Plant and Soil 67, 73–79 (1982). 0032-079X/82/0671-0073$01.05. SU-06

Regional nitrogen budgets: Approaches and problems

Los balances regionales de nitrógeno: Enfoques y problemas

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Key words Models N-budgets N-inputs N-Losses Tropics

Abstract Regional nitrogen budgets are useful for assessing what is known about nitrogen cycling in important ecosystems of a region, for placing the various regional fluxes and pools into perspective, and for providing insight into the processes that regulate both regional and global nitrogen cycling. Existing regional budgets have been used both to study groundwater nitrate pollution and to help identify local ecosystems that are important on a land-use basis but that are poorly described biogeochemically. Avoidable problems common to many budgets include inappropriate compartment components, inadequate documentation, and unjustified certainty. Though imprecise, large-scale nutrient budgets at our present stage of understanding offer to researchers and system managers important advantages that would otherwise not be available.

Resumen Los balances regionales de nitrógeno son útiles para estimar el estado del conocimiento sobre el ciclo de nitrógeno en los ecosistemas mas importantes de la región, para enfocar los flujos y reservas regionales en perspectiva y para adentrarse en los procesos que regulan tanto los ciclos regionales como los globales. Los balances regionales existentes se han utilizado para estudiar la contaminación de aguas freáticas con nitratos y para identificar aquellos ecosistemas localmente importantes desde el punto de vista del uso de la tierra pero que son poco conocidos biogeoquímicamente. Algunos problemas que son comunes a muchos balances son: la selección de compartimientos inapropiados, documentación inadecuada y la certeza injustificada. Aun cuando sean imprecisos, los balances en gran escala, en el estado actual del conocimiento, aportan a investigadores y a quienes manjean los sistemas, algunas ventajas importantes que no estarían disponibles de otro modo.

Introduction

Ecosystem nutrient budgets for individual watersheds have become an increasingly common way of examining nutrient cycling in both agricultural and natural systems. The value of this approach, in which all significant pools, sources and sinks of a nutrient as well as turnover rates between the various compartments are quantified, needs little elaboration: nutrient budgets provide a convenient and biologically meaningful context within which to organize what is known about a system's biogeochemical cycles, help to force nutrient pools and fluxes into perspective, and can lend considerable insight into processes that

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regulate nutrient cycling. They thus help to guide system management decisions and direct the course of future research.

A logical outgrowth of individual-watershed studies has been an expansion of system boundaries to include wider geographic areas. Global budgets represent the far end of this spectrum. Large-scale compilations are useful for the same reason smaller-scale studies are valuable, but because the scale is different, the specific questions addressed and the approaches taken in their construction differ.

The major difference between well-constructed watershed and landscape budgets is the massive aggregation present in the latter. Aggregation simplifies and thus makes large syntheses manageable by allowing many smaller pools and processes to be lumped into single black-box compartments. In general, aggregation expands with geographic size. The degree of simplification is a function of both our ignorance regarding certain processes and the time and effort available for close resolution, and it is made at the expense of both detailed insight and precision.

Erosion, for example, is commonly a victim of aggregation in large-scale budgets. Although erosion may be extremely important on a local level, in landscape budgets it is effectively ignored except for losses from the system via river transport. This is because soil washed from one local system largely ends up in another within the same region, and such a transfer can be considered internal and consequently ignored, in much the same way that NH_3 volatilized from beneath an unfertilized forest or corn canopy and subsequently trapped by the vegetation is considered an internal transfer in watershed studies. Insight into the local importance of erosion is thus restricted because values for regional erosion losses are usually based upon very little hard information. Data for sediment loads and nutrient contents of rivers draining most regions are unavailable, and rough extrapolation from other systems or time periods becomes necessary. Söderlund and Svensson[10], for example, estimated the global transfer of organic-N from terrestrial to marine systems via rivers by extrapolating values from Sweden, U.S. and Amazon rivers to total non-desert land areas. Even though such a value may be correct to only a factor of five, still it contributes significantly to our understanding of the global importance of this process and to our understanding of how it intereacts with others.

Taken to the extremes, of course, extrapolation yields negligible benefit. The global budget presented in Fig. 1, for example, offers very little insight into nitrogen cycle processes. More detailed global budgets (*e.g.*[9,10]), however, can help to gauge the relative importance of various N-pools and processes (*e.g.* anthropogenic *vs* natural sources of fixed nitrogen and nitrogen oxides), and to draw attention to how little is known about others (*e.g.* nitrogen fixation in the open ocean and natural sources and sinks of nitrous oxide). Information of this nature is vital if the impact of human activity on processes in the biosphere is to be adequately assessed.

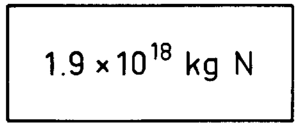

Fig. 1. A one-compartment global nitrogen model. Pool size is from Söderlund and Svensson[10].

Regional budgets

General approaches

Nutrient budgets for landscape units between the watershed and global extremes are as yet rare. Only five such budgets, all for nitrogen, presently exist in the open literature: two riverbasin studies for parts of sourthern California[1,6], two U.S. state-wide models, one for Wisconsin and one for peninsular-Florida[7], and a budget for West Africa south of the Sahara[8].

At its most detailed, a regional budget is simply a compilation and synthesis of individual-watershed budgets for the important systems of a region. Since local budgets are presently lacking for many significant system types within most regions, a major potential use for regional budgets at present is to help identify those local systems that are important on a land-use basis but that are not well-described biogeochemically. Regional syntheses at this early stage are also useful for addressing specific management problems; for example, four of the existing regional nitrogen budgets were designed to address potential groundwater pollution by nitrates. Other budgets might focus on agricultural productivity or crop residue management, and all such budgets are useful for building more detailed and presumably more precise global budgets.

As for nutrient budgets of any geographic size, the two most important decisions to be made when compiling a regional budget are first, geographic boundaries, and second, compartment components. Both choices depend on the questions to be addressed with the budget. Regional studies developed in the 1970's to better understand groundwater nitrate pollution illustrate the importance of appropriate choices. The general model used for the two California river basin studies[1,6] incorporated seven broad compartments to emphasize hydrologic fluxes (Fig. 2). Compartments included pools of atmospheric nitrogen, land-surface nitrogen, surface-water nitrogen, soil nitrogen, substrata nitrogen, and groundwater nitrogen. The model presents a logical conceptual framework for studying the movement of nitrate through the system, but because it concentrates terrestrial activity (both human and natural) into one massive compartment, the model offers little quantitative insight into ways to better focus management efforts to reduce nitrate percolation at its sources. It further fails to quantify external sources and sinks of nitrogen that are not waterborne. In agricultural areas, both nitrogen gained in fertilizer and nitrogen gained and lost *via* crop import (*e.g.* animal feed) and export are important fluxes for the entire system, and to assume that these inputs and outputs balance is unrealistic[7].

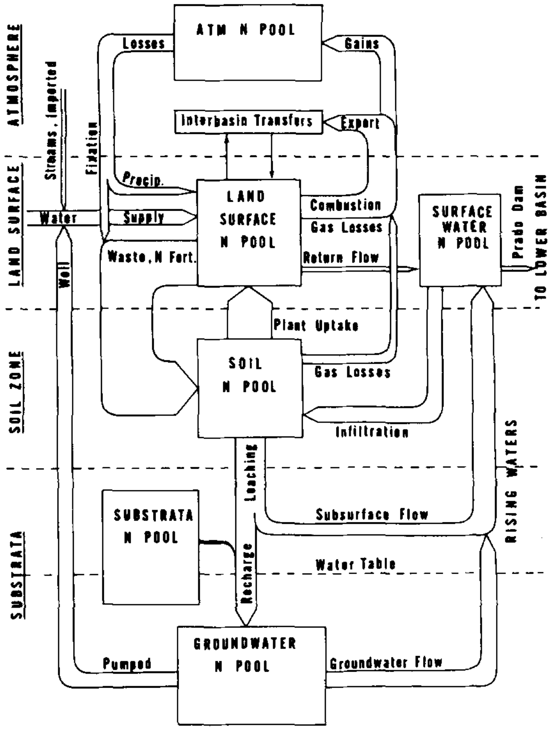

Fig. 2. Nitrogen pools and fluxes quantified in the California Santa Ana and San Joaquin Valley river basin studies[1].

Alternative hydrologic models might include these external fluxes and divide the land-surface pool into a number of separate compartments. The peninsular-Florida model[7], for example, divided the land-surface pool into animal, human, and harvested organic-N pools (Fig. 3) and further divided each of these into subcompartments where available information permitted (*e.g.* Fig. 4). Such detail can help managers accurately pinpoint nitrate hotspots in the system and suggest causal relationships as well as indicate those areas for which important information is lacking.

Common to both regional nutrient budgets and to budgets for other landscape units are at least two important problems of interpretation that are often readily avoidable. The first concerns documentation, and occurs when values are assigned to compartments and fluxes that leave the careful reader wondering 1) how the values were derived, 2) what assumptions were involved in their derivation, and 3) what scientific justifications exist for the assumptions. Careful documentation can lead to a cumbersome final product, but it is difficult to justify leaving such documentation out of a budget that is inherently unverifiable.

The second important problem is unjustified certainty. This occurs when specific values are assigned to fluxes or pools for which a wide range of values

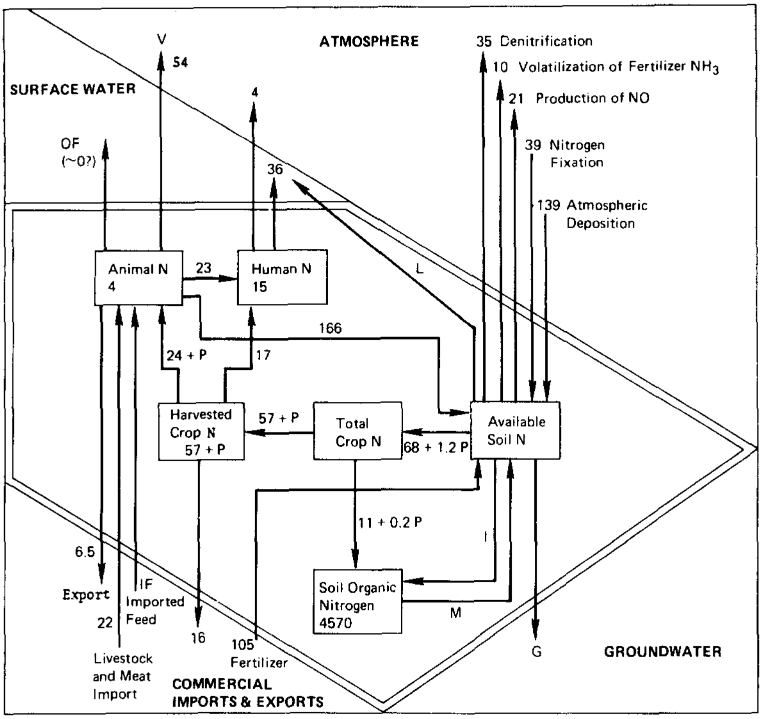

Fig. 3. Nitrogen pools and fluxes in peninsular-Florida[7]. Flux values are 10^6 kg N yr^{-1}; pool sizes are 10^6 kg N. P = pasture nitrogen, V = volatilized NH_3-N, I = microbial immobilization of fertilizer-N, L = nitrogen leached to surface water, G = nitrogen leached to groundwater, IF = imported nitrogen in feeds, OF = overland flow, and M = mineralization.

would be as accurate. This is particularly the case for basic processes such as NH_3 volatilization and denitrification which are still poorly quantified at even the watershed level. It is also the case for relatively well-understood processes such as nitrogen fixation by legumes, however, for which a high degree of uncertainty stems from uncertainty associated with actual land-use practices (*e.g.*, fertilization and planting densities). A more appropriate approach in both cases is to assign ranges of likely values to pools and fluxes. There seems little to be gained by implying certainty where none exists, and such a practice can cause considerable damage if values so-reported are actually used as a basis for system management decisions.

Approaches for tropical regions

Nutrient budgets for tropical regions present several methodological problems not usually encountered with temperate budgets. First among these are ecosystem heterogeneity and the very uneven availability of basic information regarding land use in the region and nitrogen cycling in particular important ecosystems.

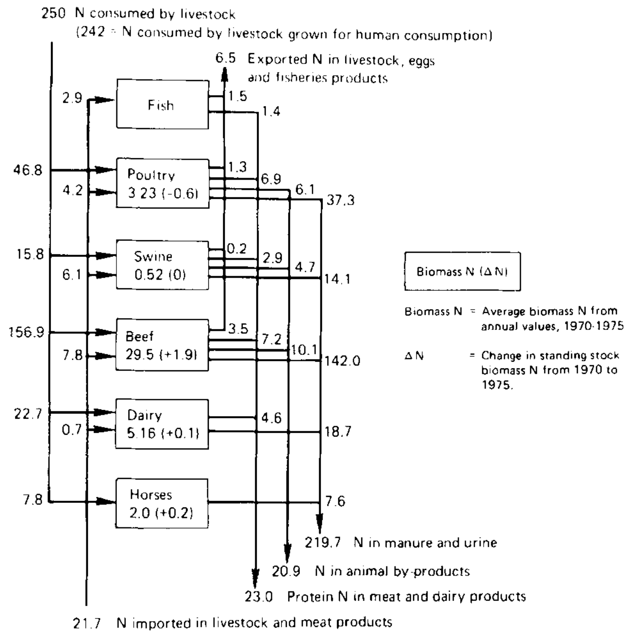

Fig. 4. Sub-compartment model of the animal-N pool in the peninsular-Florida model [7]. All values are 10^6 kg N yr^{-1}.

System heterogeneity results from a high diversity of both crops and cropping systems, in addition to often significant areas of undisturbed natural systems in various states of ecological succession. Regional values for rates such as nitrogen uptake and nitrogen fixation by crops, for example, are difficult to estimate in agricultural systems in which a large variety of crops are grown in polycultures of varying compositions and densities. The usual approach for temperate-system budgets is to calculate fluxes per unit area of monoculture and then extrapolate to regional rates based on known areas under a particular crop. In multiple-crop systems, however, the density of a given crop species may vary by an order of magnitude or more from one field to another even within the same watershed. Without data for densities and without N-uptake or N-fixation data for a range of densities, the only practical way to arrive at reasonable estimates for these fluxes is to back-calculate from total regional yield (available from FAO statistics) to total residue biomass by using a yield : residue ratio, and thereby calculate total crop biomass. The mean nitrogen content of a crop can then be used to estimate regional crop-N uptake, and then regional-N fixation by estimating from ^{15}N studies the percentage of the crop's N-uptake that represents crop-fixed nitrogen. This procedure is fairly trivial for crops with a well-defined and documented harvest (yield : residue) index, but unfortunately such indices are not often available. Indirectly calculating the index from scattered literature sources adds to the budget's imprecision; future budgets will benefit significantly from agronomic reports that include explicit harvest indices as well as nitrogen content data for all major crop components.

The lack of both land-use documentation and information on nitrogen cycling in particular systems further complicate tropical large-scale nitrogen budgets. Although nitrogen budgets of varying completeness have existed for citrus and oil palm since before 1940 (*e.g.*[3,4]) and for many non-cultivated systems such as lowland rainforest since 1960 (*e.g.*[2,5]) even simple budgets for some important crops and native systems have yet to appear in the open literature. The nitrogen budgets presented in this volume for coffee and cacao for example, appear to be among the very first published.

These and other difficulties result in regional budgets for both tropical and non-tropical regions that contain a large degree of uncertainty, and this is reflected in the very wide range of values that are at least implicitly assigned to most compartments and fluxes. The resulting inelegance is unfortunate, and for system managers hoping to use such budgets for policy decisions, probably frustrating. For formal first approximations, however, such uncertainty is unavoidable.

Successively better and more precise budgets, constructed perhaps with information from research stimulated by earlier budgets that have focused attention on neglected systems and processes, should make regional budgets at this stage of understanding well worthwhile.

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