

Comparison of Nutrient Return and Plant Uptake in Agricultural Systems  
by Martin H. Bender

**ABSTRACT.** Application of the principle of mass balance shows that nutrient return does not have a simple algebraic relationship with plant uptake. Due to plant uptake exceeding nutrient return, the total soil pool usually experienced nutrient deficits in various extensive systems. Uptake also exceeded return in intensive systems, but import of nutrients offset this so that total soil pools usually had nutrient gains. Per-hectare return of human excreta was considerable in one Asian system but not in another due to the large export of products in the latter. Failure to return human excreta would have resulted in practiced nutrient sources (return plus import) being not much greater than plant uptake, leading to deficits in the total soil pool if natural losses exceeded natural imports by a small amount. The accuracy of data from one of the Asian systems was confirmed by its fit to the equation relating plant uptake and nutrient return.

## Introduction

Maintenance of agricultural productivity requires sustained soil fertility by import or return of nutrients. While intensive farming systems obtain nutrients through purchased fertilizers and/or supplemental feed, extensive systems import little or no nutrients and rely mainly on natural sources and return of manure and plant residues. Examples of the latter system include the self-sustaining mixed livestock farms in Europe, shifting agriculture in the tropics and the paddy soil-homegarden system in south-east Asia (Frissel 1978b). In some cases, extensive systems involve gradual, long-term depletion of soil nutrients, termed the "deficit approach" (USDA 1980). Hence, it is crucial to pay attention to nutrient budgets in extensive farming systems.

The nutrient budget of a farm can be examined by calculating the change in each nutrient pool on the farm by subtracting the supplies of that nutrient from the removals (Meisinger 1984, Hauck and Tanji 1982). For each pool, the supplies are inputs and transfers from other pools, while removals are outputs and transfers to other pools. The transfers are important in extensive agricultural systems because they represent nutrient return or cycling within the farm that supply a substantial portion of the plant uptake of nutrients. For this reason, this study examines some algebraic relationships between nutrient return and plant uptake with examples from the review of 65 agroecosystems edited by Frissel (1978a). In traditional Asian peasant agriculture, considerable effort was spent to include human excreta in the nutrient return. Hence, two examples by King (1911) and Dazhong and Pimentel (1984) are included in this study to quantify the relative importance of human excreta in the nutrient return of agricultural systems.

## Concepts

This study utilizes the format described by Frissel (1978c) for the nutrient balances of the plant, animal and total soil pools, including his system and plant boundaries ([Table 1](#)). The boundaries are those of an individual farm including plants and soils (both down to the bottom of the rooting zone) plus animals but not humans. Hence, farm products used by the farm family are exports from the farm. In the two regional examples of Asian agriculture, the plant boundary includes

only the aboveground parts, and the system boundaries include humans that reside within the border of the defined region, at which exports are counted.

In the format described by Frissel (1978c), the return for a farm is the sum of nutrient in applied manure, livestock droppings on pasture or grazed crops, retained plant residues and seeds kept for sowing. Applied manure refers to the amount at the time of application to the soil. Hence, return includes that which remains after subtraction of losses from manure prior to application, as might occur in animal stalls or compost piles. Such losses are charged to the animal component of the farm ([Table 1](#)). Losses from uncollected droppings on the soil and from manure after application are counted as losses from the total soil pool.

Because the boundaries of the two Asian agroecosystems include humans, return would also include human excreta and ashes from crop residues collected for fuel. In contrast, for the systems reviewed by Frissel, these two nutrient sources would be imports for the farms, and residues collected for fuel would be exported products, even if done by the farm family since people are not within the system boundary. This difference between the two formats will not affect comparison of the Asian systems with those from Frissel. This is because none of the examples from the review by Frissel (1978a) included human excreta or ashes. Frissel's format could have been modified in this study to include humans within the system boundaries, but it was retained for consistency with his accounting.

Per-hectare plant uptake for the farm is the weighted average of per-hectare uptake in arable land and pasture on the farm. That is, it is the sum of the uptakes, each weighted by its respective proportion of the total acreage of the farm. Various authorities in the review edited by Frissel (1978a) usually reported plant uptake for whole plants, but a few gave data only for the aboveground portion (e.g., [Table 2](#), footnote d). Also, in the former case, plant residue referred to roots and stubble, while in the latter, it was stubble only. Nonetheless, in the latter case, root biomass could be assumed to be returned to the soil without affecting the relationships examined in this study between plant uptake and nutrient return.

## Equations

By the principle of mass balance, the basic nutrient budget of an agroecosystem is

(1) import - exported products - losses = total net pool change where total net pool change is the sum of the net changes in the plant, animal and total soil pools ([Table 1](#)). The nutrients returned on a farm are quantified by

(2) return = droppings + applied manure + retained plant residues + seeds kept for sowing. The algebraic relationship between plant uptake and nutrient return is derived by first applying the principle of mass balance to the nutrient flows in the plant and animal components ([Table 1](#)) to respectively yield with some rearrangement:

(3) plant uptake = net change in plant pool + consumption of crops + grazed forage + retained residues + kept seeds + exported crops - imported seed.

(4) consumption of crops + grazed forage = exported animal products - imported feed + manure losses before application + applied manure + droppings + net change in animal pool. Summation of the respective sides of Eqs. 3 and 4, cancellation of terms, and incorporation of Eq. 2 gives the desired relationship:

(5) plant uptake = return + exported products + net changes in the plant and animal pools + manure losses before application - imported feed, bedding and seed.

The format of Frissel (1978c) in [Table 1](#) is a generally adopted convention for nutrient balances, so the complex form of Eq. 5 is not due to Frissel's format containing some unusual accounting or boundary. Eq. 5 is easily verified by inserting data from any of the systems reviewed by Frissel (1978a), but in a few systems some data must first be corrected for simple arithmetic error by the reporting authorities (e.g., Newbould-2 N, Kolek-1 P, Kolek-2 N and K, and perhaps other systems). In regard to the two Asian agroecosystems, if humans had been included within the animal component, then by Frissel's format the right-hand side of Eq. 5 would include two more positive terms: nutrient losses from human excreta before application to cropland, and losses from crop residues burned for cooking and heating prior to return of ashes to cropland.

For the extensive systems in [Table 2](#), the sum of the last three terms on the right-hand side of Eq. 5 was zero or nearly so. In the case of the extensive systems containing livestock, the zero values were partly due to authorities not measuring nutrient losses from manure that occurred prior to application. In contrast, intensive systems containing livestock usually had considerable negative values for this sum, due mostly to large amounts of imported feed ([Table 3](#)).

## Comparison of extensive and intensive systems

Examples of the relationship between nutrient return and plant uptake were chosen from the review by Frissel (1978a) for nitrogen (N), phosphorus (P) and potassium (K) in three types of extensive and intensive agricultural systems: livestock, arable, and mixed arable and livestock (Tables 2 and 3). The study by Patriquin (1986) was included to provide an example of an intensive livestock system, a gap in the systems available to Frissel.

The extensive systems generally showed deficits or little gain for the total net pool change (Eq. 1) except for N in the Newbould-2 and Henkens-1 systems where symbiotic N fixation helped make imports sufficiently greater than exports ([Table 2](#)). This was due to plant uptake exceeding nutrient return, in combination with little input of nutrients, thus resulting in a deficit for the total soil pool. In contrast, the intensive systems generally had nutrient gains in the in the total net pool change with a large deficit only for the Kolek-1 N system due to large losses by denitrification and leaching ([Table 3](#)). While plant uptake also exceeded nutrient return in intensive systems, import of nutrients was large enough to meet the excess demand plus provide some nutrient gain for the total soil pool.

Nutrient return was slightly greater or nearly equal to plant uptake in the extensive Newbould-2 N, P and K systems and in the intensive Patriquin N system (Tables 2 and 3). The results in both systems were due to imported feed offsetting the small amount of exported products. The sufficiency of N through biological nitrogen fixation resulted in relatively large deficits of P and

K in the three extensive systems containing livestock with relatively large marketed export, namely the Henkens-1, Jacquard-1 and Husz-4 systems ([Table 2](#)). Practiced nutrient sources (sum of return and import), which were also calculated for the two Asian systems below, were less than the respective plant uptake for P and K only in these three systems and not the others (Tables 2 and 3).

## Two Asian systems

Two studies have documented the nutrient sources in traditional peasant Asian agriculture that included return of human excreta. As Chief of the Division of Soil Management in the U.S. Department of Agriculture, F.H. King visited China, Korea and Japan in 1911 to learn how Asian farmers maintained soil fertility despite high population densities (Parr and Hornick 1993). While much of King's book is anecdotal, Japanese researchers provided him with data on the return and import of organic materials, such as human wastes, wood ashes, wild vegetation, and composted animal manures, straw and sediment. In the other study, Dazhong and Pimentel (1984) examined unpublished agricultural statistics from 1952-54 collected by the Hailun Statistics Bureau for that county in northeastern China. Located on an important agricultural soil, the dominant practice in the county at that time was organic farming. The major energy inputs were labor and horse power, and the only fossil fuel energy inputs were for simple steel hand tools and draft implements. The data for the two traditional Asian systems is not as complete as the format in Tables 2 and 3. No nutrient data was reported for exported products, natural imports and losses, or for changes in plant, animal and soil pools. Pasture production was not included in plant uptake in either Asian system. Moreover, King (1911) did not report crop uptake on a national basis, but he did include per-hectare nutrient uptake for various crops from which I estimated a crude average for Japan. Nonetheless, some informative comparisons can be made.

The largest source of N in the Japanese system was compost, and in the Hailun county system, symbiotic N fixation ([Table 4](#)). Compost and ashes were the two dominant sources for P and K in both systems, except that commercial fertilizers and human excreta each contributed slightly more P in Japan than ashes did.

Per-hectare symbiotic N fixation through legumes was three times greater in the Hailun county system than in the Japanese one ([Table 4](#)). Symbiotic N fixation through the water fern, azolla, is not included in the practiced nutrient sources because it was not grown in Japan or Hailun county during the time periods of the respective studies. Azolla was grown as a green manure in rice paddies in some traditional Asian systems to provide nitrogen by symbiotic fixation due to the blue-green algae living on the azolla. However, prior to the 1970s, azolla was grown only in southern China and Vietnam and only in 10 percent or less of the harvested rice area in those two countries (Lumpkin and Plucknett 1982). Hence, azolla was not grown in Japan or Hailun county (northeastern China), and any azolla in rice paddies would have been wild. Since the 1970s, research has been conducted on azolla, including more cold tolerant, wild species in that genus, to introduce it into the agricultural systems of other countries. So, its geographic distribution of agricultural use may have increased during the past several decades. Azolla typically fixes at least 30 kg N/ha (27 lbs/ac) when intercropped with rice (Venkataraman 1978, Watanabe 1978, Talley and Rains 1980). This would be a substantial contribution of N averaged over the entire

Japanese system, considering that wetland rice constituted 60 percent of Japan's cultivated land, at least at the turn of the century (King 1911, pp. 271-272).

The per-hectare nutrients provided by practiced nutrient sources in Japan was roughly one-and-a-half times those for Hailun county ([Table 4](#)). One reason is that in terms of per-hectare nutrients, Japan returned almost six times as much human excreta and twice as much compost as Hailun county, but about the same amount of ashes. This is because Hailun county exported 45 percent of the biomass of its harvested crops, surely far more than the national percentage for Japan (Dazhong and Pimentel 1984). This large export left a smaller proportion of nutrients to be returned in Hailun county than in Japan. Another reason is that Hailun county did not utilize commercial fertilizers, wild vegetation (collected as green manure) or dredged sediment, for which the per-hectare total in Japan was roughly 36 kg N, 7 kg P and 14 kg K ([Table 4](#)). In Japan, commercial fertilizers supplied not quite as much nutrients as the return of human excreta, and wild vegetation, about half as much. Comparison of the per-hectare nutrient content in the composts of both systems suggests that half of the compost in Japan consisted of sediments dredged from canals and ditches. This means that dredged sediment roughly contributed as much nutrients as commercial fertilizers, or as much as human excreta.

The sum of practiced nutrient sources (return and import) exceeded plant uptake more so in the Japanese system than in the Hailun county system ([Table 4](#)). This is partly due to the above reasons for the greater amount of sources in Japan. The large export from Hailun county resulted in practiced sources being less than uptake for P and also for N and K if natural losses exceeded natural imports by a few kg/ha for the latter two nutrients. Another reason for the larger difference in the Japanese system is the possibility that my crude estimate of the crop uptake for Japan might be too small. That is, I assumed the national average nutrient uptake to be equal to that reported by King (1911) for wetland rice, grown on 60 percent of Japan's cultivated land ([Table 4](#), footnote j). Dryland yields on the remaining cropland would have been lower than this, but if they were more than offset by double cropping on some wetland and dryland, then my estimate would be too low.

The return of human excreta was negligible for Hailun county, but considerable for Japan ([Table 4](#)). Without return of human excreta, the sum of the remaining practiced nutrient sources would not have been much greater than respective plant uptake for N and K in both systems and would have been inadequate for P uptake in Hailun county, the latter already noted above. If natural losses exceeded natural imports by a few kg/ha, then there would have been nutrient deficits in the total soil pool in both systems.

Natural losses and imports were not measured for either system, except per-hectare denitrification and atmospheric N deposition were crudely estimated by Dazhong and Pimentel (1984) from the review data of Frissel (1978a) as 15 kg N loss and 10 kg N gain, respectively, for the Hailun county system. They also explicitly stated for Hailun county that the removal of crop residues for composting, cooking fuel, and animal feed exposed the soil to some erosion and runoff loss. In the Japanese system, runoff was generally accumulated in rice paddies from hillsides, not lost from paddies ([Table 4](#), footnote i). The greater amounts of practiced nutrient sources in the Japanese system gave it more latitude to withstand natural losses than the Hailun county system.

While nutrient return and import were not explicitly designated in the two studies, each reported nutrient source can be assigned wholly to one of the flows with minimal error ([Table 4](#), footnotes g-h). That is, as shown by calculations, return consisted of human excreta, compost, ashes and seed, while import was through N fixation, wild vegetation and commercial fertilizers. The moderate amount of symbiotic N fixation in the two Asian systems resulted in plant uptake and returns like those in the extensive systems with moderate amounts of N fixation, namely the Newbould-2 and Husz-4 systems ([Tables 2 and 4](#)). Return exceeded import in both Asian systems as one might expect for extensive systems, but was reversed for N in Hailun county mostly due to the large import through symbiotic N fixation ([Table 2](#)).

The accuracy of the data reported for Hailun county by Dazhong and Pimentel (1984) can be judged by substituting values into Eq. 5 and solving for the term, net change in the plant and animal pools. Plant uptake was reported by Dazhong and Pimentel (but see [Table 4](#), footnote j), and return has been calculated above. Since Hailun county was reported to be self-sufficient in animal feed and seed like the extensive systems in [Table 2](#) (Dazhong and Pimentel 1984), the nutrient values for import of feed, bedding and seed are assumed to be zero. Based on Dazhong and Pimentel's assumption that half the human and animal manure was lost before application (verified by independent calculation in [Table 4](#), footnote a), the per-hectare pre-application manure loss was 11 kg N, 4 kg P and 8 kg K. They reported a total export of 45 percent of all crops but not the individual crop exports. So, based on the assumption that 45 percent of each crop was exported, extensive calculations similar to those for P in footnote j of [Table 4](#) give a per-hectare export of 15 kg N, 6 kg P and 5 kg K. The combustion of 1.2 t/ha of crop residues for heating and cooking presumably resulted in negligible P and K losses from the ashes before return to cropland. However, with the N content of 0.75 percent reported by Dazhong and Pimentel (1984) for crop residues, 9 kg N/ha were lost from the residues during combustion.

Taking into account that humans are within the animal component in the two Asian systems (see Equations section), substitution of these values into Eq. 5 for each nutrient gives the following per-hectare values for the net change in plant and animal pools: -4 kg N, -3 kg P and -16 kg K. Dazhong and Pimentel (1984) did not report any changes in the two pools during 1952-1954, so presumably these values were zero. Considering the possible range of error in the data and estimates, the values for N and P are near zero, but the value for K does not appear to be so. A value of K near zero would require either smaller values for return, manure losses, and/or exported products, and/or a larger value for plant uptake in Eq. 5. Examination of these terms suggests that plant uptake could be the main cause of the large value for K. However, the K contents reported by Dazhong and Pimentel (1984) for products and for residues of crops in Hailun county were corroborated by my extensive calculations and by comparison with contents reported by Morrison (1950). Moreover, calculations show the biomass ratio of residues to products for all crops in Hailun county to be 1.1, which is within the range of ratios reported by Strehler and Stutzle (1987) for various cereal, pulse and root crops. Also, the inclusion of roots in plant uptake would be canceled by the identical increase in return of roots to the soil so that the value of K for the plant and animal pools would not be affected. In summary, given the lack of possible cause for the large value of K, it may be that it is within the range of error for a zero value, as with N and P.

## Conclusions

Application of the principle of mass balance showed that nutrient return and plant uptake do not have a simple algebraic relationship. In extensive and intensive systems, nutrient return was shown to be insufficient to prevent nutrient deficit in the total soil pool, except that the latter was converted into a gain in intensive systems by large nutrient imports. This confirmed the label of "deficit approach" for extensive farming (USDA 1980).

The nutrient return and plant uptake in the two traditional Asian systems, which had moderate amounts of biological N fixation, resembled the respective ones in the Newbould-2 and Husz-4 extensive livestock systems that had similar amounts of fixation as well. However, the relationship between practiced nutrient sources (return plus import) and plant uptake for Hailun county was similar to that for the Henkens-1, Jacquard-1 and Husz-4 extensive livestock systems containing relatively large amounts of exported products. That is, the export of 45 percent of harvested crop biomass out of Hailun county led to practiced sources being less than uptake for P and also for N and K if natural losses exceeded natural imports by a few kg/ha for the latter two nutrients.

Per-hectare return of human excreta was considerable in Japan but was negligible in Hailun county due to its large export of products. Failure to return human excreta would have resulted in practiced sources being not much greater than plant uptake, including the above deficit for P for Hailun county. If natural losses exceeded natural imports by a few kg/ha, then the other nutrients would also have been in deficit in the two Asian systems.

The equation relating nutrient return and plant uptake can be used as a diagnostic tool to confirm the accuracy of data reported for nutrient flows. For example, the data reported for Hailun county appeared to fit Eq. 5 within the range of error expected for data and estimates with the possible exception of K.

In summary, due to the nutrient deficits often encountered in extensive agricultural systems, nutrient losses must be minimized to increase return, and reduce depletion of the soil nutrient pool. These practices will help maintain soil fertility and agricultural productivity.

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