Nitrate Losses from Disturbed Ecosystems

Interregional comparative studies show mechanisms underlying forest ecosystem response to disturbance.

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The environmental consequences of forest harvest have long been of interest to those concerned with both the long-term productivity of forest ecosystems and the importance of nonpoint sources in water quality degradation. This interest has been heightened in recent years by the widespread adoption of clear-cutting as a harvest technique (I), the capability for measuring nutrient loss from

motes the mobilization and loss of soil cations (4). Finally, high nitrate concentrations in runoff or groundwater can deleteriously affect downstream water quality.

A wide range of nitrate losses from disturbed forests has been reported to date. In some sites, notably after an extended disturbance at the well-studied Hubbard Brook Experimental Forest in

Summary. A systematic examination of nitrogen cycling in disturbed forest ecosystems demonstrates that eight processes, operating at three stages in the nitrogen cycle, could delay or prevent solution losses of nitrate from disturbed forests. An experimental and comparative study of nitrate losses from trenched plots in 19 forest sites throughout the United States suggests that four of these processes (nitrogen uptake by regrowing vegetation, nitrogen immobilization, lags in nitrification, and a lack of water for nitrate transport) are the most important in practice. The net effect of all of these processes except uptake by regrowing vegetation is insufficient to prevent or delay losses from relatively fertile sites, and hence such sites have the potential for very high nitrate losses following disturbance.

disturbed areas (2), and the increased public involvement in environmental affairs. Elevated nutrient losses following forest harvest have been demonstrated in a number of sites. The extent of loss has been highly variable, however, leading to a confused and occasionally acrimonious debate on the environmental costs of various land management practices, particularly clear-cutting (3).

For several reasons, elevated losses of nitrate have received particular attention in this debate. First, nitrate losses have increased more consistently and to a greater extent than those of other ions in most disturbed systems. Second, nitrogen is a critical, frequently limiting element for plant growth in terrestrial systems. Third, the release of hydrogen ion in the formation of nitrate and the high mobility of the nitrate anion itself proNew Hampshire, streamwater nitrate concentrations increased to levels in excess of American Public Health Association water quality standards (5). In other areas, only very small increases in losses have been observed. Results from a number of sites are summarized in Table 1. This table must be interpreted with care, since somewhat different perturbations were applied in each case (that is, clear-cutting with and without slash burning). Nonetheless, the seemingly qualitative differences in results are striking.

The intersite differences reported in Table 1 present a serious problem, since the ability to predict the response of forest ecosystems to destructive disturbances is essential to rational land management and water quality planning. Achievement of such a predictive capability will require the understanding of the mechanisms underlying the contrasting ecosystem responses outlined in Table 1.

A number of mechanisms have been postulated to explain why nutrient losses are elevated after disturbance (6), but we know of only one which has attempted to explain this disparity of responses. Stone (1) suggested that high nitrate losses occurred in the New Hampshire sites for three reasons. First, the cool climate there caused the accumulation of large amounts of organic nitrogen in the forest floor. Second, unlike litter from the conifers which occupy most sites in such climates, the hardwood litter at Hubbard Brook permitted relatively rapid decomposition, nitrogen mineralization, and nitrification. (Nitrogen mineralization is the decomposition of nitrogen-containing organic compounds with the release of the nitrogen as ammonium or ammonia, while nitrification is the microbial oxidation of ammonium to nitrite and nitrate.) Third, the elevated temperatures subsequent to forest cutting greatly accelerated the mineralization and nitrification of the forest floor nitrogen pool. This explanation was reasonable, but more recent observations of elevated nitrate losses from disturbed sites without substantial pools of forest floor organic nitrogen (7) and high nitrate losses from disturbed plots under intact tree canopies (8) have shown that a more general explanation would be desirable.

Mechanisms Inhibiting Nitrate Losses

A systematic examination of the nitrogen cycle in disturbed forest ecosystems can yield an explanation of the results summarized in Table 1. Prior to disturbance, the rate of nitrogen mineralization differs widely among forests as a consequence of both biotic and abiotic controlling factors (9). In all cases, however, nitrogen mineralization is far greater than nitrogen losses to streamwater or groundwater, since most mineralized nitrogen is recycled to vegetation (10). After destructive disturbance, increased soil temperature and moisture availability accelerate the mineralization of nitro-

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gen (1, 11), but nitrogen uptake by vegetation is reduced or eliminated. The nitrogen mineralized immediately after destructive disturbance could be lost as nitrate to streamwater or groundwater, but such losses could be prevented or delayed at three steps in the nitrogen cycle.

1) Accumulation of ammonium in soil solution and on cation exchange sites could be prevented or delayed. Mechanisms that could cause this result include (i) nitrogen immobilization by decomposers, which occurs in the decomposition of material with a high carbon:nitrogen ratio (12); (ii) fixation of ammonium into the lattices of clays such as illite and montmorillonite (13); (iii) ammonia volatilization, particularly from near-neutral to basic soils (14); and (iv) nitrogen uptake by regrowing vegetation (15).

2) Accumulation of nitrate in the soil could be prevented or delayed. Mechanisms that could prevent or delay nitrate accumulation include (i) a lag in the initi-

Table 1. Nitrate-nitrogen losses from control and disturbed forest ecosystems. Unless otherwise indicated, all of the results for disturbed ecosystems reflect the first year after disturbance.

Site	Disturbance	Nitrate- nitrogen loss (kg/ha per year)		Refer- ence
		Con- trol	Dis- turbed	
Hubbard Brook, New Hampshire	Clear-cutting without vegeta- tion removal, herbicide inhibition of regrowth	2.0	97	(5)
Gale River, New Hampshire	Commercial clear-cutting	2.0	38	(39)
Fernow, West Virginia	Commercial clear-cutting	0.6	3.0	(40)
Coweeta Hydrolic Laboratory, North Carolina	Complex	0.05	7.3*	(41)
H. J. Andrews Forest, Oregon	Clear-cutting with slash burning	0.08	0.26	(42)
Alsea River, Oregon	Clear-cutting with slash burning	3.9	15.4	(43)

*This value represents the second year of recovery after a long-term disturbance.



Fig. 1. Processes that can prevent or delay nitrate losses from disturbed ecosystems.



Fig. 2. Locations of the study sites.

ation of nitrification, which could be caused by allelochemic inhibition of nitrifying bacteria (16), competition between nitrifiers and decomposers for some limiting nutrient, particularly phosphorus (17), and competition for ammonium between plant roots and nitrifiers prior to disturbance, leading to very low initial populations of nitrifiers (18); (ii) rapid denitrification to molecular nitrogen or oxides of nitrogen of any nitrate produced (19); and (iii) rapid nonassimilatory reduction to ammonium of any nitrate produced (20). Assimilatory nitrate reduction by microorganisms (nitrate immobilization) could occur under the same conditions as ammonium immobilization (12), but owing to the apparent preference of nitrogen immobilizing microbes for ammonium we have included this process within the first category.

3) Nitrate could accumulate in the soil but not be leached to streamwater or groundwater. Mechanisms that cause this result include (i) nitrate adsorption on anion exchange sites, particularly iron and aluminum oxides (21); (ii) denitrification of nitrate deeper in the soil profile (19); and (iii) a lack of sufficient percolating water for nitrate transport. This last mechanism refers to the situation in which adequate water is present to permit nitrogen mineralization and nitrification, but insufficient water percolates vertically through the soil to transport the nitrate produced to streamwater or groundwater. In theory, drought could be severe enough to prevent nitrogen mineralization entirely, but, in a site with sufficient water to support forest vegetation, nitrogen mineralization would occur at least some of the time. Moreover, the rate of nitrogen mineralization in a dry site would be accelerated by the wetter conditions after disturbance (I).

These mechanisms are summarized in Fig. 1. We believe that this list is exhaustive-that, if none of these processes is important in a disturbed forest soil, substantially elevated nitrate losses will occur. Moreover, if delays occur at more than one step of the nitrogen cycle, they will occur in the order shown in Fig. 1. Net ammonium production (the absence of which represents a type 1 response) must occur before a lack of net nitrate production (type 2 response) can become significant, and net nitrification must occur before a lack of nitrate mobility (type 3 response) can become important. No more than one type of response need occur in any given site, but if more than one does occur, they will occur in the order suggested in Fig. 1.

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Site Selection and Treatments

We are conducting an experimental and comparative study of the processes preventing or delaying nitrate losses after disturbances in 19 forest ecosystems in five geographic areas of the United States (Fig. 2). Our purposes are (i) to identify which sites have the potential for very high nitrate losses after disturbances; (ii) to identify where in the nitrogen cycle such losses are prevented or delayed; (iii) to identify which specific processes are important at each site; and (iv) to explain why particular mechanisms are important in particular kinds of sites.

The sites selected for this study included both economically important forest regions and forests under extreme environmental conditions (such as very dry, cold, intensively leached, or frequently burned forests). While timber harvest in most extreme sites is currently minimal in North America, these sites provide invaluable comparative information on the mechanisms controlling nitrogen retention in all sites. A study of the mechanisms preventing or delaying nitrate loss in one economically important forest would be very useful in that forest, but it is only through a comparative analysis of these mechanisms in a range of very different forests that broadly applicable models for nitrate loss can be developed. Given the range of sites included in this study (Fig. 2), we believe that our results should be applicable to most well-drained temperate and boreal forests.

Initially, one basic experiment was performed in each site. Trenches 1 meter deep were dug around many (generally 20) plots. All of the plots were 1 by 1 meter or larger. The locations of trenched plots were selected to avoid including canopy trees within the plots. The trenches were lined with plastic and back-filled, all vegetation within each plot was cut and left in place, and vegetation regrowth was prevented by continual weeding. Porous cup lysimeters were installed in half the trenched plots and in an equal number of control plots (22); the remainder of the trenched plots were used for soil sampling only. The plots were installed in November 1976 through June 1977, in the various sites; and forest floor, mineral soil, and lysimeter leachate samples were then collected on a regular basis until December 1978 and analyzed for ammonium and nitrate (23). In addition, quantitative vegetation studies and a thorough physical and chemical characterization of the forest floor and soil were undertaken at each site, and 4 MAY 1979

the amount and chemical composition of litterfall was determined at most sites (24).

The purpose of trenching plots was to prevent plant uptake of nutrients and water (8, 25). This experimental perturbation differs from clear-cutting and other whole-system destructive disturbances in that the forest canopy remains intact over the disturbed plots (minimizing changes in insolation and soil temperature following disturbances), and in that system recovery (through regrowth of the biota) is prevented. It is similar to whole-system destructive disturbances in that it interrupts plant nitrogen uptake without decreasing nitrogen mineralization, so that the nitrogen produced (but not taken up by plants) must either be retained by one or more of the processes discussed earlier or lost to the system. This procedure thus allowed us to focus on the mechanisms preventing or delaying losses of this nitrogen.

Responses to Trenching

The important types of response to disturbance in each site were identified through an examination of changes in soil ammonium and nitrate and lysimeter leachate nitrate concentrations after trenching. Particular emphasis was placed on responses during the plant growth season. We characterized the responses as type 1 where no significant increases in ammonium or nitrate concentrations were observed in trenched (relative to control) plots; as type 2 where significant increases in soil ammonium concentrations, but no large increases in soil nitrate or lysimeter nitrate concentrations, were observed in trenched plots; as type 3 where significant increases in soil but not lysimeter nitrate concentrations were observed; and as type 4 where (i) significant increases in lysimeter nitrate concentrations were observed and (ii) trenched plot lysimeter nitrate concentrations averaged more than 100 $\mu eq/liter.$

Several sites had small (but statistically significant) absolute increases in lysimeter nitrate concentrations (to less than 100 μ eq/liter) with much larger increases in trenched plot soil ammonium concentrations. Since our goal was the identification of the mechanisms preventing, reducing, or delaying the large losses of nitrate observed in some watershed studies (Table 1), we characterized such sites as having type 2 responses. The relatively low losses of nitrate observed in these sites could be functionally significant in a disturbed forest, however, particularly if they persisted for a long time after disturbance.

The statistical significance of our results was assessed by means of twosample *t*-tests on log-transformed data. In most cases, the results of trenching were very clear, as we were examining large changes in relatively small pools and fluxes of nitrogen. The amount of nitrogen mineralized annually is generally larger than the pool size of inorganic nitrogen in the soil of undisturbed forests, and it is always very much larger than nitrogen loss from undisturbed forests (9).

The way that we examined the results of trenching in each site can be illustrated with the results from the three Indiana sites (Fig. 3) (26). The maple sitea species-rich, productive, mesic forest-had no effective lags in nitrate losses after disturbance, and so exhibited a type 4 response (no inhibition of losses). Nitrate production and loss were delayed during the winter after trenching, but they proceeded at rapid rates as soon as soil temperatures increased in the spring. The absence of other than seasonal delays was confirmed by trenching another set of plots late in May 1978. By late June 1978, the new trenched plots had nitrate concentrations indistinguishable from plots trenched 18 months previously.

The oak-dominated site, a xeric ridgetop forest, initially responded to trenching with an increase in soil ammonium concentrations, thus exhibiting a type 2 response (increase in soil ammonium but not soil nitrate). By mid-summer, nitrate production and loss were significant, and the oak site rapidly moved into a type 4 response. Finally, the pine site, a nutrient-poor shortleaf pine plantation, exhibited a brief type 1 response (no significant elevation in soil ammonium or nitrate), followed by a prolonged type 2 response. Net nitrate production was finally observed in June 1978, more than a year after trenching. Nitrate production and loss in the maple and oak sites varied seasonally, with the greatest production in the summer months and the highest concentrations in the lysimeters several months later.

The responses of all 19 sites are summarized in Table 2. All four types of responses were observed, although types 2 and 4 predominated. The results at these sites cannot be simply related to their location, vegetation, or any single soil factor. Both very high and very low nitrate losses were observed in both eastern and western sites and under both coniferous and deciduous vegetation. The observation of high nitrate losses from several of the coniferous forests in widely different regions is particularly striking.

The systematic examination of nitrogen cycling in disturbed forest ecosystems presented earlier (Fig. 1) helps to explain these results. The type 1 responses that we observed were probably caused by the immobilization of nitrogen by decomposers. Of the other possible causes of type 1 responses, nitrogen uptake by regrowing vegetation was prevented in this experiment, the absence of increased ammonium concentrations in organic soil horizons makes ammonium fixation by clays unlikely, and the fact that all sites in this class progressed to type 2 responses makes ammonia volatilization unlikely as a major causative process. The sites with type 1 responses had high ratios of carbon to nitrogen in the forest floor, further supporting the suggestion that these responses were caused by nitrogen immobilization. For example, at the Indiana maple, oak, and pine sites the forest floor carbon: nitrogen ratios were 29, 27, and 54, respectively.

Trees growing under nitrogen stress internally recycle nitrogen highly efficiently, with the resultant production of litter with a high carbon:nitrogen ratio (27). Consequently, substantial nitrogen immobilization could be expected on sites where nitrogen stress was caused by climatically controlled low decomposition and nitrogen mineralization rates, frequent fires, which volatilize nitrogen as they mineralize most other nutrients (28), or large masses of nutrient-poor woody detritus, which promotes competition between plants and decomposers for available nitrogen (11). Nitrogen immobilization progressively lowers the ratio of carbon to nitrogen in detritus, leading eventually to net nitrogen mineralization.

Lags in nitrification were probably responsible for the type 2 responses observed since most sites with this response eventually exhibited net nitrate production. As was described earlier, at least three distinct mechanisms could cause such lags (16-18). Because of the widespread importance of this response, further study of its causal mechanisms is essential.

The type 3 responses observed in the New Mexico mixed conifer site and the Oregon western hemlock site were probably caused by a lack of percolating water for nitrate transport. With regard to the other possible causes, nitrate sorption is minimal in most temperature forest soils (21), and denitrification is unlikely to be the major causative process since both sites were relatively dry and since both sites eventually progressed to type 4 responses. The Oregon coastal hemlock site is generally moist even in the summer, but the summer of 1977 followed a severe drought over the winter of 1976-1977. The type 3 response observed may be atypical in this site, but it is probably caused by drought and not denitrification.

We view the rapid nitrate production

and loss that defined type 4 sites as resulting from the absence of processes preventing or delaying nitrate production and loss. While there were no gross geographic or vegetational correlates of rapid nitrate loss, type 4 responses developed most rapidly in sites considered fertile in a regional environmental context. For example, the most fertile (and productive) site in our New Mexico sequence is the mixed conifer (29). Here conditions for both growth and decomposition are the most favorable observed along an environmental gradient ranging from the hot, dry ponderosa pine site to the cold, moist spruce and fir site. Similarly, in the Pacific Northwest the nitrogen-fixing alder site and the extremely nutrient-rich hemlock and sitka spruce site (30) are more fertile (and productive) than the cold, wet Pacific silver fir site. Analogous comparisons have already been made for the Indiana sites (Fig. 3) and can be made for the other areas (Table 2).

This association of rapid type 4 responses with the more fertile sites is reasonable in terms of the mechanisms controlling nutrient losses, as can be demonstrated with Fig. 4. Nitrate losses from disturbed ecosystems can be delayed by the processes discussed above, and the overall delay will be the sum of the delays at all three of the possible stages in the nitrogen cycle (Fig. 1). Not all types of response need to occur in any given site, however. In fertile sites, type 1 responses would not be expected,





Disturbance Fig. 3 (left). The results of trenching in the Indiana sites. The values plotted represent the difference between mean concentrations in the trenched plots and mean concentrations in the control plots, and the vertical bars represent ± 1 standard error of the difference in means. Fig. 4 (right). Responses of soil ammonium, soil nitrate, and lysimeter nitrate concentrations to disturbance in a hypothetical ecosystem in which all three types of delays in nitrate losses are observed. The lines represent increases in a disturbed system relative to a control or to the levels prior to treatment. Any or all of these delays may be absent in specific kinds of site, reducing or eliminating the overall delay.

since nitrogen immobilization will be much lower than nitrogen mineralization in a system rich in available nitrogen. Nor would prolonged type 3 responses be expected, since there should be adequate percolating water for nitrate transport. To the extent that type 2 responses are caused by competition between decomposers and nitrifiers for some nutrient other than nitrogen (17), or by competition between nitrifiers and plant roots for ammonium prior to disturbance (18), they too would be minimized in nutrient-rich sites. There is even evidence suggesting that the production of potentially inhibitory biochemicals is greater in less fertile sites (31). Thus we would predict that most of the important delays to nitrate losses would be absent in fertile sites, and that consequently they would rapidly display a type 4 response. The comparison of Fig. 4 (the results expected if all the delays occurred) and Fig. 3 (the delays actually observed in the Indiana sites) illustrates this suggestion.

We point out that "fertile" is not a precise designation in ecological usage (32), but in general it refers to sites with a high availability of plant nutrients and optimum water supply. High nutrient availability is usually a product of the parent material of the soil (the geological substrate from which soil develops), a favorable combination of temperature and moisture for decomposition and nutrient release (33), and readily decomposable plant litter (33). A strong positive correlation between soil fertility and the rate of nitrification is well recognized in agricultural soils; indeed, the rate of nitrification has been proposed as a direct measure of soil fertility (34). Other workers have suggested that the rate of nitrogen accumulation in trenched plots (without lysimeters) can be used to measure soil fertility (35). Our results from a wide range of forest soils support this association and suggest some mechanisms causing it. They further point to an association between soil fertility and the potential for greatly elevated nitrate (and cation) losses after forest disturbance.

It should be stressed that without revegetation, almost all systems will eventually proceed to type 4 responses as organic material decomposes and nutrients are released, inhibitors of nitrification decompose (if any were present), populations of nitrifying bacteria increase, and sufficient water accumulates to permit transport of nitrate to drainage systems. Time is thus a crucial element in the response of forest ecosystems to disturbance. With revegetation, the overall response is, in a sense, a race between the elimination of the sequence of lags we have described (Fig. 1) and a resumption of ion uptake and other controls by regenerating vegetation.

Overall ecosystem responses to perturbation can thus be separated into two components, which have been termed resistance and resilience (36). Resistance is defined as the relative magnitude of response to a given perturbation, while resilience is the relative rate of recovery after perturbation. In the context of this article, the processes that prevent or delay nutrient losses confer resistance on an ecosystem, while the direct and indirect effects of vegetation recovery confer resilience.

Our results and our model apply to the resistance component of ecosystem responses to disturbance. We have shown which sites (and what kinds of sites) have the potential for high nitrate losses following disturbance, but without information on the resilience of these sites we cannot predict quantitatively how much of that potential would be realized in practice. It seems reasonable that fertile sites revegetate more rapidly (and hence are more resilient) than other sites, but we lack information on how the mechanisms we have discussed affect resilience. A thorough understanding of overall ecosystem responses to disturbance will require a detailed, mechanism-oriented examination of resilience as well as resistance.

Application

The results of our study demonstrate that the variability in forest ecosystem responses discussed earlier (Table 1) can be explained in terms of site characteristics. With a more thorough understanding of the critical mechanisms identified in this research (particularly the causes of lags in nitrification and the control of rates of vegetation recovery), precise predictive capability should be attainable. Moreover, this approach is not limited to examining the effects of destructive disturbance on nitrate (and cation)

Table 2. Responses of forest ecosystems to trenching. The response type (or types) (1, no increase in ammonium or nitrate, soils or lysimeters; 2, increased ammonium in soil, but little or no increase in nitrate, soils or lysimeters; 3, increased soil nitrate, but no increase in lysimeter nitrate; and 4, increased nitrate in lysimeters, to levels $\geq 100 \ \mu$ eq/liter; see text for additional information). Peak mean monthly lysimeter concentrations for the first 15 months after trenching are reported. Control plot lysimeter nitrate concentrations for the same month are also reported.

Site	Response type	Lysimeter nitrate concentrations (µeq/liter)		
		Con- trol	Trenched	
Indiana	· ·			
Maple, beech	4	15	2150	
Oak, hickory	2, then 4	12	1510	
Shortleaf pine	1, then 2, then 4	20	175	
Massachusetts				
Oak, pine	2, then 4	0	932	
Red pine	1, then 2, then 4	0	263	
Oak, red maple	1, then 2, then 4	1	140	
New Hampshire				
Maple, beech	4	105	1055	
Balsam fir	4	45	570	
New Mexico				
Ponderosa pine	1. then 2	1	60	
Mixed conifer	3, then 4	Ô	784	
Aspen	4	0	645	
Spruce, subalpine fir	1, then 2	1	24	
North Carolina				
Mixed oak	Mixed*	0.5	434	
White pine	4	1.9	610	
Oregon				
Western hemlock	3. then 4	25	730	
Washington	,		,	
Alder	4	371	1571	
Douglas fir (low site quality)	1. then 4	1.4	114	
Douglas fir (high site quality)	4	6.1	779	
Pacific silver fir	2	6.2	56	
	-	0.2	510	

*Trenched plots were placed in several different communities within one watershed, and responses to trenching differed in the different communities. losses. With minor modification, the same model (Figs. 1 and 4) can be used to evaluate the effects of forest fertilization (37), on land waste-water and sewage sludge disposal (38), and other land management practices on nitrate production and loss in forests and on downstream water quality.

References and Notes

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- water samplers were placed at a depth of 55 to 70 cm and maintained at a tension of -0.2 bar.
- Sampling was carried out weekly for lysimeters and monthly for forest floors and soils. Forest 23 floor and soil samples were extracted with 2M KCl. Chemical analyses were performed with dual-channel Technicon AutoAnalyzer II instrumentation at Indiana and New Mexico. All sam-ples were preserved with phenylmercuric acetate (0.5 ppm) for shipment to the analytical lab-
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Basic Research in the United States

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the requirements to assure our national

security; our desire to pursue peaceful

uses of the atom and, later, to assure a

continuing energy supply; a vision of

what scientific advance might do to im-

prove the public health; recognition of

the role of science in enhancing agricul-

tural productivity; the sense of adven-

ture and enhancement of our prestige

among nations as we sought to place man on the moon; recognition of the innumer-

able applications of space platforms for

observational purposes; appreciation of

the dwindling resources of the earth's

crust, particularly that portion that un-

derlies the United States; awareness of

the fragility of the natural environment: general acceptance of the view that sci-

In the years immediately after World War II, basic science in the United States was supported by the Department of Defense, the Atomic Energy Commission, and the infant National Institutes of Health. The Bureau of Standards, the Geological Survey, and the Department of Agriculture functioned much as they do today, although on a smaller scale. The scientific enterprise grew in consequence of our national perception of

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entific and technological advance brings social and economic progress; and a perhaps less widely but no less firmly held belief that understanding of man and the universe is, in itself, a national goal.

In 1950 the National Science Foundation (NSF) was established as the special means to assure the balance of the national program in basic research and education in science; it was then thought that most basic research as well as applied research and development would be funded privately and by appropriate mission agencies.

Since then, Congress has created the National Oceanic and Atmospheric Administration, the Environmental Protection Agency, and the Department of Energy, and has proliferated institutes at the National Institutes of Health (NIH). Nevertheless, the NSF is no longer merely a gap filler; it has become the primary vehicle for government support of basic research in a variety of scientific fields, while fulfilling several other missions as well. Its appropriation has grown almost 40-fold over the last 25 years, and the President's budget request for fiscal year 1980, with its total of about \$32.5 billion for research and

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