

Nutrient Cycling in Ecosystems versus Nutrient Budgets of Agricultural Systems



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INTRODUCTION

Research traditions on 'nutrient cycling' in (semi) natural ecosystems date back to the middle of the 20th century (Odum, 1953), while 'nutrient budgets' of agricultural fields have been made and discussed since the middle of the 19th century (Russell, 1912). This book is thus based on a long research tradition – and on wheels being reinvented. What is new in the present book, apart from some of the rhetoric and way of phrasing classical problems? Global concerns and the relationships between similar phenomena at different scales take a prominent place in current discussions and in this book. Consequences of local nutrient excesses and local nutrient shortages are evaluated from a number of perspectives. The standard recipes of maintaining nutrient flows through agricultural systems by continuously applying new inputs have not worked in practice in major parts of the world and are under environmental scrutiny in the rest of the world where they may have worked too well. An analysis is needed of the social, economic and political context of the various technical solutions. This book should contribute to that debate, on the basis of a conceptual framework and a series of case studies.

In this introductory chapter the evolution of agroecosystems will be considered in relation to nutrient cycles and flows, and agroecosystem nutrient use efficiency will be treated as a scale problem. Scaling in space is linked to 'lateral resource flows' and 'lateral resource capture', while scaling in time gives a new interpretation to 'residual effects'.

RESEARCH QUESTIONS IN AGRONOMIC SOIL FERTILITY RESEARCH

Over the past one-and-a-half centuries, agronomic soil fertility research has gradually evolved from a situation where theories and experiments were largely at odds (mid 19th century), via a century of research where field experiments dominated (the next century), to a situation where models have become integrated with experiments. In the last few decades new questions have emerged, which cannot be directly answered by field experiments.

Von Liebig's theories in the 19th century about nutrient balances ('a farmer must replace by fertilizer all nutrients removed from the field by crop harvest') were soon discredited by experiments of Lawes and Gilbert, which showed that, at least in the initial years of long-term experiments, the best crop growth was obtained with amounts of and nutrient ratios in fertilizer very different from that in the harvested products (Russell, 1912). Was von Liebig's theory, based on nutrient budget calculations, wrong? No, but it was incomplete and did not have the time-scale correct. Yet, the obvious failure of his theoretical predictions and the more tangible results of 'empiricists' such as Lawes and Gilbert, who started the Rothamsted experimental station, have certainly helped to establish a research tradition in soil fertility research based on 'trial and error', rather than models and theory. Research strategy became based on 'the survival of the fitter', by using models which are so flexible that they (in hindsight) can fit any data set and thus survive any validation test. Much of current 'agricultural research design' is still essentially based on the model that the yield of a crop on a given site and in a given year is equal to some intrinsically unpredictable 'control' yield, plus terms for the specific treatment combinations used with coefficients that are unknown beforehand, plus 'error' terms.

When somebody reviewed the list of experiments on nitrogen fertilizer use for lowland rice in Indonesia two decades ago, and noticed that many experiments had been continued for years and years, he was given as an explanation: 'we continue them, because every year we get different results' (Van Keulen, personal communication). He remarked 'then you may as well stop the experiments, because you'll never be able to predict how the response will be in the next year' and then helped establish a method for data analysis focusing on the site differences and between-year variability.

Traditional questions in soil fertility research are (Fig. 1.1):

1. To which extent are nutrients (individually and in combination) limiting crop yield on a given field?
2. How to measure inherent soil fertility (stock of 'available' nutrients)?
3. How effective are recently added nutrients relative to inherent soil fertility, depending on fertilizer type (organic and/or inorganic), timing and

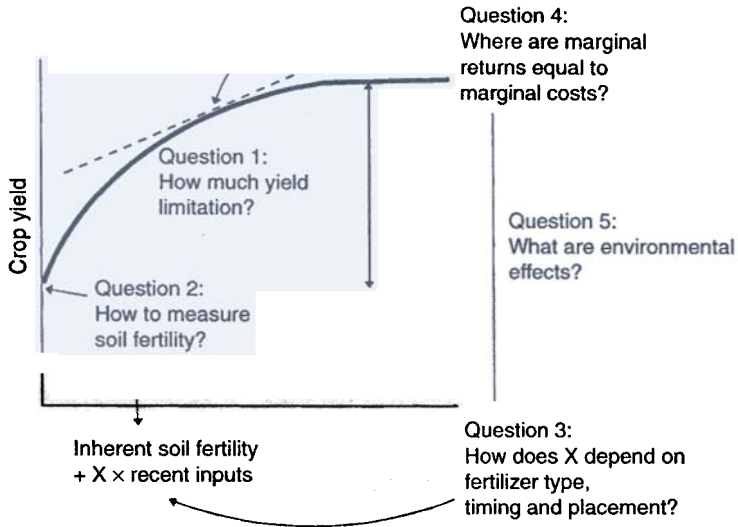


Fig. 1.1 Categories of questions in traditional soil fertility research.

placement? (Questions 2 and 3 together define the x-axis of the yield response curve.)

4. At which input level are additional (marginal) benefits equal to additional costs?

As the answers to these four questions depend on the crop, climate, inherent soil properties, other soil management factors, fertilizer type and application method and prices, it is easily understood that a century of empirical research was not enough to exhaust this field of research.

Later on a fifth question was added:

5. What are the environmental effects of different levels of input use?

The last few decades saw a drastic shift from an overriding importance of field experiments and purely empirical development of soil testing methods, to a balanced approach including theory development and modelling. For question 1, a comparison of real yields and 'potential production' estimates from crop growth models which simply assume the absence of nutrient limitations (Van Keulen and Wolf, 1986) helped in predicting where nutrient problems exist. For questions 1 and 2, more refined spatial extrapolation methods in combination with a functional interpretation of soil survey results helped to establish the broad domains (Sanchez, 1976). For questions 2 and 3, development of a quantitative framework for combining soil chemical, soil physical and plant physiological aspects of the soil-plant system (De Wit, 1953; Nye and Tinker, 1977; Barber, 1984;

De Willigen and Van Noordwijk, 1987; Van Noordwijk and van de Geijn, 1996) helped to support and partly replace the direct empirical approach. Soil biological effects and organic-inorganic interactions remain as the major frontier of data synthesis (Woomer and Swift, 1994). A process-based approach, linked to quantitative models for synthesis of knowledge, was essential in starting to address question number 5.

Question 4 has for a long time been part of agricultural economics and has focused on the financial profitability of fertilizer use. Serious misunderstanding between agricultural economists and agronomists persisted on whether or not different types of fertilizer can substitute for each other (Lanzer *et al.*, 1987). Recently a more truly economical approach is emerging, considering 'costs' and 'benefits' in a broader perspective: both the over-use and the lack of fertilizer use may cause environmental costs.

Overall, system analysis and modelling have allowed us to address broader questions of nutrient cycling and flow in our agroecosystem which the neat rectangles of a classical soil fertility experiment cannot address. The 'sustainability' of our modes of food production is at stake both in excess and in deficit areas (Smaling and Oenema, 1997). In some parts of the globe excessive use of nutrients causes damage to other environmental compartments, in other parts of the globe nutrient stocks are depleted, as the change from a nutrient cycle in a subsistence economy to a nutrient flow after market integration was not accompanied by the use of external nutrient inputs. Economically this is bound to happen where an export economy becomes based on high-volume, low-value products (such as fodder) rather than on high-value commodities.

Except for the negligible amount of nutrients lost in interplanetary traffic, all nutrients of the global ecosystem are recycled at some spatial and temporal scale. Yet, in the current global economy based on mining non-renewable resources many nutrients become tied up in pools from which recycling into agriculture will not be feasible within the human lifetime. A shift will eventually be needed from this approach to one based on recycling all nutrients within urban-rural agroecosystems. Recycling has a substantial energy cost and global energy concerns will probably limit the distance bulk nutrient sources can travel around the globe if recycling becomes mandatory.

Current compartment-flow models applied to a global GIS with discrete colour codes for smoothed polygons provide a first step only in the analysis of a global nutrient economy. As a complement, we will have to include a hierarchy of system boundaries and to scale across fuzzy boundaries in time and space. Also, the traditional phasing of biophysical (questions 1, 2, 3 and 5) and economical (question 4) research should be replaced by a more interdisciplinary analysis of causes and effects of use and misuse of nutrient resources.

NUTRIENT CYCLING IN NATURAL ECOSYSTEMS

The basic concept that natural ecosystems maintain closed nutrient cycles (Chapin, 1980; Jordan, 1985; Brown *et al.*, 1994) depends on spatial and temporal scales. Nutrient cycles will be 'closed' in situations where 'demand' for nutrients by the growing biomass exceeds current supply. In early and late successional stages, however, considerable nutrient losses may occur when a nutrient balance is made at patch scale. In early stages above-ground demand and ability to capture below-ground resources may be too small for making use of all (temporary) nutrient flushes available; in mature systems nutrient demand may be less than current supply. Losses at patch scale can lead to lateral transfers between sites, via groundwater, surface runoff or dust and can support an aggrading phase of vegetation elsewhere. Losses for one patch may provide opportunities for others and a patch-mosaic may therefore be more efficient in nutrient cycling than a summation of supposedly independent units would suggest. On a geological time-scale leaching and erosion on hill slopes dominate soil formation; a transfer occurs from nutrient degrading sites to nutrient aggrading sedimentation zones and colluvial sites, with a net loss of nutrients into the oceans. This differentiation into rich and poor sites increases overall biodiversity.

Nutrient cycling differs between ecological zones and one should be careful with generalizations. Differences are due to climate factors affecting loss rates by erosion and leaching, differences in soil type and in the effective buffering of nutrients in the root zone and differences in the response of vegetation. In mixed vegetation relatively deep-rooted components can provide a 'safety net' for nutrients leaching from topsoil (van Noordwijk *et al.*, 1996). Soil zones with high physico-chemical adsorption constants can, by analogy, be interpreted as 'chemical safety nets'.

In the tropical rain forest zone, water availability may allow roots to focus on the surface layers where most nutrients are available. In fact, on nutrient-poor soils where plants resorb most nutrients from their leaves before litterfall and thus 'litter quality' is low and decomposition slow, a substantial part of the roots may be found in the 'root mats' within the surface layer, on top of the mineral soil. Under these circumstances nutrient cycling can avoid the mineral soil with its strong chemical (aluminium (Al) and iron (Fe)) sinks for phosphorus (P) (Tiessen *et al.*, 1994). Trees with ecto-mycorrhizal associations, such as *Dipterocarpaceae*, tend to dominate in the more mature phases of these systems (Smits, 1994), whereas plants with vesicular-arbuscular (VA) mycorrhiza are more prominent in early successional stages and where the mineral soil is the major nutrient resource (Alexander, 1989; Höglberg, 1989). Where individual trees fall and create a gap ('chablis'), the roots of neighbouring vegetation still provide a safety net which can intercept the nutrient flush which follows the inputs to the soil of large amounts of dead organic material.

Nutrient losses from natural ecosystems may occur under the influence of 'extreme events' (fire, cyclone, earthquakes, landslides), when above-ground biomass is disturbed over a large area simultaneously. Fires may mobilize substantial amounts of nutrients locked up in above-ground biomass as well as in resistant organic pools in the soil, and thus bypass the slow decomposition cascade.

The nutrient cycle in natural ecosystems involves uptake by plant roots from (largely) mineral nutrient sources, utilization of these nutrients in plant biomass for a certain period of time, and return to the soil in organic or inorganic form with litterfall, as seeds or as dead plant remains at the end of the plant's life cycle. A considerable part of the nutrients may pass through herbivores before they return to the soil. A fraction of the nutrients may pass through one or more carnivore steps, but eventually most of the nutrients brought above the soil surface by plants return to the soil surface in organic or inorganic form; the remainder may enter riverain and marine ecosystems and return to the soil only at a geological time-scale, or (largely confined to nitrogen and sulphur) become part of atmospheric pools and return as wet and dry deposition or via N-fixation. Most of the nutrients, however, may return to the soil within the direct vicinity of where they were taken up. Decomposition of organic inputs to the soil ecosystem returns the nutrients to the inorganic (mineral) form, but there can be considerable delays involved. Inorganic nutrients are part of physical-chemical equilibria in the soil, governing their current concentration in soil solution. Transfers of nutrients between neighbouring land units can occur, via movement of soil or in water-soluble form, but usually such transfers are small.

NUTRIENT CYCLES BECOME NUTRIENT FLOWS IN AGROECOSYSTEMS

Nutrient losses from natural ecosystems tend to increase under human management. Logging practices lead to serious nutrient losses from tropical forests via stream flow, especially during brief periods after burning; under low-impact management the losses can be largely confined to the nutrients in the harvested wood (Malmer, 1996). Patch size in logging practices influences nutrient losses, as the 'safety net' function of neighbouring tree roots has a limited spatial extent. In small patches the whole nutrient flush can be absorbed, in large patches, only the flush from a border zone (Brouwer, 1995).

Agriculture has its roots in 'slash and burn' techniques for opening forest land, all over the world. 'Fire-clearance husbandry' (Steensberg, 1993) makes use of the nutrient mobilization effect of fire to concentrate resources gradually accumulated during a fallow period into crops grown for a few years (Nye and Greenland, 1960). Again, when this technique is applied on small patches of land, in low population density areas, with a large share of fallow land in the landscape mosaic, overall losses may be small. When

slash and burn methods are applied over large areas simultaneously, greater losses are inevitable.

All processes of the nutrient cycle described in the previous section can be recognized in agroecosystems as well, where farmer management is aimed at the nutrient uptake and associated plant productivity of one (or a limited number of) plant and/or herbivore species (Fig. 1.2). A major difference starts at harvest time, however, when products are removed from the field where they grew. In a subsistence economy, most nutrients still stay in the ecosystem from which they were derived in plant uptake and will be returned around the homestead. As long as culture is based on 'shifting homesteads', human systems can stay part of the natural nutrient cycle, and spontaneous vegetation can reclaim the accumulated nutrient stocks from the soil. With increasing integration of agriculture into world markets the distance travelled has increased enormously and in the vast majority of current farms a return flow of nutrients in waste products is no longer feasible. The nutrient cycle has thus become a nutrient flow process based on mining, with substantial on-site losses in each cycle and accumulation in peri-urban areas (Fig. 1.3).

Unless new nutrient inputs are provided and depending on the nutrient buffer capacity of the soil, this nutrient flow results in a contracting spiral with further reductions of plant productivity at each cycle. The more successful the farmer is in manipulating the ecosystem to facilitate nutrient uptake by the desired crops (and/or animals), the faster this depletion proceeds.

Where primary (plant) and secondary (animal) production become spatially segregated on specialized farms, the animal production units will lead to a local surplus of nutrients. In the last decades certain parts of Europe have thus become nutrient-aggrading zones, at the cost of nutrient depletion in the soils from which fodder crops were exported.

The nutrient transfers in the (partial) cycle can be quantified by accounting for all flows or by looking at changes in stocks (pool sizes). In a closed cycle, recording pool sizes may not reveal any activity, and measurements have to focus on the turnover and flows. Where the nutrient cycle has become a nutrient flow, changes in stock sizes may become measurable and may help to predict how long the flow can continue. This raises the question of whether total pool sizes of nutrients in soil are important or only the 'bio-available' fractions.

BIO-AVAILABILITY

Interdisciplinary research on plant-soil relations has probably been hampered by the concept of 'bio-availability'. To many biologists this term suggested that a clear-cut distinction can be made between pools of each substance (water, nutrient, pollutant) which are important, and those which

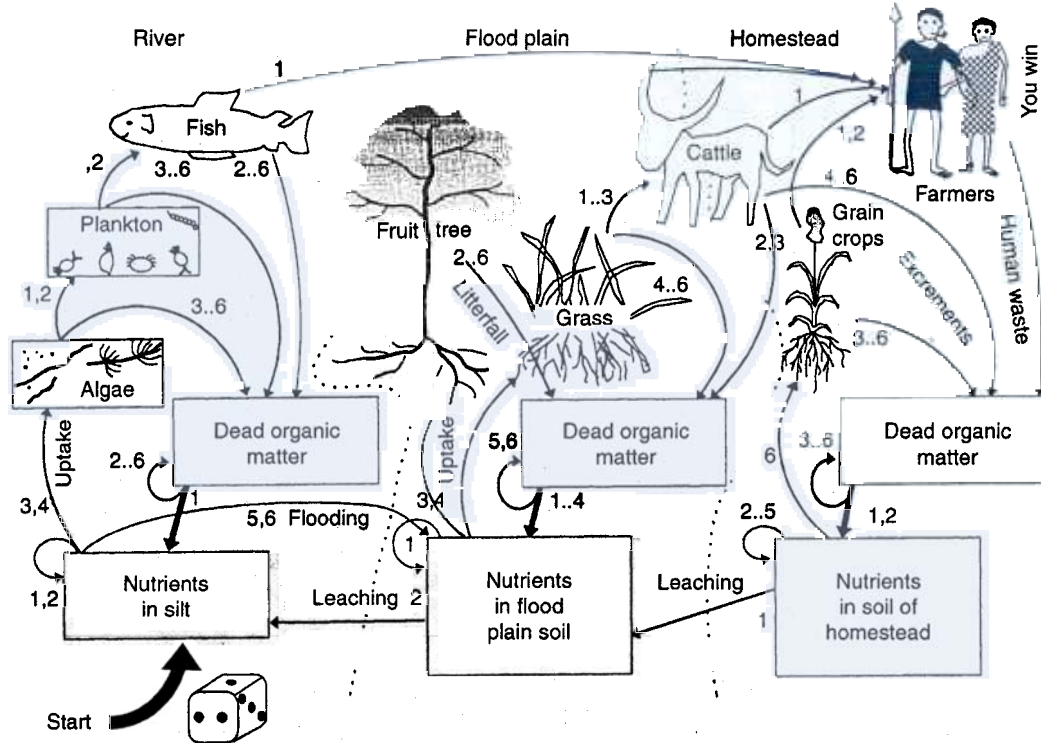


Fig. 1.2. Nutrient cycling in a traditional agricultural system on the floodplain of the Nile in southern Sudan; the diagram can be used as a board game (played with dice, all players simulating nutrients moving over the board; the first players to reach the farmer wins) (van Noordwijk, 1984).

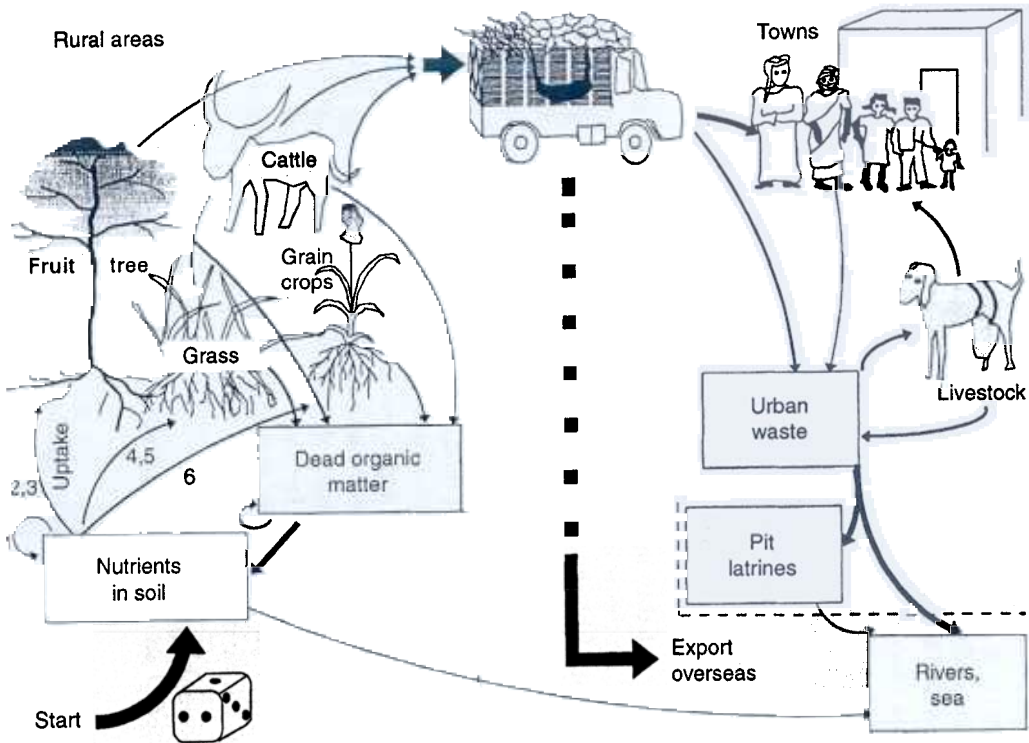


Fig. 1.3. Nutrient flow for an agricultural system producing for urban or export markets (a game can be played as in Fig. 1.2, but it will be of limited duration) (van Noordwijk, 1984).

are not, for uptake processes. To soil chemists and physicists the term suggested that for all biota the same distinction between pools will be relevant. Both interpretations are obviously gross simplifications and may have been misleading. The confusion was increased because the practical methods for measuring 'availability' used actual uptake as the criterion for testing and improving them. These methods are thus useful indicators of the plant-soil interaction under study, but they are not measurements of the pool size implied in the definitions given. In many instances, existing 'availability indices' are treated in models as if they measure pool sizes, and researchers may express surprise when actual plants can take up more of a resource than they thought was present on the basis of an availability index. If an availability index was really a measurement of the available pool, however, it would probably not be a good predictor of actual uptake across a range of plants and conditions. The difference between index and measure can be small for highly mobile nutrients such as nitrate, but will be important for nutrients of lower mobility, such as phosphate.

What is needed to resolve this confusion, is to recognize that both on the plant and on the soil side of the interaction, a large diversity of situations can exist. If bio-availability is really defined as the 'pool from which uptake can occur', it should be accompanied by a concept of 'acquisition strength' of the organisms involved, reflecting the 'part of the available pool which can actually be acquired'. Measurements of the available pool size, especially for nutrients of low mobility, should not be expected to correlate with actual uptake, but should form the basis for comparing the acquisition strength of different biota. A large number of models has been developed for nutrient acquisition which describe transport around single roots, with all its complexities, on a relatively short time span. Scaling up such results to whole plants and complete life cycles is still a major issue. For practical applications of bio-availability indices, a large number of interdependent choices has to be made:

- sampling depth,
- number of samples to be pooled and spatial sampling scheme to be used,
- sampling time,
- method for sample handling and storage,
- method for sample analysis.

Understanding the processes underlying the plant-soil interaction will probably not lead to a better 'universal' method for measuring an index which predicts actual uptake, but it may help to quantify the compromises to be made for any simple index and to predict how existing methods should be modified for new situations. The interpretation of any measurement of a pool size will depend on the types of flow in which we are specifically interested.

AGROECOSYSTEM NUTRIENT USE EFFICIENCY

The term efficiency generally indicates an output/input ratio of transfers (flows) into and out of pools, and thus efficiency depends on the boundaries where inputs and outputs are measured. The term '*nutrient use efficiency*' is often used without specifying the boundaries of the system in space and time. Efficiency attributes are not necessarily conserved across system scales, however, and thus systems which are efficient from a given perspective may be inefficient when considered with other system boundaries.

It is convenient to use a four-quadrant graphical representation to clarify the various components of nutrient use efficiency on a patch or plot scale (Fig. 1.4). In quadrant III (lower left) of this graph, a relationship is indicated between the inputs of nutrients to the soil (in whatever organic or inorganic form) and the amount of available nutrients in the soil during the growing season. The output/input ratio here can be defined as '*application efficiency*'. This efficiency depends on timing, placement, quantity and quality of the inputs (Cadisch and Giller, 1997). In quadrant IV (lower right) this available amount is related to the amount of nutrients taken up over a given period of time. The output/input ratio here can be defined as '*uptake efficiency*', and is the domain of acquisition strength and root ecology

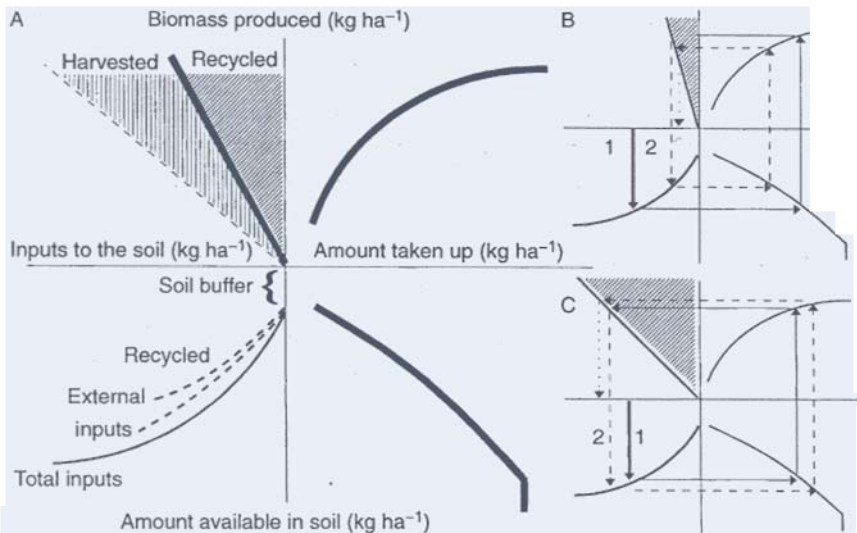


Fig. 1.4. (A) Four-quadrant representation of nutrient flows at a patch/plot level – see explanation in text (modified from van Noordwijk and De Willigen, 1986); (B) and (C) show how sequences of plant growth can follow contracting or expanding spirals, depending on the *replenishment* efficiency of quadrant II (the slope of the line).

(van Noordwijk and De Willigen, 1986; van Noordwijk and Brouwer, 1997). In quadrant I of the graph (upper right) the relation is given between plant biomass production and nutrient uptake; the output/input ratio here can be defined as '*utilization efficiency*'. Finally in quadrant II we can express the conversion of total biomass into harvested products (where the '*harvest efficiency*' or '*harvest index*' gives the conversion efficiency as output/input ratio), and convert the non-harvested part as organic inputs back into the system for the next cycle. For grain crops the term harvest index is normally used to refer to the grain only, but if straw is removed from the field the real harvest index may approach 100% of above-ground biomass, although the harvested products (grain and straw) will differ in value per unit dry weight. The '*agronomic efficiency*' of fertilizer use (increment in yield per unit additional fertilizer input, can now be expressed as a product of four partial (marginal) efficiencies: application, uptake, utilization and harvest efficiency, where the output of each step forms the input to the next one.

The form chosen in Fig. 1.4 allows one to continue into the next cropping cycle, as crop residues from the current crop modify nutrient availability in the next season. The intercept with the availability axis in quadrant III is determined by additions to the available pool from 'external' sources (which may include weathering of minerals, inputs from dry and wet deposition etc.). If the harvested amount of nutrients exceeds these free inputs, one would normally expect a contracting spiral during a sequence of crops – the higher the harvest index, the greater the contraction. During fallow periods a natural or man-made vegetation with a low harvest index may restore fertility by an expanding spiral from year to year, depending on the free inputs from other environmental compartments.

Apart from the organic recycling, based on the non-harvested part, we can also regard a functional link between the harvested part and external organic or inorganic inputs, with a financial linkage of costs and benefits. We can define a '*replenishment efficiency*' as the amount of nutrients acquired by the farmer per unit nutrient in yield products harvested from the field.

Scaling up from patch/plot to field, the input–output relationships will change due to the spatial variability within the field (see below). *Farm-level nutrient use efficiency* can be understood from the nutrient use efficiency of the various components of the farm, but taking due account of which inputs of farm components are based on outputs of other components. Similarly, nutrient use efficiency at the society level depends on the farm level efficiency, but should take transfers among sectors into account. Even if the field-level efficiency of using recycled wastes is lower than that of using 'new' external inputs, the *national-level nutrient use efficiency* can be greatly enhanced by recycling. Agricultural development as exemplified by western Europe is often based on farm specialization, increased distance between production sites and markets and a reduction of recycling. Even if crop-level nutrient use efficiency has been maintained, the global

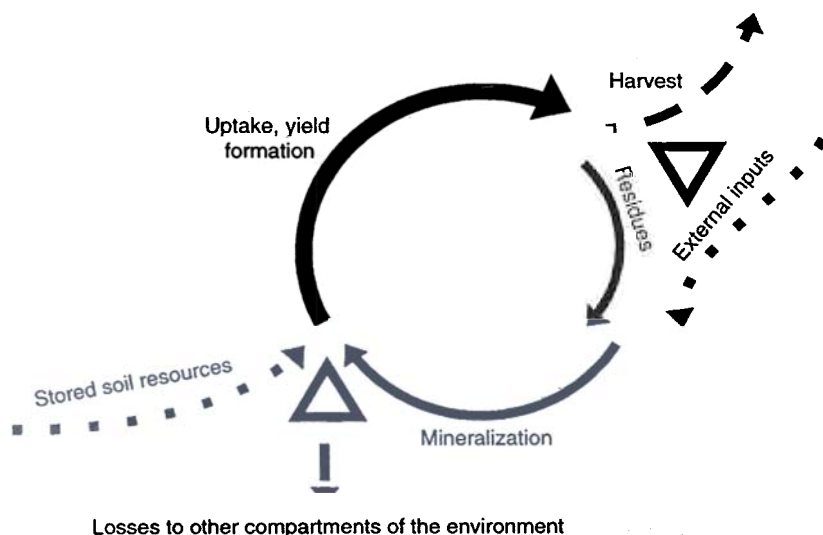


Fig. 1.5. Schematic nutrient flow and/or cycle in agroecosystems, emphasizing four aspects of efficiency: uptake efficiency, utilization efficiency, recycling/replenishment and application efficiency (van Noordwijk and Garrity, 1995).

nutrient use efficiency has decreased and environmental concerns have increased.

Figure 1.5 gives a schematic view of the key processes in nutrient cycling in agricultural systems on a field scale, and focuses on four aspects:

1. (lower left corner) Plant nutrient uptake from stored as well as recently added organic and/or inorganic resources (uptake efficiency).
2. (upper left arc) Internal redistribution in the plant and yield formation (utilization efficiency).
3. (upper right corner) Removal of harvest products, their exchange for external inputs and the recycling of harvest residues in the system (replenishment efficiency).
4. (lower right arc) Increase in available nutrient pool as a result of recycled on-farm or external inputs used to replenish soil fertility (application efficiency).

Aspects 1 and 4 are traditionally studied in soil fertility research (questions 2, 3 and 5 of Fig. 1.1) and aspect 2 in plant physiological research (question 1 of Fig. 1.1). Aspect 3 is normally included in farming systems and agroeconomic studies (question 4 of Fig. 1.1).

Figure 1.6 shows different categories of problems that may reduce the nutrient use efficiency of agroecosystems, depending on climate, soil, topography and cropping system. These problems occur at different spatial scales (van Noordwijk and Garrity, 1995):

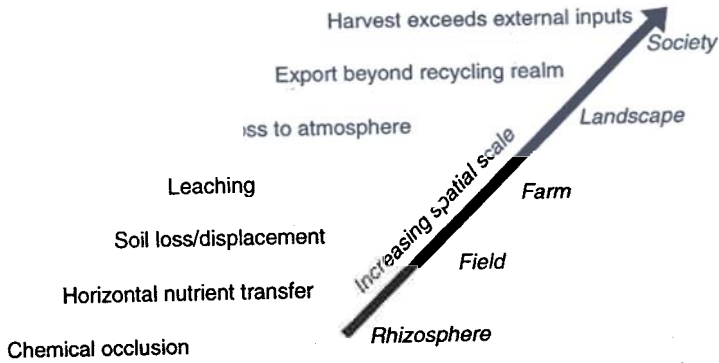


Fig. 1.6. Categories of problems for efficient nutrient use in agroecosystems at different scales (van Noordwijk and Garrity, 1995).

1. Chemical occlusion (and similar soil biological and soil physical phenomena) limits uptake of stored soil resources and/or the utilization of fresh inputs in the root zone at large, or more specifically in the rhizosphere.
2. A number of processes lead to spatial heterogeneity of nutrient supply at the field scale:
 - (a) horizontal nutrient transfer by trees, crops or farmer's practices, creating depletion and enrichment zones,
 - (b) soil loss and displacement by erosion/deposition cycles, especially on sloping lands, and thus reduce the overall stability (Whitmore and van Noordwijk, 1995).
3. Leaching leading to vertical nutrient transfer to deeper layers, often beyond the reach of shallow-rooted crops.
4. Losses to the atmosphere in gaseous form (especially nitrogen (N) and sulphur (S)), dust (wind erosion) or as particulate ash during fire; the last two lead to deposition elsewhere in the landscape.
5. Export of harvest products beyond the realm where recycling is possible: increasing economic integration of farms and/or hygiene-motivated reductions in waste recycling cause reduction of recycling as part of 'development'.
6. Economic conditions that prevent the use of external inputs to replace the exported nutrients, or that stimulate excessive use of inputs for high-value products.

The relative importance of these six efficiency aspects differs between agricultural systems, for both technical and economic reasons. The farm gate price of agricultural products is not related to their nutrient content, yet the amount of nutrients which have to be used to replenish soil fertility does depend on the exports, as well as on application efficiency. Large differences thus exist in the ratio of financial returns to sale of harvest products and the costs of replenishing the nutrient stock.

Table 1.1. Comparison of nutrient replacement value of various agricultural products and their farm gate price; financial parameters relate to the situation in Lampung (Indonesia) in 1995 (modified from van Noordwijk *et al.*, 1997).

	A			B	C	D
	Nutrient removal ^a			Nutrient	Farm gate	Relative
	R_i (g kg ⁻¹ product)			replacement	value of	replacement
	N	P	K	costs	product	costs, B/C
				$SR_i \times P_i$	(Rp kg ⁻¹)	
Cassava (fresh tuber)	1.4	0.24	3.6	15	25–100	0.15–0.60
Rice (grain + husk)	12	2.4	2.0	49	400	0.12
Maize (grain)	16	1.8	3.2	49	250	0.20
Cowpea (grain) ^b	34	3.0	15	80	300	0.27
Sugar-cane (cane dry weight)	1.5	0.8	3.5	22	40	0.54
Rubber (kg latex (DRC))	6.3	1.3	4.3	35	2000	0.02
Oil palm (bunches)	2.9	0.4	3.7	19	60	0.31
Replacement costs						
P_i in Rp g ⁻¹ nutrient in the exported crop ^c	1.2	12	2.9			

DRC, dry rubber content.

^aSources: Ahn (1993) and Höweler (1991).

^bAssuming that the N harvest index equals the percentage of N derived from the atmosphere, so that no net N is exported from the field.

^cReplacement costs, P_i , are based on a price of 260, 480 and 400 Rp kg⁻¹ for urea, TSP and KCl (based on prices for December 1995, Suyanto, personal communication; for an exchange rate of 2200 Rp/\$), a nutrient content of 0.45 (N), 0.20 (P) and 0.46 (K), respectively, and a long-term recovery (kg nutrient in crop kg⁻¹ nutrient in fertilizer) of 0.5, 0.2 and 0.3, respectively; combined, these estimates lead to the indicated replacement costs P_i in Rp g⁻¹ nutrient in the exported crop (e.g. $260/(0.45 \times 0.5 \times 1000) = 1.16$).

As a first approximation, the costs of inorganic fertilizer needed for replenishment at reasonable application efficiency can be expressed as a fraction of farm gate price (Table 1.1). Nutrient contents per unit weight of harvested product, R_i , multiplied by the replacement cost per unit nutrient in the crop, p_i^f , can give the market value of the products which would require all cash obtained to be spent on fertilizer, just to maintain chemical soil fertility. Where this price is more than say 30% of the actual farm gate price (as it is for cassava and sugar-cane in the example of Table 1.1, low-value bulk products with high nutrient contents), fertilizer use is unlikely to be economically justified at any rate. Local prices of both products and inputs may differ from those at the global market, but the range of

these 'relative replenishment costs' includes values of more than 50% , such as cassava in Table 1.1, and values close to zero (high-value, low-volume products and/or products of low nutrient content such as rubber).

Existing technical opportunities to increase the agronomic efficiency (output/input ratio) of fertilizer use may not be utilized by farmers if the price ratio of fertilizer and yield products is too low (van Noordwijk and Scholten, 1994). If fertilizer inputs are cheap, no incentive is given to high application efficiency; if fertilizer is expensive, it may not be used at all; in an intermediate range improving fertilizer application efficiency may pay off to the farmer.

Trees can increase nutrient concentrations on small areas of land, at the expense of nutrients elsewhere. If their source of nutrients is deep soil layers (point 3 discussed above), chemically occluded soil nutrient sources (point 1), airborne dust (4) or soil material moving downslope with surface runoff (2b), one may expect that trees increase the nutrient stocks available for other components of the system, such as crops (Buresh, 1995). As long as deep and chemically occluded sources last and as long as wind erosion up-wind and water erosion up-slope continue, these nutrient sources can be sustainable from the agroforest farmers' point of view. None of these processes is easy to prove and quantify, however. If most of the nutrients which the trees absorb come from topsoil layers (point 2a), and this may even extend to 50 m from the tree in some cases, the role of trees is only positive in as far as topsoil nutrients would not be utilized by other components and get lost from the system. The large horizontal spread of tree roots appears to have been neglected in the design of many agroforestry experiments. Positive conclusions about increased nutrient storage and/or crop yields for agroforestry treatments of such experiments, as compared to neighbouring 'control' plots, may in fact be partly due to tree roots mining the soil under the neighbouring plots as well as in their own (Coe, 1994).

The time dimension also causes concern in the definition of nutrient use efficiency of agroecosystems, especially where perennial crops are concerned or for nutrients with strong 'residual effects'.

SPATIAL VARIABILITY

In early stages of fertilizer research, results were interpreted as universal truths, leading to blanket fertilizer recommendation schemes, which differentiate between crops, but not soils. Gradually more detailed recommendations have been developed which are based on soil groups and/or field-level soil analysis. Such schemes can greatly enhance field-level nutrient use efficiency.

Agronomic research has for a long time made the implicit assumption that results of relatively small plots, selected on the basis of their homogeneity for 'proper' experiments, were directly relevant for the field scale.

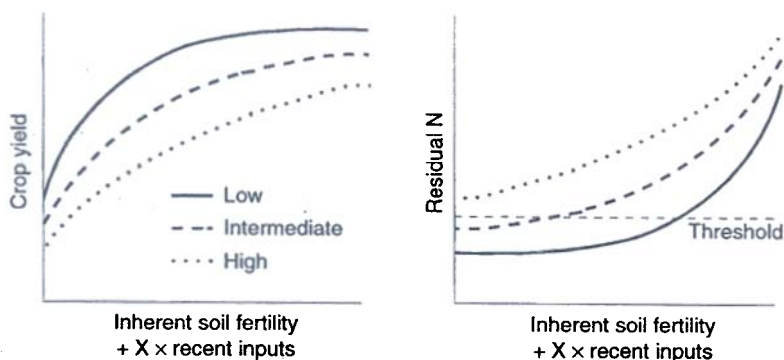


Fig. 1.7. Effects of within-field spatial heterogeneity on the shape of the fertilizer–yield response curve as well as on the amounts of residual mineral N at harvest (based on van Noordwijk and Wadman, 1992).

Van Noordwijk and Wadman (1992) showed that the agronomic efficiency of a crop production system, defined as crop output per unit input, decreased with increasing internal variability of the field, all other parameters being equal (Fig. 1.7). Independently, Cassman and Plant (1992) developed a similar model and applied it to field results. Field heterogeneity does not affect nutrient use efficiency in the linear response range, where it may be most visible in the crop. Heterogeneity affects efficiency especially when the nutrient supply to part of the plants exceeds the requirements for maximum yield.

Field heterogeneity has a direct effect on the production–environment conflict, as the amounts of inputs needed for ‘economically optimum’ yield increase, while the amounts of inputs which can be tolerated from an environmental point of view decrease. In heterogeneous fields, nutrient use efficiency can be improved by site-specific input decisions. Technical options for such decisions are being developed for large-scale mechanized farming. The small-scale farmer with intimate knowledge of his or her land may be directly inclined to apply nutrients where needed most. This is only possible, however, if the rich and poor strata of the field can be recognized from easily observable patterns.

Spatial variability may under some circumstances help in reducing risks in crop production under uncertain rainfall conditions (Brouwer *et al.*, 1993; van Noordwijk *et al.*, 1994).

SPATIAL EXTRAPOLATION: NOT JUST STRATIFIED SAMPLING

It has become a common phrase that we should study our subject at different spatial and temporal scales. What does this mean in practice? We will discuss two aspects here: ‘stratification’ and ‘scaling rules’.