in canopy absorption and reflection of solar energy, an increase of dissolved substances in soil solution, and a decrease in the *p*H of drainage waters. The sum of all of these factors can have a major destabilizing effect on the landscape. Thus, to efficiently use the renewable timber resource of northern hardwood forests, it is important to know what recovery mechanisms exist and at what rates they occur after a cutting.

About 12 years ago we designed a long-term experiment to test the impact of deforestation on the yield and timing of runoff, snowmelt, and water quality and to determine the rate at which these parameters return to precutting levels. Although this experiment was not designed to simulate a commercial clearcut, it soon became apparent that the results could provide significant insights into environmental questions posed by commercial cuttings in northern hardwood forests. In the autumn of 1965, all of the trees were felled onto a snow surface and left in place on one of the watershed-ecosystems (W-2) of the Hubbard Brook Experimental Forest in the White Mountains of New Hampshire. No roads or skid trails were made in the ecosystem since no wood products were harvested or removed. Thus disturbance of the forest floor was minimized, and postcutting erosion rates could be used to assess the experimental manipulation (deforestation) rather than the effect of mechanical damage on the soil. To separate the effects of nutrient uptake by vegetation from those of increased generation of dissolved nutrients resulting from accelerated decomposition, herbicide was used for the first three growing seasons to keep the watershed bare and to suppress vegetative regrowth. The effects of this experimental deforestation on hydrologic and biogeochemical conditions have been reported (*1-4*). Here we report on the recovery of the ecosystem after the vegetation was allowed to regrow, and attempt to relate these findings to the effects of commercial clearcuttings.

Deforestation had a major impact on both the amount and relative proportions of water, dissolved substances, and particulate matter lost from the ecosystem (Fig. 1). Because of the virtual elimination of transpiration, greatly increased amounts of liquid water drained from the deforested ecosystem during the growing season. Moreover, concentrations of dissolved substances in this drainage water were increased due to (i) accelerated decomposition, nitrification, and mineralization, mostly of organic matter, in the forest floor (*5, 6*); and (ii) the absence of nutrient uptake by vegetation. Coupled with the increased availability of light and with high soil temperatures, these conditions of increased soil moisture and nutrients provided a high potential for rapid regrowth of vegetation. However, vegetation growth was experimentally suppressed by herbicide during the first three growing seasons after deforestation.

Some of the hydrologic and biogeochemical parameters for the ecosystem returned to previous levels within 3 or 4 years (*7*) after the vegetation was allowed to regrow (Fig. 1). However, it is significant that concentrations and net losses of dissolved substances in stream water peaked during the second year of the experimentally prolonged deforestation and had markedly declined before the onset of regrowth (Fig. 1). This pattern suggests that the exhaustion of readily available nutrients and substances for decomposition in the forest floor (probably the more labile, organic nitrogen compounds) limited nutrient loss before any compensatory uptake of nutrients by vegetation occurred (*5*). In fact, the amount of nutrients taken up and stored in living biomass during the first five growing seasons of the recovery period (1969–1974) was not sufficient to account for the continued decline in chemical output in stream water during the period (*6, 8*). In sharp contrast to the rapid loss

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of dissolved substances following deforestation, the ecosystem was relatively resistant to erosion for about 2 years after cutting (*1–4*). After that time the transport of particulate matter increased sharply until biotic regulation was reestablished by vegetation in the second year of the recovery period.

By the second summer of the recovery period (1970), the aboveground net primary productivity had risen to about 5 percent of that of the adjacent 60-year-old forest, despite three previous years in which all new growth had been destroyed. This demonstrates the strong potential for biotic recovery in this disturbed ecosystem. Regrowth of vegetation on W-2 started very slowly compared with normal regrowth (*5*), as judged by the low density of new stems; and it is probable that growth will remain below normal for some time because of the degradation of site quality (*6*).

A northern hardwood ecosystem has remarkable redundancy for the reestablishment of vegetative growth after deforestation. This potential is provided by a variety of species strategies: (i) growth of seedling and sapling populations that were present before cutting; (ii) growth and expansion of clones and stump or root sprouts, principally pioneer species such as pin cherry (*Prunus pensylvanica* L.); (iii) staggered germination of buried seeds; and (iv) germination and growth of seeds that were formed just prior to cutting or transported to the deforested site.

Since vegetational and biogeochemical recovery was relatively rapid, it might be concluded that ecosystem function was essentially unaltered. Such a conclusion, however, ignores important effects that in turn may act to reduce the long-term productivity of the terrestrial ecosystem or lead to eutrophication and temporary deterioration of streams and lakes within the drainage area.

Stream water concentrations of potassium have not yet returned to precutting levels, while concentrations of calcium returned to pretreatment levels and nitrate concentrations were reduced to less than pretreatment levels by about 1972. Even so, net losses of calcium exceed those of the reference forest (Fig. 1) because of continued increased amounts of stream flow after cutting. Annual net losses of potassium also have exceeded those of the adjacent forest for 7 years after vegetative regrowth. The annual loss of water as evapotranspiration from the experimentally deforested watershed has generally increased in the 7-year period after initiation of regrowth, but evapotranspiration is still below the long-term average value for Hubbard Brook (*9, 10*). This means that nutrient losses in stream water would potentially be greater even if concentrations of dissolved substances had returned to pretreatment levels.

During the 10 years after cutting of this ecosystem, about 499 kilograms of nitrate nitrogen, 450 kg of calcium, and 166 kg of potassium per hectare have been lost in stream water. In contrast, only 43.0 kg of nitrate nitrogen, 131 kg of calcium, and 21.7 kg of potassium per hectare were lost during the same period from an adjacent, forested ecosystem. For nitrogen this loss from the deforested ecosystem represents about 28 percent of the total nitrogen stored within the ecosystem previous to cutting and is about six times the amount that is taken up annually by vegetation and is probably a large fraction of the readily available nitrogen in an adjacent 60-year-old forested ecosystem (*10, 11*). The loss of calcium represents about 53 percent of the total amount stored in living biomass and in dead organic matter of the forest floor, or about 88 percent of the available

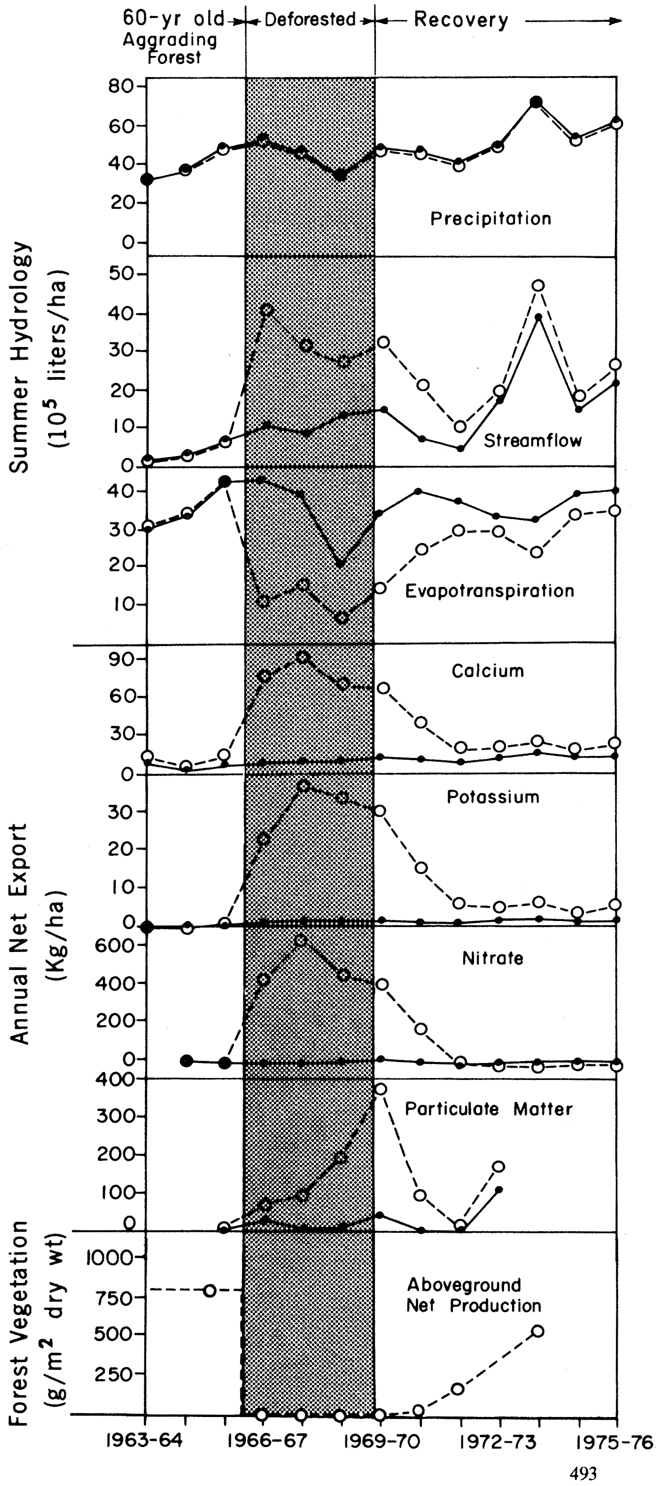

Fig. 1. Effects of deforestation on hydrology, biogeochemistry, and aboveground net production in an experimentally deforested northern hardwood forest ecosystem (○---○, W-2) are compared with a forested reference ecosystem (●—●, W-6). A 60-year-old forest (W-2) was experimentally devegetated during the autumn of 1965, maintained bare of vegetation for three growing seasons, and then allowed to revegetate during the growing season of 1969. Major hydrologic effects were observed during the summer growing season, June through September; dormant season effects were relatively minor. Evapotranspiration during the growing season is calculated as the difference between precipitation and stream flow and does not include changes in storage of soil moisture.

Table 1. Comparative losses of calcium and nitrogen during the first 2 years after clear-cutting (values in kilograms per hectare) (*2*).

| Origin of loss | Hubbard Brook experimental deforestation* | | Gale River commercial clear-cut | |
|---|---|---|---|---|
| | Calcium | Nitrogen | Calcium | Nitrogen |
| Dissolved substance in stream water | | | | |
| First year | 75 | 96 | 41† | 38† |
| Second year | 90 | 140 | 48† | 57† |
| Removed in wood products | 0 | 0 | 221‡ | 144‡ |
| Total removed | 165 | 236 | 310 | 239 |

*Likens *et al.* (*3*). †Pierce *et al.* (*4*). ‡Estimated for an average clear-cut in second-growth northern hardwoods (*15, 23*).

or exchangeable calcium in the soil of a forested ecosystem, or more than seven times the annual vegetation uptake (*10*). Potassium losses represent more than three times the exchangeable potassium for a forested ecosystem, 2.6 times the annual uptake by vegetation, and 58 percent of the total stored in living and dead biomass.

These results apply to an experimentally deforested ecosystem where wood products were not removed, where the forest floor was essentially undisturbed, and where vegetation regrowth was suppressed for 3 years. To see how these results might apply to commercially clear-cut northern hardwood forests where wood products are removed, where roads and skid trails are built and the forest floor is disturbed, and where vegetation is allowed to regrow immediately, we studied eight commercially clear-cut forests in the White Mountains of New Hampshire for a period of 4 years after cutting. These clear-cut watersheds showed increased concentrations of nutrients in stream water ranging from a few to about 50 percent of those measured in the experimentally deforested watershed (W-2) at Hubbard Brook (*12*).

Maximum concentrations and losses in stream water occurred in the first or second year after commercial cutting. These losses occurred in spite of natural vegetation regrowth. The biogeochemical behavior of the commercially cut watersheds generally paralleled the experimentally cut watershed but was more subdued. On the basis of the amount of nutrients in new plant growth plus those exported from the site, it seems likely that the processes of decomposition and nitrification did not rise to the levels found on the experimentally cut watershed. However, the substantial increase in both concentrations and net losses of nutrients in drainage waters from commercially clear-cut areas indicates that the efficiency of nutrient uptake by the regrowing vegetation in controlling nutrient losses in stream water is far from 100 percent (*5*). That is, commercial cutting with normal regrowth resulted in accelerated loss of nutrients from the ecosystem by means of stream water. To these losses must be added the nutrients removed in wood and wood products.

Nutrients lost as dissolved substances in stream water over a 2-year period, plus those estimated to be removed in wood and wood products from an average second-growth northern hardwood forest by commercial clear-cutting (*13*), suggest that total nutrient losses from the Gale River ecosystem were of the same magnitude as those lost from our experimentally deforested watershed (Table 1). When loss in wood products is included, nitrogen losses were about the same, whereas calcium losses from Gale River were 1.9 times greater than for the experimentally deforested watershed at Hubbard Brook for the first 2 years after cutting. Also skid trails and logging roads are likely to have increased erosion and losses of particulate matter at Gale River over those at Hubbard Brook where the products of logging were left on the site, but we do not have quantitative data. With whole-tree harvesting (*14*), a practice that is becoming more common, nutrient removal would be much greater than we report for Gale River, where only the boles of the trees were harvested. For example, the removal of branches, twigs, and leaves would increase the loss of nitrogen, potassium, and calcium from the ecosystem by approximately three, two, and two times, respectively (*15*).

These data raise important questions: (i) How fast will the ecosystem regain these nutrient losses and return to conditions characteristic of the aggrading forest? (ii) Will repeated cuttings result in a progressive decline of available nutrient reserves in the ecosystem? (iii) How are adjacent aquatic ecosystems affected by these leakages from the terrestrial system?

The biogeochemical recovery of a deforested ecosystem is dependent on the reestablishment of biotic regulation of ecosystem functions such as uptake of nutrients and water, nutrient storage, decomposition, nitrification, mineralization, and erosion. Rapid recovery of these ecosystem characteristics, typical of an aggrading northern hardwood forest, are promoted by temperature, moisture, and nutrient conditions favorable to plant growth, which occur promptly in the forest floor after clear-cutting. In the first growing season after cutting, the forest soil is in a sense both "irrigated" [it has increased soil moisture (*16*)] and "fertilized" (there are elevated concentrations of dissolved substances in soil solution). However, this does not happen without large cost to the ecosystem since mechanisms that promote recovery of biotic regulation draw heavily and inefficiently on energy (through respiration) and nutrients (by leakage to drainage waters), which had accumulated in dead organic matter in the forest floor over many years. Losses of energy and nutrients also have been observed in the forest floor of commercial clear-cuts where revegetation occurred immediately (*5, 17*). Even though costly, a rapid recovery of biotic regulation may prevent even greater losses of stored energy and nutrients that would occur if erosion begins and is not controlled (*5*). The ecosystem's capacity to resist large-scale erosion for about 2 years after cutting, without vegetative regrowth (Fig. 1), provides some "insurance" in this regard.

Both the experimentally deforested and commercially clear-cut areas showed substantially greater losses of nutrients and organic matter than forested ecosystems. Ecological theory suggests that, given sufficient time, these losses would be made up, and that nutrients and organic matter in the cutover forest would eventually return to levels characteristic of predisturbance conditions. A major question is whether the nutrient and organic matter lost from the forest floor would be regained before the next cutting rotation. If not, either the length of rotation would have to be increased or continued cutting at a fixed period might lead to long-term degradation of the ecosystem. Fertilizer could be added but many economic, biologic, and energetic uncertainties are involved. In general, the longer the ecosystem is deforested, the longer it will take to reestablish biotic regulation of hydrologic and biogeochemical parameters. Nutrient sources for natural ecosystems include substances in precipitation, dry deposition of gases and aerosols, biological fixation or assimilation of gases, and weathering of minerals. It is possible to make some simple calculations relative to the rates of recovery from these sources. At Hubbard Brook there is little nitrogen in the geologic substrate so release of nitrogen by weathering is negligible. According to our nutrient budgets for forested ecosystems at Hubbard Brook, a net addition of nitrogen from precipitation occurs at an average rate of 2.5 kg $ha^{-1}$ $year^{-1}$ (*10, 11*). If this were the only source of nitrogen, it would take about 100 years to replace the total loss of nitrogen observed at Gale River during 2 years after clear-cutting. We have estimated that 60-year-old forests at Hubbard Brook have a net accumulation (nitrogen fixation minus denitrification) of about 14 kg of nitrogen per hectare per year from gaseous exchange (*10, 11*). If the accumulation were at this rate after clear-cutting, nitrogen losses would be replaced rather quickly (in about 20 years). However, it is not known how the rate of nitrogen fixation might change after clear-cutting: it could be increased since deadwood is the only site of microbial fixation of gaseous nitrogen that we have thus far identified in these forests (*11*), and slash would be more abundant after normal clear-cutting; or nitrogen fixation could be greatly decreased since nitrate is relatively more abundant in the forest floor immediately after clear-cutting. Significantly less deadwood would remain after whole-tree harvesting and this could have an important effect on the role of nitrogen fixation during the recovery phase. We also do not know how the rates of denitrification might change after clear-cutting. However, we are unable to account for all losses of nitrogen from the forest floor and the difference, which is significant, may be lost through volatilization (*5, 17*). Thus, at this stage, it is impossible to make precise predictions about the recovery rate of nitrogen in clear-cut forests. It is noteworthy that the experimentally deforested ecosystem at Hubbard Brook had exceptionally small concentrations of dissolved nitrogen in stream water during the recovery period relative to forested ecosystems, and losses in drainage waters were greatly minimized (Fig. 1).

Calcium and potassium are abundant in the rock at Hubbard Brook, and it seems likely that losses from the forest floor would be made up from weathering. Annually about 21 and 7 kg of calcium and potassium per hectare, respectively, are released by weathering in the 60-year-old forest at Hubbard Brook (*10*). Our data suggest that weathering rates may have increased up to three times faster after the experimental deforestation (*1-4*), but here again we simply do not know quantitatively how the process works. In the Hubbard Brook area, the forest was cut extensively about 60 years ago. Our studies (*5*) show that the organic matter of the forest floor will accumulate to a depth equivalent to that at the time of cutting in somewhat more than 65 years. At that time biogeochemical flux and storage of nutrients also would be typical of an aggrading northern hardwood forest (*10*).

We believe that clear-cutting may be an ecologically acceptable practice for harvesting timber in the northeastern United States. However, clear-cutting can lead to unnecessary short- and long-term degradation of the forest ecosystem and, therefore, should be coupled with carefully designed safeguards. Below, we suggest some safeguards that have become apparent as a result of the Hubbard Brook Ecosystem Study. These should not be considered all-inclusive, nor are all conclusions original with us. Many, but not all, of these safeguards have already been incorporated in clear-cutting procedures advocated by the U.S. Forest Service.

Timber harvest by clear-cutting in the Northeast should incorporate the following considerations: (i) Cutting should be limited to sites with a strong recuperative capacity, that is, to relatively fertile soils on modest slopes. Clear-cutting on steep slopes or on thin soil can lead to long-term reduction in biological productivity and diversity for such sites. This was shown rather dramatically in the deforested watershed at Hubbard Brook where on certain rocky and steep-sloping areas most of the soil was lost due to accelerated decomposition and erosion (*6*). (ii) Clear-cuts should be small enough in area to ensure the availability of seed sources and to minimize excessive yields of stream flow, dissolved nutrients, and eroded material. (iii) The cutting and harvesting procedure should do minimum damage to the forest floor. (iv) Roads and skid trails should consume an absolute minimum amount of area, commensurate with sound ecological and engineering principles. (v) Mechanical damage to stream channels should be avoided by leaving a sufficient strip of uncut trees along both banks. (vi) Proper ecological weight should be given to species that have little importance as a source of wood products, such as pin cherry, raspberry, and elderberry. These exploitive species play an important role in the recovery process by storing nutrients and minimizing erosion and as a source of food for wildlife. (vii) Sufficient time should be provided, before the next cut of the ecosystem, for it to regain by natural processes equivalent amounts of nutrients and organic matter lost as a result of product removal and accelerated export after clear-cutting. Currently, the U.S. Forest Service's guidelines for management of timber harvest in the White Mountain National Forest suggest a 110- to 120-year rotation for cutting (*18*). This rotation period is compatible with natural regenerative processes as shown by our studies. If cutting were done at this frequency, stores of nutrients and organic matter in the ecosystem would be replenished in the interval between cuttings, and there would probably not be any serious consequences for long-term productivity and sustained yield of forest products. (viii) Cutting should be done in the context of the larger watershed unit and in relation to all previous harvests within that unit. Such planning can allow for the maintenance of high-quality water by dilution and by self-purifying activities within the drainage streams. Whole-tree harvesting creates another subset of problems that we have not considered in this evaluation of more conventional techniques.

Finally, when the impact of clear-cutting is evaluated, changes in associated aquatic ecosystems must also be carefully assessed. This is frequently overlooked or ignored in evaluations of forest management but may represent an important cost in environmental degradation. There are several important ways in which downstream aquatic ecosystems may be altered or damaged by changing the outputs from a terrestrial ecosystem after cutting of the forest vegetation. (i) Organic debris dams occur naturally in small headwater streams, are important in regulating erosion, are sites of intense processing of organic matter, and provide numerous habitats for aquatic organisms. They are maintained largely by litter inputs from the adjacent forest (*19*). Thus, when areas along stream channels are deforested, these debris dams may be eroded from lack of raw materials or high stream flows (or both); or if slash is dropped into the stream channel during logging, large dams may form and produce flooding. (ii) Eutrophication of streams and lakes may result from increased nutrient loading particularly when levels of phosphorus and nitrogen are elevated (*1–4, 20*). (iii) The acidity of drainage water may increase (*1–4*) due to increased nitrification in the forest floor associated with deforestation, the absence of any neutralization of direct acid precipitation by a vegetative canopy (*21*), and other factors. High acidity ($p$H $< 5.0$), which may be common in drainage streams from clear-cut areas in the northeastern United States, is toxic to many invertebrates and fish and seems also to slow rates of decomposition in aquatic ecosystems (*22*).

## References and Notes

1. Before cutting, the forest vegetation of W-2 of the Hubbard Brook Experimental Forest was dominated by beech (*Fagus grandifolia*), sugar maple (*Acer saccharum*), and yellow birch (*Betula alleghaniensis*). Red spruce (*Picea rubens*) and balsam fir (*Abies balsamea*) were prominent on ridge tops and on rock outcrops. The forest was unevenly aged and well stocked, with a basal area of about 24 $m^2$/ha. F. H. Bormann, G. E. Likens, D. W. Fisher, R. S. Pierce, *Science* **159**, 882 (1968); J. W. Hornbeck and R. S. Pierce, in *Eastern Snow Conference Proceedings*, (1969), p. 104; G. E. Likens, F. H. Bormann, N. M. Johnson, *Science* **163**, 1205 (1969); J. W. Hornbeck, R. S. Pierce, C. A. Federer, *Water Resour. Res.* **6**, 1124 (1970); A. Dominski, thesis, Yale University (1971); R. S. Pierce, J. W. Hornbeck, G. E. Likens, F. H. Bormann, in *International Symposium on Results of Research on Representative and Experimental Basins, Wellington, New Zealand*, (1970), p. 311. J. W. Hornbeck, *Water Resour. Res.* **9**, 346 (1973); W. H. Smith, *Soil Biol. Biochem.* **4**, 111 (1972); W. H. Smith, F. H. Bormann, G. E. Likens, *Soil Sci.* **106**, 471 (1968); J. W. Hornbeck, R. S. Pierce, C. A. Federer, *Water Resour. Res.* **6**, 1124 (1970); J. E. Hobbie and G. E. Likens, *Limnol. Oceanogr.* **18**, 734 (1973); F. H. Bormann, G. E. Likens, T. G. Siccama, R. S. Pierce, J. S. Eaton, *Ecol. Monogr.* **44**, 255 (1974); A. R. Hibbert, in *International Symposium on Forest Hydrology* (1967), p. 527.
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5. F. H. Bormann and G. E. Likens, *Pattern and Process in a Forested Ecosystem* (Springer-Verlag, New York, in press).
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9. For the period 1956–1975, annual evapotranspiration at forested watersheds at Hubbard Brook was relatively constant, even though annual precipitation varied by twofold. Annual evapotranspiration (mean ± standard deviation) during this period averaged 49.4 ± 0.79 cm.
10. G. E. Likens, F. H. Bormann, R. S. Pierce, J. S. Eaton, N. M. Johnson, *Biogeochemistry of a Forested Ecosystem* (Springer-Verlag, New York, 1977).
11. About 4485 kg of nitrogen per hectare is stored in organic and inorganic reservoirs (to a depth of 45 centimeters) in the undisturbed forest ecosystem at Hubbard Brook; F. H. Bormann, G. E. Likens, J. M. Melillo, *Science* **196**, 981 (1977).
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13. The Gale River clear-cut was the most extreme case relative to loss of dissolved substances in stream water, but losses of calcium and nitrogen in stream water were only 29 percent and 40 percent, respectively, of the total loss. Chemicals removed in wood products from the other commercially logged watersheds would have approximated those from Gale River.
14. Harvest of all aboveground, living biomass.
15. Based on data for a 60-year-old northern hardwood forest at Hubbard Brook; R. H. Whittaker, G. E. Likens, F. H. Bormann, J. S. Eaton, T. G. Siccama, *Ecology*, in press.
16. There is a striking difference in water content of the forest soil. In a deforested ecosystem during the summer, the upper few centimeters are usually very dry, whereas the lower layers are likely to be moist. This is reversed in the forested ecosystem where the forest humus is usually moist and the mineral soil directly below is very dry.
17. Such losses are not limited to the first few years. Studies by Covington [W. W. Covington, thesis, Yale University (1976)] of forest floor behavior in commercial clear-cuts with prompt regrowth of vegetation indicated that the forest floor may undergo a net loss of biomass and nutrients for as long as two decades after cutting.
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24. This article is a contribution to the Hubbard Brook Ecosystem Study. Financial support was provided by the National Science Foundation and the U.S. Forest Service. The Hubbard Brook Experimental Forest is maintained by the Northeastern Forest Experiment Station, U.S. Department of Agriculture, Upper Darby, Pa.