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Developing Practical Strategies

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CHAPTER 8

Field-Scale Nutrient Cycling and Sustainability: Comparing Natural and Agricultural Ecosystems

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8.1 INTRODUCTION

Nutrient cycling — the movement of nutrients from the biotic components of ecosystems to their abiotic components and back again — is an essential function

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of all ecosystems (Odum, 1969). Nutrient cycles are never completely closed; all systems receive some external inputs (e.g., from precipitation) and experience some losses to the outside environment (e.g., through denitrification).

Compared to natural ecosystems in general, agroecosystems have relatively open nutrient cycles because they are designed to produce nutrient rich products that are harvested and removed from the system. Many agroecosystems are more leaky than need be. The tillage and exposure of soils between cropping seasons can cause large nutrient losses through leaching and erosion, contaminating ground and surface waters, and requiring large fertilizer inputs to maintain yields (Cox and Atkins, 1979; Odum, 1969).

The more closed an agroecosystem's nutrient cycle, the more it will resemble natural ecosystems and will be ecologically sustainable over the long-term (Ewel, 1999; Jarrell, 1990; Woodmansee, 1984). In designing sustainable agroecosystems, it is useful to compare indicators of nutrient cycling between different management patterns of agroecosystems and natural ecosystems to find systems with more closed nutrient cycles (Gliessman, 1990; 1998).

This chapter explores the use of indicators, focusing on the Cycling Index (CI), a relative measure of material cycling derived from flow analysis (Finn, 1976). Our purpose is to assess the use of the CI and its associated cycling measures as field scale indicators of ecological sustainability in agroecosystems. We do this using three case studies of nitrogen cycling: organic and conventional monocropped strawberry systems in California (Gliessman, et al., 1996), organic and conventional strawberry-paddy rice double-cropping systems in Nanjing, China (Li, et al., 1998), and a natural chaparral ecosystem in California (Grey, 1982).

8.2 FLOW ANALYSIS AND THE SOIL-PLANT MODEL

Flow analysis, also known as input–output analysis, is a set of methods used to analyze flows within compartmental models (Hannon, 1973; Ulanowicz, 1986). Based on flow analysis, Finn (1976, 1978, 1980, 1982) developed a set of indicators to describe different aspects of nutrient cycling in ecosystems, including the CI.

The CI is a whole system property, defined as "the fraction of total system throughflow that is cycled," and has been used to describe nutrient cycling in natural ecosystems (Finn, 1978; Patten and Finn, 1979; Christensen, 1995; Han, 1997) and in agricultural ecosystems on the farm scale (Luo and Lin, 1991; Fores and Christian, 1993; Dalsgaard and Oficial, 1997). Because CI is sensitive to model structure (Finn, 1976), we use a standardized two-pool soil–plant model for comparing soil-plant nutrient cycling across agroecosystems and natural ecosystems (Figure 8.1). The model consists of two nutrient pools (soil and plant) and six flows. Pool size represents the change over time in the magnitude of the pool (Δ plant pool, Δ soil pool). Each flow is expressed as the sum of component flows. Figure 8.2, which illustrates nitrogen flows and their components in the case studies, is an example of the use of this model.

Although the two-pool system is a vastly oversimplified model of ecosystems, it can be prepared for virtually any terrestrial ecosystem and serves as a convenient reference standard for quantitative comparisons between ecosystems.

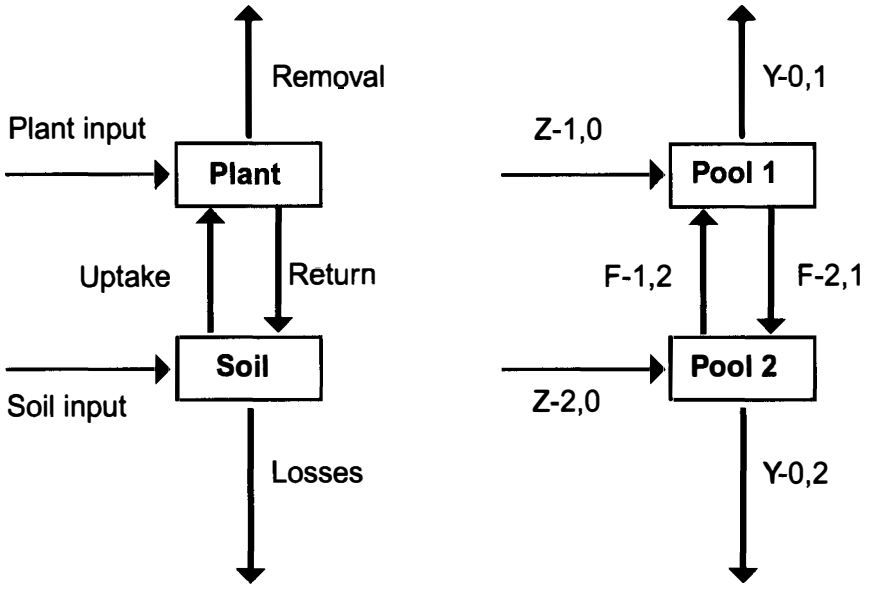

Figure 8.1 Standardized two-pool soil-plant model, showing conceptual model (left) and formal description (right).

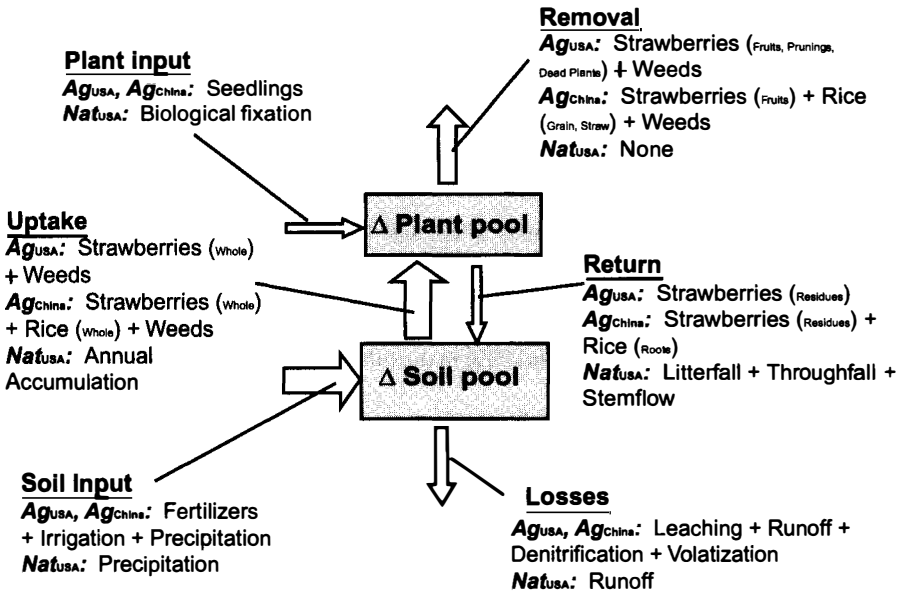

Figure 8.2 Components of nitrogen flows in natural and agricultural ecosystems in California and in Nanjing. Ag_{USA}: Strawberry agroecosystem in California. Ag_{China}: Strawberry-paddy rice agroecosystem in Nanjing. Nat_{USA}: Chaparral natural ecosystem in California.

8.3 ORGANIC AND CONVENTIONAL STRAWBERRY SYSTEMS IN CALIFORNIA AND IN NANJING

We use on-farm field experiments comparing organic and conventional strawberry systems in California (Gliessman et al., 1996) and in Nanjing, China (Li et al., 1998), as case studies in agroecosystem nutrient cycling. These experiments were conducted over 3-year periods to investigate yield and ecosystem process responses to alternative farming practices.

Under a Mediterranean climate, strawberries are grown as annual crops off the central coast of California. They have a 5- to 6-month harvest period and are the most economically valuable crops in the region. The temperate, sunny climate, the long rain free bearing season, and the sandy loam soils of California's coastal valleys promote possibly the heaviest harvests of strawberries in the world (Processing Strawberry Advisory Board, 1989, cited by Wells, 1996). Strawberries represent a high value specialty crop with exacting cosmetic standards. They are one of the most input-intensive field crops in California, involving soil fumigation, plastic mulch, irrigation, and concentrated semi permanent hand labor in all production phases. Acreage planted for certified organic strawberries on the central coast is on the rise, due to increased demand and higher profit margins.

The California experiment was conducted in Davenport from September 1987 to August 1990. The organic plot was managed according to the guidelines of the California Certified Organic Farmers, where conventional plot management conformed to local farm adviser's recommendations.

The strawberry–paddy rice system in Nanjing represents an intensive wet rice system common in many countries in Asia. Crop yields, especially those of rice, were quite high, as were the rates of fertilizer application. The Nanjing experiment was conducted from October 1992 to October 1995. We applied animal manure (pig and cow) and biogas sludge for strawberries in the organic plot and chemical fertilizers in the conventional plot; chemical fertilizers were applied in both plots for rice.

Table 8.1 describes the two study sites, and Table 8.2 summarizes the fertilizer application regimes used in each.

Strawberry yield was much higher in California than in Nanjing. Organic system yields in California were depressed relative to conventional system yields by 39% in the first year, 30% in the second, and 28% in the third (Gliessman et al., 1996). Organic

Table 8.1 Characteristics of the Study Sites

	USA	China
Site	Davenport, California	Zhujiang, Nanjing
Climate Zone	Mediterranean	Subtropical monsoon
Yearly Mean Temperature	13°C	16°C
Mean Annual Precipitation	760 mm	1106 mm
Soil Type	Pinto loam (typic argixeroll)	Brown loam
Cropping System	Strawberry mono cropping	Strawberry–rice double cropping

Table 8.2 Fertilizer Application for the Study Sites (Third Year)

		Conventional plot		Organic plot	
Site	Crop	Fertilizer	kg N/ha	Fertilizer	kg N/ha
USA	Strawberries	Controlled release fertilizer	102	Commercial compost Bloodmeal, bone meal	220
		total N	102	total N	220
China	Strawberries	Chemical fertilizers[a]	408	Pig and cow manure Plant ash, biogas sludge	325
	Rice	Chemical fertilizers[a]	215	Chemical fertilizers[a]	215
		total N	623	total N	540

[a] Compound fertilizer, potassium chloride, ammonium bicarbonate, and urea were used.

plots had higher yields of rice and strawberries compared with the conventional plots and maintained better soil quality over three years in Nanjing (Li et al., 1998).

To demonstrate our methods for nutrient cycling analysis, we use nitrogen balance data from the third year of each experiment. Crop yields for the third year of each experiment are shown in Table 8.3. Nutrient cycling data for chaparral scrub ecosystems (Grey, 1982) are used as a benchmark for comparison with the California agroecosystem experiments; chaparral scrub is one of the representative natural ecosystems on the central coast of California.

Figure 8.2 summarizes the nitrogen flows and pools that we identified in the three case studies.

8.4 OBSERVATIONAL UNCERTAINTY ANALYSIS

To conduct a statistically reliable analysis of nitrogen flow, we use an observational uncertainty analysis system based on methods described by Ellis et al., 2000. This system uses probability distribution functions (PDFs) to describe our degree of belief, or betting odds, for the mean of every variable measured or estimated in this study. Monte Carlo methods are used to estimate probability densities for variables, such as Cycling Indexes, that are calculated as functions of other variables. For most variables, lognormal PDFs were used to avoid negative values unless otherwise stated.

Table 8.3 Third Year Yield of Strawberries and Rice

		Yield (tons/ha)	
Site	Crop	Conventional plot	Organic plot
USA	Strawberries[a]	56.3[b]	40.3[b]
China	Strawberries[a]	10.7	12.0
	Rice (grain)	8.3[c]	9.0[c]

[a] Fresh yield.
[b] Marketable fruit yield.
[c] Average of three years.

For U.S. strawberry fields, PDFs for uptake, removal, return, and plant input were calculated from direct measurements or regressions of directly measured data (Hunt, 1982). Fertilizer PDFs were derived by combining direct measurements, guaranteed analysis values, supplier's analytical records, and data from references (Jones, 1979; Soil Improvement Committee, 1995). PDFs of losses from soil (denitrification, volatilization, leaching, and runoff) were estimated based on Meisinger and Randall (1991), Huntley et al. (1997), and Smith and Cassel (1991), using beta-subjective PDFs (Palisade Corporation, 1996). PDFs for precipitation deposition were estimated from monthly precipitation in the central coast region (California Department of Water Resources, 1998) and inorganic nitrogen (NH_4-N + NO_3-N) concentration in precipitation in California (The National Atmospheric Deposition Program/National Trends Network, 1998) during the experiment period. PDFs for nitrogen loading from irrigation were estimated from the analysis record of the water sources (Santa Cruz Water Quality Laboratory, personal communication) and the farm irrigation record. We standardized the data with a growth period weighted annual average.

For the Chinese strawberry–paddy rice system, PDFs of uptake, removal, return, plant input (seedlings), and soil input (fertilizers) were calculated from direct measurements. PDFs of deposition through precipitation were estimated based on Lu and Shi (1979); nitrogen loading from irrigation and losses from soils (leaching, runoff, denitrification, and volatilization) were estimated based on Xi (1986). Since no variability data was available for the Chinese field experimental data, we used PDFs with sigmas set to a CV of 30% for direct measured variables and 50% for the other variables.

Nitrogen flow data for the undisturbed chaparral natural ecosystem were collected from references. We used data from Grey (1982), Mooney and Rundell (1979), and Marion et al. (1980) for plant uptake and return, from Schlesinger and Grey (1982) for plant input (biological fixation), and for soil output (runoff). To be conservative, we used a 50% CV, or a range (minimum × 0.5, maximum × 1.5) to calculate the PDFs of nitrogen flows in chaparral.

Δ plant and Δ soil pools were calculated by subtracting the outflows from the inflows of each pool. Results are presented as means and 90% credible intervals from 10,000 Monte Carlo simulation iterations (CIN; Morgan and Henrion, 1990; Ellis et al., 2000).

8.5 NITROGEN FLOWS AND POOLS

Figure 8.3 shows the mean and CIN (5%, 95%) of nitrogen flows and Δ plant/soil pools of the ecosystems analyzed (kg N/ha/yr). This figure shows distinctive differences in nitrogen flows across the ecosystems.

In California*, the conventional system (in which controlled release fertilizers were applied and the soil fumigated) was highly efficient in nitrogen use:

* In the third year of the California strawberry experiment, we used the strawberry plants planted in the second year. Thus, no seedlings were brought into the systems. At the end of the third year, all plants were incorporated into the soil in both the organic and conventional systems. Hence, Δ plant pool was negative regardless of management practice in the California experiment.

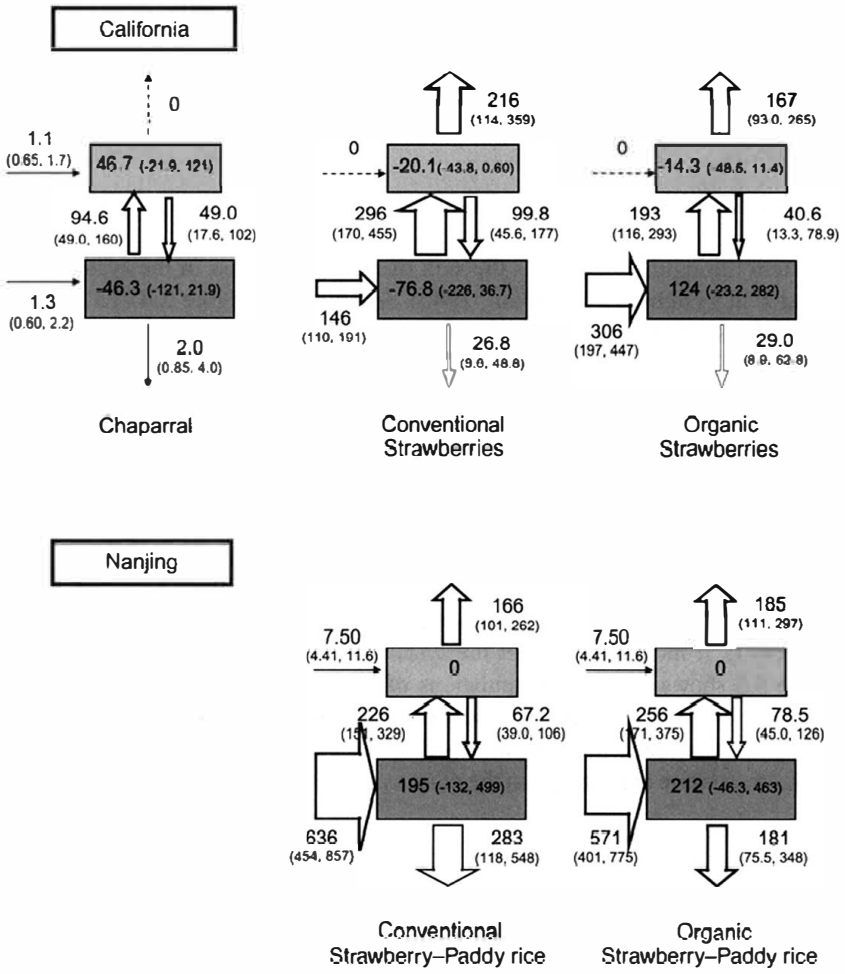

Figure 8.3 Mean and CIN (5%, 95%) of nitrogen flows and Δ pools (kg N/ha/yr) in natural and agricultural ecosystems in California and in Nanjing.

inputs were lower than those of the organic plot (about half), the harvest was higher (28% higher than the organic plot), more N was returned to the soil, and N losses were slightly lower. However the mean Δ soil pool in the conventional system was negative, suggesting that soil nitrogen was mined from the soil by the plants.

Compared to the California strawberry systems, the strawberry–paddy rice system in Nanjing had greater soil input (~600 kg N/ha/yr) and higher N losses (180 to 280 kg N/ha/yr as means). Most of the N loss is believed to have occurred during the paddy rice period in gaseous form.

The natural chaparral ecosystem had very small inflows and outflows to the environment. Importantly, there was no removal of N in the form of harvest.

8.6 INDICATORS OF NUTRIENT CYCLING

To describe and compare nutrient cycling status across the ecosystems, we calculated three system level indicators: total system throughflow (TST), net accumulation, and the Cycling Index (CI), according to Finn (1978, 1982).

8.6.1 Total System Throughflow

Total system throughflow (TST) is the sum of all throughflows in the system and is an indicator of system activity (Finn, 1980). As shown in Figure 8.4, TST was the highest in the strawberry-paddy rice system in China due mainly to its large soil input (~600 kg N/ha/yr). Both types of strawberry fields in California had TSTs that were about two thirds those of the fields in China. Chaparral, a natural ecosystem in California, had the lowest TST. Differences in TST between practices at the same locale were relatively small.

8.6.2 Net Accumulation

Net accumulation, derived by subtracting the sum of the outputs from the sum of the inputs, is a modified version of the output/input ratio (Finn, 1982; Vitousek and Reiners, 1975). It indicates whether the system is a net loser or a net accumulator.

Figure 8.5 shows the net accumulations of N in the five systems. The mean net accumulation in chaparral was ~0. In contrast, mean net accumulations in the agroecosystems differed widely, from negative (–97 in the conventional strawberry system in California) to positive (110 to 220 in the other systems). The negative net accumulation

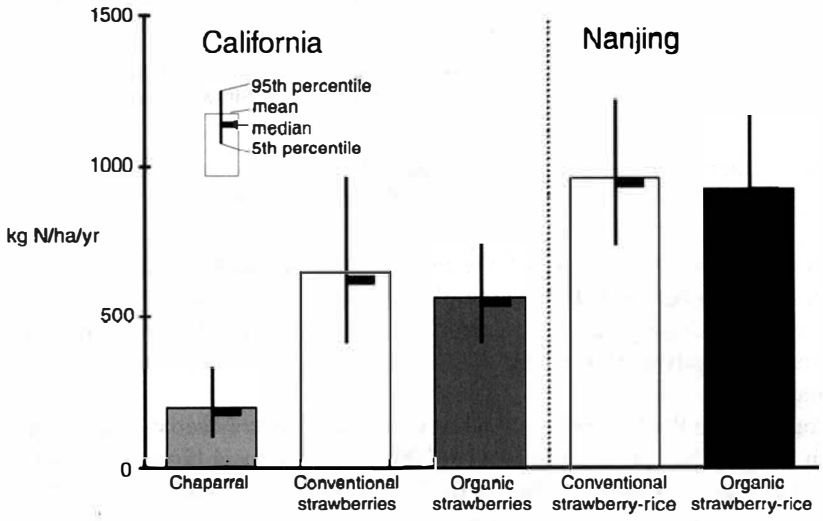

Figure 8.4 Total system throughflow (TST) of nitrogen in natural and agricultural ecosystems in California and in Nanjing.

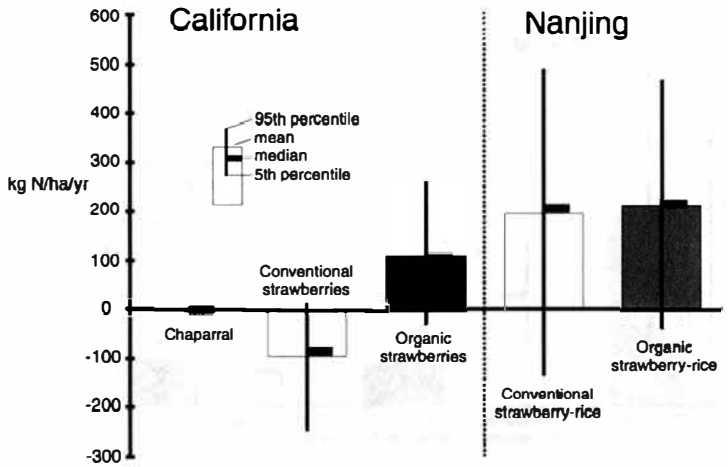

Figure 8.5 Net accumulations of nitrogen in natural and agricultural ecosystems in California, and in Nanjing.

in the conventional strawberry system in California indicates that nitrogen was mined from the soil. This might have resulted from the enhancement of soil nitrogen mineralization (Rovira, 1976) and of root development due to root disease control (Yuen, et al., 1991) brought about by the soil fumigation. These net accumulation values are very uncertain. For example, Monte Carlo simulations yield a 7 to 13% probability that the net accumulations of the California organic and Chinese agroecosystems are actually negative. Moreover, there is a ~13% probability that net accumulation in the California conventional strawberry system is positive and a ~8% probability that this accumulation is actually greater than that of the Chinese conventional system. Clearly, the calculation of soil and ecosystem nutrient balances by subtracting outputs from inputs is an uncertain endeavor that can yield misleading results.

8.6.3 Cycling Index

The Cycling Index (CI) is a measure of the amount of material cycled relative to the total amount moving within and through the system. It varies from 0 (no cycling) to 1 (all material is cycled).

As shown in Figure 8.6, the highest mean CI (0.49) was recorded for California chaparral. Among the agroecosystems, the highest CI (0.29) belongs to the California conventional system, in which greater quantities of plant residues were returned to the soil compared to the organic system (CI = 0.11). Mean CIs in the Chinese organic and the Chinese conventional strawberry-paddy rice systems were 0.12 and 0.09, respectively. The higher the mean CI, the greater the uncertainty of the CI.

To examine the relationship between the amount of plant residue returned to the systems and CI, we conducted three scenario analyses (Table 8.4). In scenario A,

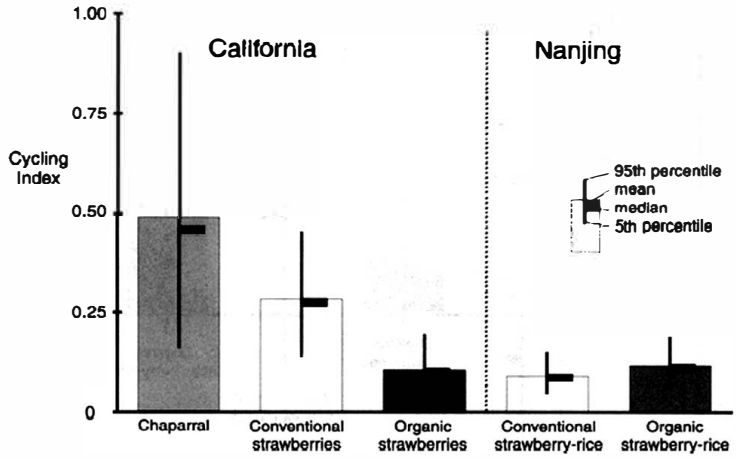

Figure 8.6 The Cycling Index (CI) for nitrogen in natural and agricultural ecosystems in California and Nanjing.

no residue is returned. In scenario B, crop residues are returned (California: strawberry residues, except prunings; Nanjing: strawberry residues plus rice roots). In scenario C, both crop residues and weeds are returned (California: scenario B plus weeds; Nanjing: scenario B plus rice straw plus weeds). Regardless of practice and site, CI is zero when no plant residues are returned to the system. When plant residues are returned, CI increases with the amount of biomass returned, although the maximum (0.31, for California conventional under scenario C) is still short of the CI for the chaparral ecosystem (0.49).

8.7 NUTRIENT CYCLING IN AGROECOSYSTEMS VS. NATURAL ECOSYSTEMS

Our flow analyses indicate that regardless of site and management practice, agroecosystems tend to have high TSTs, a wide range of net accumulation, low CIs, and

Table 8.4 Cycling Index Values for Three Scenarios of Plant Residue Return

		Scenario A (no return)	Scenario B (crop residue)	Scenario C (crop residue + weeds)
USA[a]	Conventional	0.00	0.29	0.31
	Organic	0.00	0.11	0.14
China[b]	Conventional	0.00	0.09	0.14
	Organic	0.00	0.12	0.16

[a] For California, Scenario A: No residue return. Scenario B: Strawberry residue return (except pruning). Scenario C: Scenario B plus weeds return.
[b] For Nanjing, Scenario A: No residue return. Scenario B: Strawberry residue plus rice roots return. Scenario C: Scenario B plus rice straw plus weeds return.

Table 8.5 Summary of Nutrient Cycling Status for Natural and Agricultural Ecosystems

	Agroecosystem	Natural Ecosystem
TST	High	Low
Net accumulation	Negative to High	~ 0
Cycling Index	Low	High
Harvest removal	High	None

high removal through harvest. These values contrast with those of the natural system we analyzed, which has a low TST, approximately zero net accumulation, a high CI, and no harvest. These generalizations, summarized in Table 8.5, agree well with the observation that net accumulation in an long undisturbed ecosystem tends to be close to zero (Vitousek and Reiners, 1975; Finn, 1982).

Although further investigation is required, some important points regarding the Cycling Index can be drawn from this analysis. Although a higher CI may be correlated with greater sustainability, there are clear limits to how far CI can be increased without affecting harvests. A CI approaching that of a natural ecosystem is not desirable, since it would be achieved at the cost of reducing harvests to zero. Practically speaking, there are many constraints to increasing the CI of agroecosystems. Although CI tends to increase when the amount of plant residue returned to the soil is increased (Table 8.4), achieving an increased return contrasts sharply with the general direction of crop breeding, which aims to increase the harvest indices (edible biomass/above ground biomass) of crops (e.g., Loomis and Connor, 1992).

8.8 FUTURE STUDIES

Some important questions about nutrient cycling need to be answered by future research: How far we can increase CI without decreasing harvest? What are effective techniques for increasing CI? We need quantitative studies on the relationship between CI and other indices such as crop harvest, nitrogen use efficiency, and nutrient balance. Jarrell (1990) states that, "Efforts should be made to close the N cycle as nearly as possible and to introduce N into the farm in the most efficient manner for long-term production." To accomplish this goal, we need to apply field-scale CI and N-use efficiency as indicators.

Future research should:

- Further test the two-pool model by (1) analyzing the cycling of other elements, (2) applying the model to different farming systems (e.g., inter-cropping systems, cover cropping systems, and agroforestry systems), and (3) applying it to different management practices.
- Base nutrient cycling analyses on time scales rather than annual increments (e.g., monthly).
- Develop an indicator for cycling rate because CI says nothing about the rate of nutrient cycling (Finn, 1978).
- Measure the Δ soil pool directly by comparing soil nutrient content two or more times, and examine the effect of this method on the indicators.

8.9 CONCLUSIONS

Flow analysis based on a standardized two pool soil-plant model is a simple and useful method for quantitative comparisons of nutrient cycling across natural ecosystems and agroecosystems. Indicators, including total system throughflow (for system activity), net accumulation (for nutrient balance), and the Cycling Index (for nutrient cycling), can be used to compare different aspects of nutrient cycling in ecosystems. When used with observational uncertainty analysis, these indicators can be compared in a statistically reliable way. The two-pool model is too simplistic to evaluate agroecosystem nutrient cycling at scales larger than that of a field.

The Cycling Index may be a valuable indicator of the ecological sustainability of agroecosystems at the field scale. Comparisons between agroecosystems and a natural ecosystem suggest that a contradiction exists between the degree of nutrient cycling (as measured by the Cycling Index) and crop yield.

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