Fertilizer Research **42**: 277–296, 1995.

Managing nitrogen for sustainable crop production

C.A. Campbell[1], R.J.K. Myers[2] & D. Curtin[1]
[1]*Agriculture and Agri-Food Canada, Research Station, P.O. Box 1030, Swift Current, Saskatchewan, S9H 3X2, Canada and* [2]*IBSRAM, P.O. Box 9–109, Bangkken, Bangkok, Thailand*

Key words: nutrient cycling, socioeconomic constraints, sustainable agriculture, temperate/boreal ecosystems, tropical ecosystem

Abstract

This paper discusses the influence of N resources (fertilizer, legume, soil) on sustainable agriculture in temperate/boreal ecosystems (exemplified by the Canadian prairies), and in the humid, subhumid and semi-arid tropic (exemplified by southeast Asia and central and south America). A sustainable agricultural system is one that is economically viable, provides safe, nutritious food, and. conserves or enhances the environment. Consequently, we discuss the impact of N on crop yields, nitrogen use efficiency (NUE), food quality, environmental quality and on socioeconomic factors. Considerably more long-term research has been conducted in the temperate regions, consequently this was where most information was available. However, the principles governing the behaviour of N are very similar in all ecosystems. It is mainly the rates of nutrient cycling and the socioeconomic constraints that differ. Legumes and N fertilizers, used in a responsible manner, will increase crop production, provide quality food, increase net returns, reduce risk of monetary loss, improve soil quality, and reduce N loss via leaching and gaseous means. The key to sustainable management of N is to synchronize N supply with N use by the crop. Because societies in most temperate ecosystems are more affluent they are better positioned to encourage adoption of management techniques that promote sustainability. In contrast, most producers in the tropics are, subsistence farmers; consequently, their immediate goal is economic survival, not preservation of the environment.

Introduction

Sustainable land management, sustainable agriculture and sustainable cropping systems all command considerable attention in all developed and in many developing countries. Here we discuss a microcosm of this large problem, namely, how N (sometimes in combination with P) influences sustainable crop management, concentrating on the general principles applicable to most ecosystems. We present this information in two parts: (a) agroecosystems in developed countries in temperate/boreal climates where large commercialized production predominates [e.g. Canada, USA, Europe and most of the Organization of Economic Cooperation and Development (OECD) member states], and (b) developing countries, mainly located in humid, sub-humid, and semi-arid. tropics and subtropics, where agriculture is predominantly conducted on small, subsistence-type farming systems (e.g. Africa, Southeast Asia, South America, Caribbean). We use the Canadian prairies for (a), and primarily Southeast Asia for (b).

Temperate/boreal ecosystems with large commercialized production systems - the Canadian prairies

Background

Only 7% (67 million ha) of Canada's land area is arable while another 6% is suitable for grazing [12]. Of the arable land, 79% (53 million ha) is located in the three prairie provinces of Alberta, Saskatchewan, and Manitoba (Fig. 1). Long, cold winters; short, hot summers; low, variable precipitation; characterize the climate

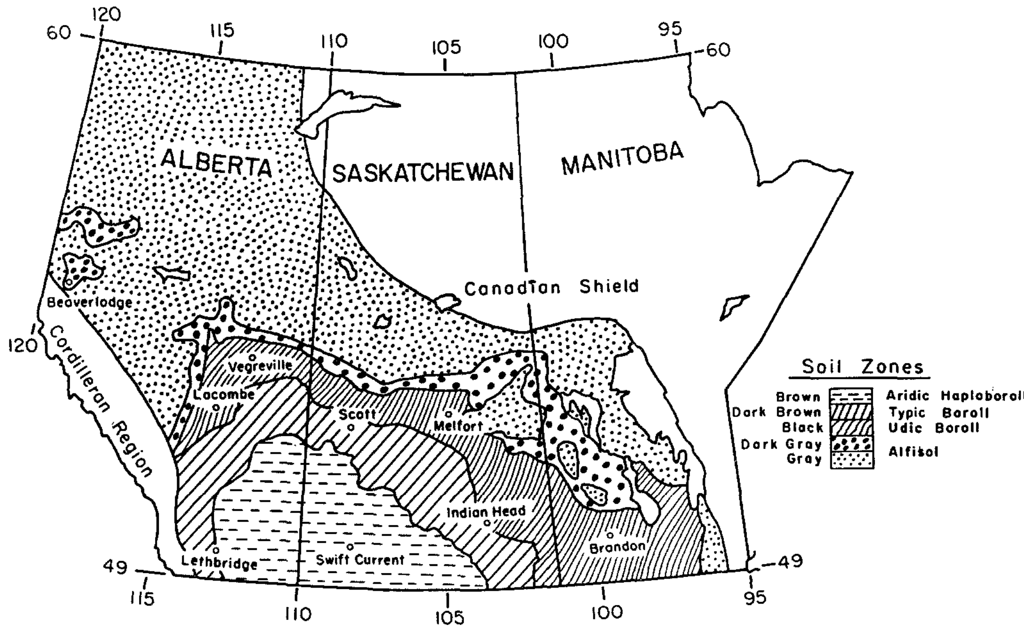

Fig. 1. Prairie Provinces of Canada, showing major soil zones.

and dictate cropping practices. Prairie soils are young and inherently fertile. Thus, crops mainly require N and P fertilizer, in limited cases S, but rarely K. Farms are large (most exceed 4.5 km^2) and highly mechanized to allow timely operations in the 4-month growing season (May–September). Cereals [mainly hard red spring wheat (*Triticum aestivum* L.)) predominate, but mixed farming (grain and livestock) is common on the more humid Gray and Dark Gray Luvisolic soil zones (Alfisols) in the northerly areas, while oilseeds and pulses are significant components of crop rotations on Black Chernozems (Udic Borolls). Monoculture wheat with varying degree of summerfallow (land left bare to conserve water, control weeds, or reduce incidence of disease) predominates in the more arid southern areas where Brown and Dark Brown Chernozems (Aridic and Typic Borolls) predominate. Summerfallow is significant even in the more humid areas. Low precipitation causes low yields (most < 3.5 t ha^{-1} and many only 1.75 t ha^{-1}) requiring low fertilizer inputs. Severe climate helps to control some pests, thereby reducing pesticide requirements. Irrigation is not common except in Alberta where just over 0.4 million ha of land is irrigated. Cereals occupy 50% and hay occupies 25% of the irrigated land [12].

Sustainable agriculture production - The problem

According to Agriculture and Agri-Food Canada, Sustainable Agriculture refers to "agrifood systems that are economically viable, provide safe nutritious food, and allows conservation or enhancement of soil, air and water." On the Canadian prairies, low fertilizer and pesticide use plus low precipitation minimize concerns for air and water pollution. However, soil degradation (soil organic matter loss, salinization, erosion) and especially economics, are major concerns.

The native grassland soils of the prairies were very stable but, when cultivated, lower plant biomass inputs, higher rates of organic matter decomposition, and susceptibility to erosion, made loss of organic matter and fertility inevitable. Furthermore, frequent summerfallowing to conserve water and reduce risk of crop failure hastened soil degradation and increased salinity. Thus, use of improper summerfallow techniques resulted in severe erosion in the dry, windy 1930s ('Dirty Thirties'). Since then, research has led to implementation of several conservation techniques (e.g. stubble mulch tillage, strip cropping, contour farming, use of tree shelterbelts, grass waterways, use of proper crop rotations) and these have helped to abate the problem. However, prairie soils which seldom required N fertilizer in the 1940s and 1950s, now often require this nutrient even after a year of summerfallow because the inherent fertility of the soil has been substantially depleted [66],

Despite the obvious positive contributions of fertilizers in maintaining food production (and as shown later, maintaining soil quality), 75% of Canadians surveyed in 1989 said that they were concerned about fertilizer use [12]. Thus, there is an urgent need to critically assess the true impact of fertilizers (in this case N) on the components of sustainable production systems.

Impact of N on yields and economics

Many studies have been conducted on the Canadian prairies that examine the influence of fertilizers on yield, nutritional quality and economics. Most of these studies were summarized in two recent reviews [23, 66]; thus, only a few pertinent highlights will be discussed in this paper. Studies typically show positive yield responses of all crops to N in all soil zones if moisture is non-limiting and if available N is not already over-abundant [66].

Nitrogen use efficiency

Sustainable crop production requires improved nitrogen use efficiency (NUE). Many factors influence NUE, with perhaps the main factor, weather, being unpredictable. However, historical weather records allow us to estimate the probabilities of obtaining average, or above- or below- average weather conditions, and we can use these to guide our management decisions. In the semiarid climate of southwestern Saskatchewan, yield, and therefore NUE response to N, was shown to be directly influenced by available water (Fig. 2). In this 9 year continuous no-till spring wheat study, the N-supplying capacity of the soil was improved by the combined effect of fertilizing, increasing cropping frequency, and reducing tillage, so that NUE was directly related to soil available N, but it was inversely related to rate of fertilizer N [27]. Factors that will affect NUE are placement of N (banding superior to broadcasting), timing of application (spring application near seeding time superior to fall application), and N source (ammonium nitrate generally superior to urea which may volatilize easily) [27,75]. But, with all these options, the farmer is required to balance the improved NUE against the extra cost (e.g., for banding > broadcasting; ammonium nitrate more costly than urea; fertilizer cheaper when bought in fall than in

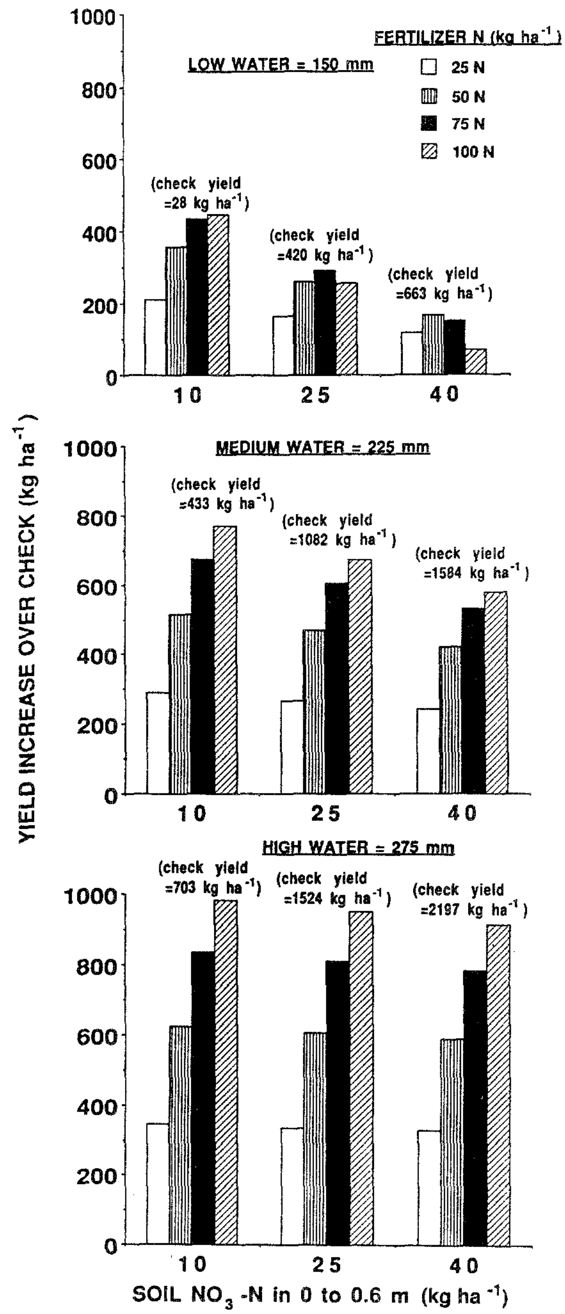

Fig. 2. Yield increase over zero N yields of spring wheat as estimated for some soil water, soil and fertilizer N situations in a 9-year no-till continuous wheat experiment conducted on a Brown Chernozem at Swift Current, Saskatchewan [27].

spring), and they must consider the convenience in terms of distribution of labour [85].

Long-term yield trends

A crop rotation study on a thin Black Chernozem at Indian Head, Saskatchewan [16], demonstrates how fertilizers may influence long-term yield trends. Treatments compared were stubble-crop wheat in fertilized (N and P) and unfertilized fallow-wheat-wheat and continuous wheat systems, and unfertilized sweetclover (*Melilotus officinalis* L.) green manure-wheat-wheat and fallow-wheat-wheat-hay-hay-hay systems. Hay was a mixture of alfalfa (*Medicago sativa* L.) and bromegrass (*Bromus inermis* Leyss). In the first 20 years of this study (1958–1977), N and P fertilizers were low because they were applied based on general recommendations for the crop and soil, but from 1978 a soil test was used as the criterion for fertilizer requirements and the N rates were tripled (on average) compared to rates in the first 20 years.

The benefit of N and P fertilizer in improving yields was readily apparent from the beginning of this study and, after the N rate was increased in 1978, the yield response to fertilizer was even more apparent (Fig. 3). The average rate of increase in yield of fertilized monoculture wheat grown on stubble was 30–33 kg ha^{-1} yr^{-1} (Table 1). The widening difference between fertilized and unfertilized systems over time was partly due to the higher rates of N applied after 1977, and partly because yields on the unfertilized plots had gradually declined, reflecting a decline in fertility of the soil (Table 1).

The rate of decline in yields of the unfertilized treatments was much greater in the fallow-wheat-wheat system (-28 kg ha^{-1} yr^{-1}) than in continuous wheat (-11 kg ha^{-1} yr^{-1}), probably reflecting greater erosion in the fallow-containing system [45]. Further evidence of the decline in fertility of the unfertilized soil was seen in the lower soil organic matter content and N-supplying power of the fallow-containing system compared to the continuous wheat (Table 1).

Sweetclover green manure increased yields of wheat grown on stubble compared to unfertilized fallow-wheat-wheat (Fig. 3), probably a result of N fixation, as evidenced by a 57% higher N-supplying power in the soil under green manure (Table 1). Even so, the yield of wheat grown on stubble in the green manure system has declined by 26 kg ha^{-1} yr^{-1}, much like that of the unfertilized fallow-wheat-wheat. This negative yield trend in the green manure system was partly because legumes do not supply P (Table 1). These results suggest that, on a yield basis, the fertilized system is more sustainable than the green manure system.

Yields of wheat grown on stubble in the 6-yr hay-containing system was much higher than those of stubble-wheat in the fertilized fallow-wheat-wheat system in the first 20 years of study (Fig. 3). This was partly due to less erosion [45], and partly because of the high N-supplying power of soil in the 6-yr rotation (Table 1). However, because the hay crop provides no P (Table 1), and because hay is harvested two in every six years, the 6-yr rotation also did not maintain wheat yields at as high a level as those obtained for the fertilized fallow-wheat-wheat system after the fertilizer rates were based on soil tests.

Although the benefits of N cannot be separated from that of P in this study, the results, clearly show that proper fertilization is required if we are to achieve sustainable crop production. Further, where legumes are used, adequate P must also be applied.

Economics

A prime consideration in achieving sustainability is having an economically viable operation. Much research has been conducted to assess the influence of fertilizers and legumes on the economic viability of crop rotation systems on the Canadian prairies [23]. The optimal system will depend, *inter alia*, entirely on the cost of fertilizer and price obtained for produce and often on Government policies and subsidies.

Under arid conditions (e.g., Brown soil zone), use of N and P fertilizers is profitable for continuous wheat in most economic situations, and fertilizer use often minimized losses (Fig. 4) [84]. However, for fallow-containing wheat rotations, it is only when wheat prices are high, or fertilizer costs low, that applying both N and P fertilizers results in higher net incomes than for rotations to which only N or P is applied.

In the sub-humid, thin Black Chernozemic soil at Indian Head, Saskatchewan, the economic benefit from fertilization is generally significant, particularly for the more intensive cropping systems [84]. Proper fertilization amplifies net income in years of favourable weather, and reduces economic losses in years of unfavourable growing conditions. Prior to 1977, when the fertilizer rates used in the Indian Head study were lower than economic optimums, net returns for legume-containing systems were superior to those of fertilized or unfertilized fallow-wheat-wheat (Table 2). But, after fertilizer rates were increased, the differential between fertilized and unfertilized monocul-

Table 1. Average annual rate of change in yield trends over 34 yr and organic N, available P and potential nitrogen-supplying power of soil at Indian Head, Saskatchewan in 1987 [16]

Rotation and fertilizer treatment[a]	Average yield increase[b] ($kg\ ha^{-1}\ yr^{-1}$)	Organic N ($t\ ha^{-1}$)	Potential nitrogen-supplying power[c] ($kg\ ha^{-1}\ wk^{-1}$)	Available-P in 0–1.2 m[d] ($kg\ ha^{-1}$)
F-W-(W)	-28	3.00	28	37
F-W-(W) (N+P)	+30	3.24	38	55
Cont (W)	-11	3.17	36	31
Cont (W) (N+P)	+33	3.46	55	42
GM-W-(W)	-26	3.37	44	26
F-W-(W)-H-H-H	-5	3.58	48	24
LSD(P<0.10)	–	0.31	8	13

[a]F = fallow, W = wheat, Cont = continuous, GM = sweetclover green manure, H = alfalfa-bromegrass hay and () denotes rotation phase sampled.
[b]Average slope of yield trends lines over time.
[c]The initial potential rate of N mineralization (i.e. $N_0 \times K$).
[d]Olsen-P.

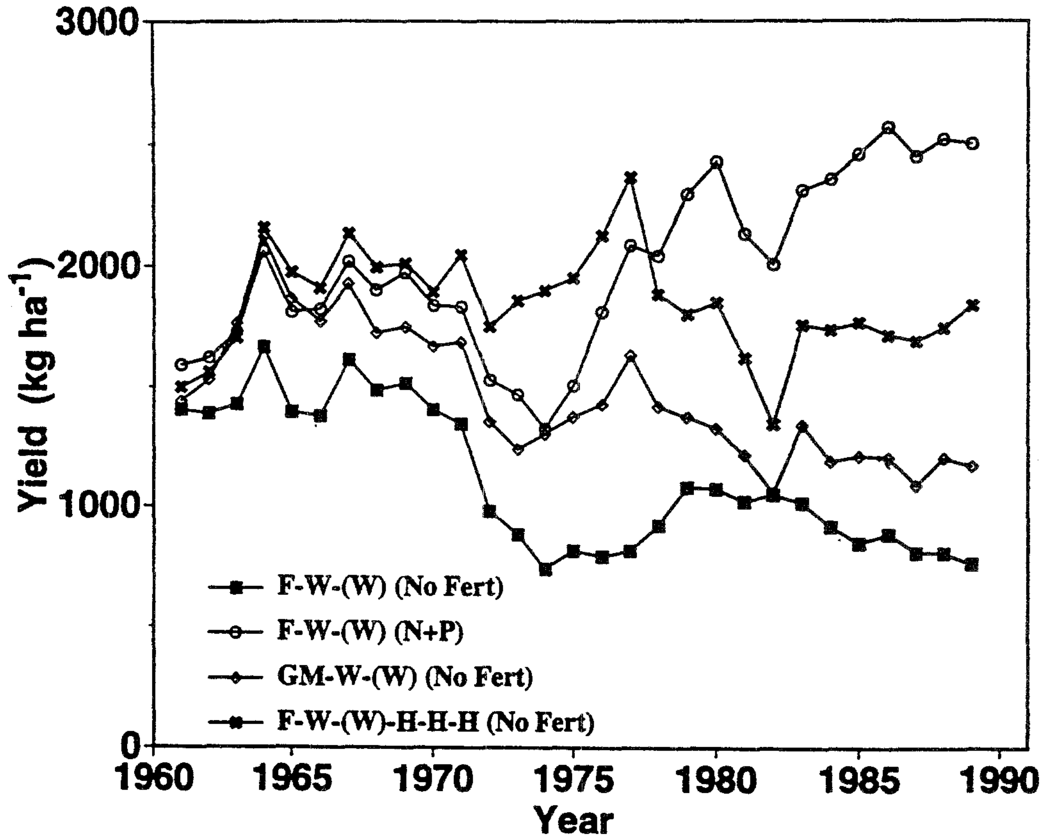

Fig. 3. Yield trends of hard red spring wheat grown on stubble in a fallow-wheat-wheat rotation on a thin Black Chernozem at Indian Head, Saskatchewan, showing the influence of sweetclover green manure, legume-grass hay crops, and of fertilizer. All points are 5-year running means [16].

Table 2. Annual net incomes[a] for rotations during two fertility periods[b] [24]

Rotation Sequence	N and P Fertilized	1960–77 Mean	Min	Max	1978–84 Mean	Min	Max
		(-$ ha^{-1})					
F-W	No	10	−100	122	−12	−80	103
F-W	Yes	17	−110	122	3	−80	122
F-W-W	No	−5	−128	155	−25	−115	85
F-W-W	Yes	15	−128	155	17	−73	142
GM-W-W	No	42	−128	180	22	−45	97
F-W-W-H-H-H	No	22	−110	152	32	−45	103
Cont. W	No	−57	−160	175	−99	−248	75
Cont. W	Yes	−10	−178	243	17	−240	233

[a]Base assumptions: Wheat = $147/t; hay = $67/t; fertilizer N = $0.57/kg; P_2O_5 = $0.60/t; labour = $10/hr; interest = 11%.
[b]Fertilized according to general recommendations for the region in period 1960–77, but according to soil tests in 1978–84; the latter period required much higher rates of N.

ture wheat widened in favour of the fertilized systems while net returns decreased relative to the first period. The hay-containing system still performed well in this second period. Thus, these economic trends appeared to mimic the long-term yield trends discussed earlier (Table 1 and Fig. 3).

Where soils are very fertile, such as on the thick Black Chernozem at Melfort, Saskatchewan, the economic benefit from fertilization may be much lower than in a less fertile soil where the driving variables are equally good (e.g., Indian Head) (Fig. 4). Thus, the influence of fertilizer on net returns depends on the likelihood of gaining significant enough crop response to overcome added cost of inputs, and this will depend on the inherent fertility of the soil, the weather conditions, and the rates of fertilizer used.

Impact of N on environmental quality

Earlier we showed that adequate fertilization is required to maintain the fertility of soil, otherwise it will degrade, thereby leading to lower crop production. Even the inclusion of legume systems, though they reduce the rate of degradation, may not be sufficient to maintain crop production at a level equivalent to when proper fertilization practices are employed. Let us now consider how some soil characteristics may be influenced by fertilizers and legumes over time.

Impact on soil quality

Although prairie soils have experienced considerable degradation due to poor soil management, most soils still have adequate quantities of organic matter to sustain acceptable crop production [22]. The rate of loss of organic matter from prairie soils was rapid in the first 20 years after the grassland was broken, but then decreased and organic matter levels have begun to approach a steady state in reasonably managed soils [22, 59].

What influence have fertilizers had on the quantity of organic matter in soils? Long-term studies carried out in the various soil zones in western Canada have shown that, without fertilization, soil organic matter levels will not increase and will likely continue to decline, particularly where summerfallow occupies a significant component of the rotation [20]. However, proper fertilization can either reduce the rate of loss in organic matter or, where summerfallow is kept to a minimum, it may increase the soil organic matter content modestly (Table 1 and [20]). If the organic matter level is already high, however, it is unlikely that fertilizers will increase the level very much [14].

Like fertilizers, legumes, whether used as green manure, hay, or pulse crops, can increase the soil organic matter content if used for a long enough period (Table 1 and [20]). In fact, any management practice that results in an increase in the amount of crop residues (especially roots) returned to the land will have a positive influence on soil organic matter content, unless organic matter is already high [13,14].

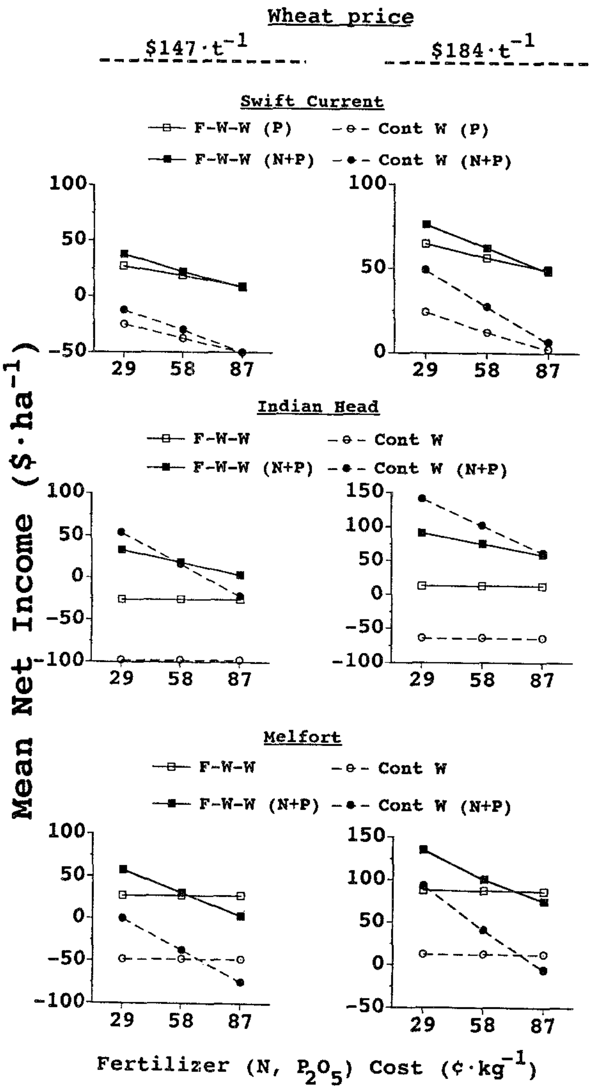

Fig. 4. Effect of wheat price and fertilizer cost on net income from fertilization for long-term crop rotations at Swift Current (Brown Chernozem), at Indian Head and Melfort (Black Chernozems), Saskatchewan. (F - fallow, Cont - continuous cropping, W - spring wheat) [84].

Because crop residue production is directly related to crop production, there will generally be a direct relationship between the maintenance of soil organic matter levels and economic performance. The export of grain or other produce from the land takes with it large amounts of N, P, K and S [11]. If these nutrients are not replaced (e.g., by additions of fertilizers) soil organic matter and the fertility of the soil will gradually decline. This has been well documented for N in a long-term rotation study at Swift Current (Fig. 5).

Table 3. Influence of grain legume on trend in fertilizer N requirements for spring wheat in two continuously cropped systems receiving N and P based on soil tests over a 12-yr period at Swift Current, Saskatchewan [26]

	N fertilizer applied to rotation phase indicated by () (kg ha^{-1})		
Year	Cont (W)	W-(Len)[b]	Cont(W) minus W-(Len)
1979	39	50	−11
1980	61	61	0
1981	33	28	5
1982	27	27	0
1983	20	21	−1
1984	44	11	33
1985	11	5	6
1986	11	5	6
1987	41	3	38
1988	56	4	52
1989	9	2	7
1990	17	0	17

[a]Prior to commencement of this experiment this land was cropped continuously to spring wheat fertilized with N and P for 12 yr.
[b]The comparison was made between Cont W and the lentil phase of W-Len because the N requirements of the lentil was dictated by the wheat phase of the rotation.

Not only is the amount of organic matter influenced by fertilizers, legumes, or reduced inputs, so too is the quality of the soil organic matter. For example, the number of microbes and their activity in the soil are directly related to fertilizer rates and to the amount of legume inputs into soil [26,54]. Here, too, the impact of fertilizer interacts with cropping frequency (Table 1).

Because fertilizers (and legumes) increase the N-supplying power of soils, their regular use, year after year, can lead to significant improvement in the fertility of the soil. This may then reduce the fertilizer requirements of such land in future years (Table 3).

As stated earlier, fertilization will have a positive effect on crop residues [18]; in turn, this will have a direct effect on soil aggregation (Fig. 6). The latter will influence soil structure, erodibility, soil workability, and water infiltration. Thus, the adoption of proper fertilization practices is imperative for maintaining soil in good physical condition for crop production. Legumes (green manure, and particularly grass-alfalfa hay crops) are very effective in promoting good soil aggregation [18].

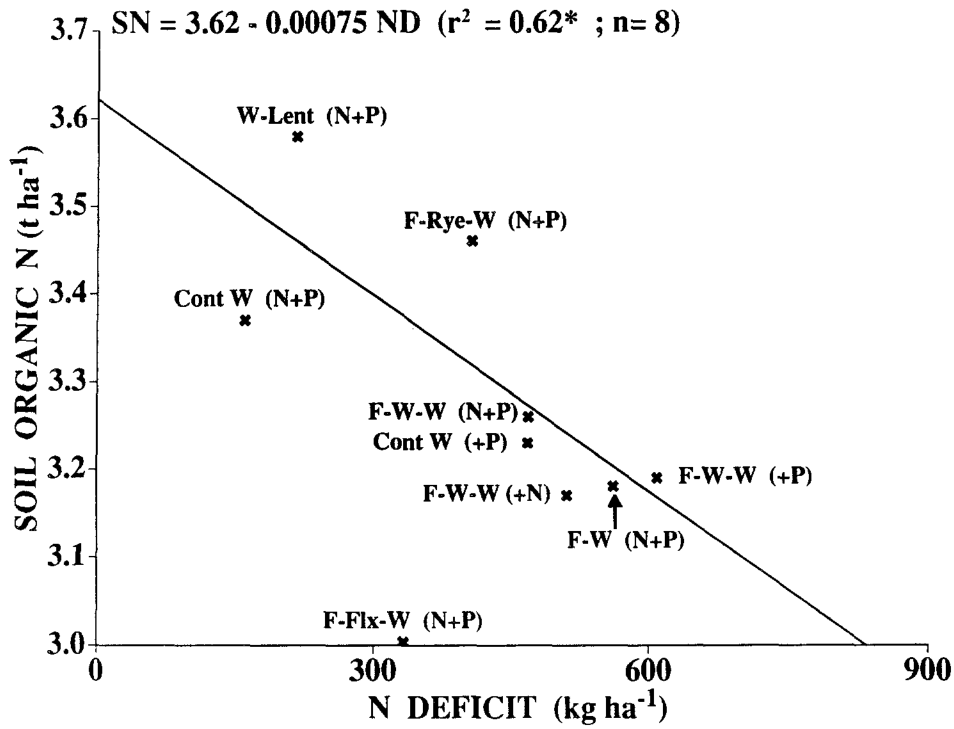

Fig. 5. Relationship between soil organic N in the surface 15 cm of soil and apparent N deficit (i.e. N exported in grain minus N applied as fertilizer) in a 25-yr crop rotation experiment at Swift Current, Saskatchewan. F = fallow; CF = chemical fallow; W - spring wheat, WW - winter wheat, Rye - fall rye, Flx - flax, Lent - grain lentil, Cont - continuous [21].

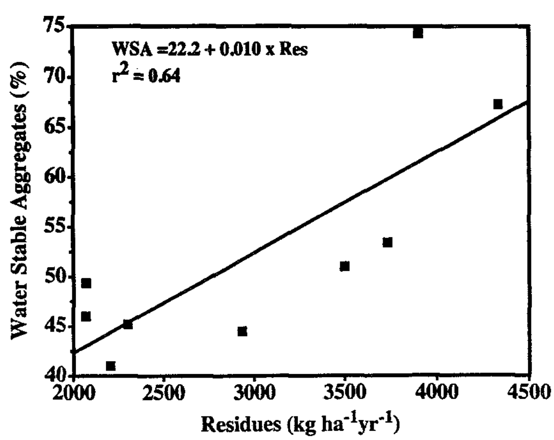

Fig. 6. Relationship between water stable aggregates and crop residues for various treatments in a long-term crop rotation experiment at Indian Head, Saskatchewan [18].

Impact on water quality

High nitrate content in drinking water can be a health hazard, causing methaemoglobinaemia. Although the climate of the Canadian prairies is semiarid, thus resulting in severe moisture deficits on a regular basis, nitrate leaching can take place, especially in the more humid regions, such as in the Black and Grey Luvisolic soil zones [17,30]. This is particularly true where summerfallow constitutes a significant component of the crop rotation, because this allows storage of water, thereby priming the soil for 'leakage'. Further, in the summerfallow period mineralization and nitrification predominates and, without much plant uptake of N, nitrate can be easily leached during early, wet springs (Fig. 7, and [6]).

If fertilizers are applied based on soil test criteria, then nitrate leaching is minimized, especially when continuous cropping is also practiced (Fig. 7) [17]. In contrast, over-fertilization, which may result from use of general fertilization criteria for a crop and soil (Fig. 8), as well as under-fertilization [25], can sometimes lead to large amounts of nitrate being leached. Nor is the use of legumes less likely to result in nitrate leaching than will mineral fertilizers (Fig. 9). This is because legumes increase the N-supplying power of soils (Table 1) and, when they are plowed down, the mineralized/nitrified N can be easily leached, especially if summerfallowing is a component of the rotation. Thus, the key to reducing nitrate leaching is to reduce

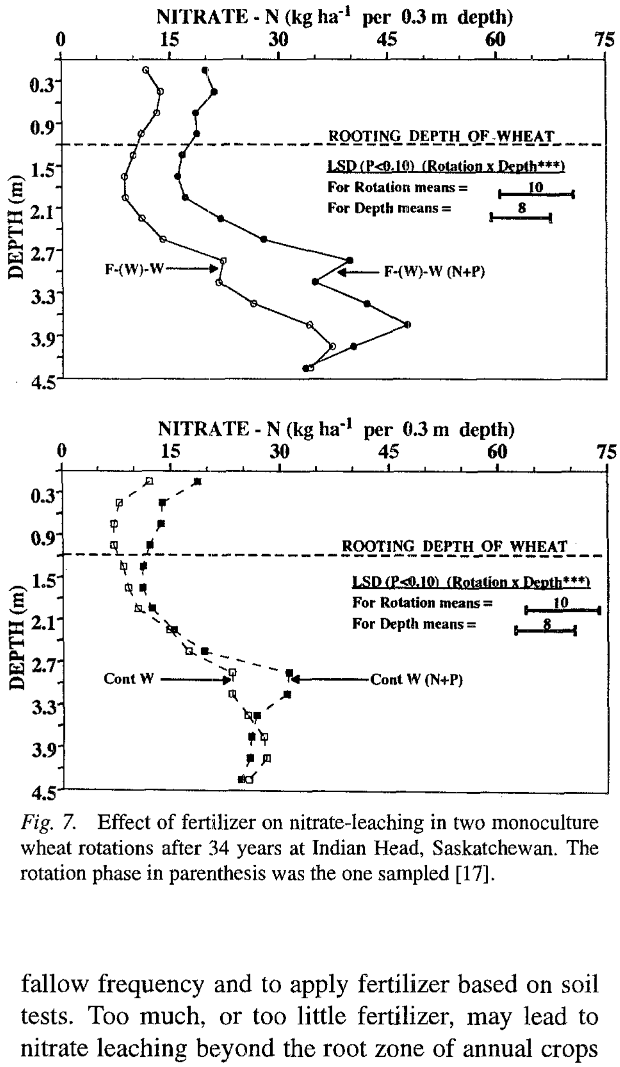

Fig. 7. Effect of fertilizer on nitrate-leaching in two monoculture wheat rotations after 34 years at Indian Head, Saskatchewan. The rotation phase in parenthesis was the one sampled [17].

fallow frequency and to apply fertilizer based on soil tests. Too much, or too little fertilizer, may lead to nitrate leaching beyond the root zone of annual crops [15,25]. Nonetheless, to date there has been no evidence to suggest that the use of fertilizers or legumes have resulted in nitrate pollution of ground waters on the Canadian prairies [47,48]. In the few cases where high concentrations of nitrates have been detected in ground water on the prairies, these were associated with farmsteads, or were located in the vicinity of towns and villages where human and animal wastes were concentrated. [30].

Impact on air quality

When we think of air quality with regard to the impact of N fertilizers, "greenhouse gases", such as CO_2 and the oxides of nitrogen, come to mind. Although the influence of N fertilizers and legumes on evolution of CO_2 from soil (C mineralization or respiration) has been much studied on disturbed soil in the laboratory, few such studies have been conducted *in situ* on the Canadian prairies. Nitrogen fertilization has been shown to reduce CO_2 respiration [56,57], probably due to the negative impact of fertilizers on microbial activity resulting from the lowered pH accompanying N addition [56]. However, incubation studies with disturbed soil from long-term rotations in Saskatchewan, usually show increased CO_2 respiration from soils having a history of regular fertilizer addition (as was observed for N mineralization as well) [13].

The main N-containing greenhouse N gas is nitrous oxide (N_2O). The chief processes responsible for N_2O production in soils are denitrification and nitrification, with the former being the main mechanism involved [68]. Under anaerobic conditions, nitrate or other oxides of N serve as alternative terminal electron acceptors to O_2 for denitrifying bacteria. Thus, the presence of oxides of N is a prerequisite for N_2O production by this process. It is not surprising therefore that the application of N fertilizers can result in dramatic increases in N_2O emissions in the field [31,38]. Annual losses of N as N_2O from fertilized field soil can be as high as 40 kg ha^{-1} [67] compared to that from unfertilized soils being < 2 kg ha^{-1} [68]. Based on a summary of 104 field experiments conducted in temperate climates, it was reported that all but one showed evidence of fertilizer-derived N_2O emissions [38]. Further, N_2O emissions generally increased with increasing rate of N. Anhydrous ammonia appeared to cause considerably higher N_2O emissions than other common fertilizers, though the reason for this is uncertain [38]. Most of the N_2O emission occurred soon after the fertilizer was applied. Little information of this type has been published in western Canada, although overwinter loss of N from fall-applied fertilizer has been attributed to denitrification [58]. Denitrification was observed to increase in a Blaine Lake soil in Saskatchewan after fertilization, but the extent of the N emission was not specified [79].

Legumes, like N fertilizers, have been shown to contribute to increased N_2O emissions [38]. Denitrification was increased significantly by clover plowdown at two sites in Saskatchewan [2]; however, the added easily- decomposable organic matter was felt to be a factor in the enhanced denitrification.

In Saskatchewan, significant emission of N_2O was found to accompany the nitrification of ammonia fertilizers under aerobic conditions [3]. However, the amount of N_2O emitted by this mechanism is much less than that lost via denitrification. Further, several recent reports suggest that NO, not N_2O, is the dom-

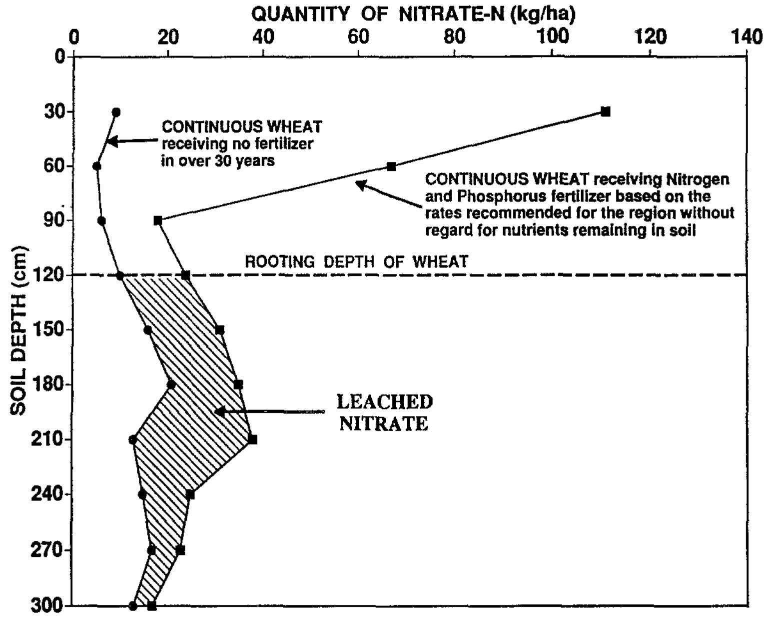

Fig. 8. Application of N fertilizer based on general recommendations for the crop and soil can lead to overfertilization resulting in excessive nitrates in surface and subsoil even in a continuous wheat system, as seen at Melfolt, Saskatchewan. (Campbell, unpubl. data from Melfort crop rotation experiment).

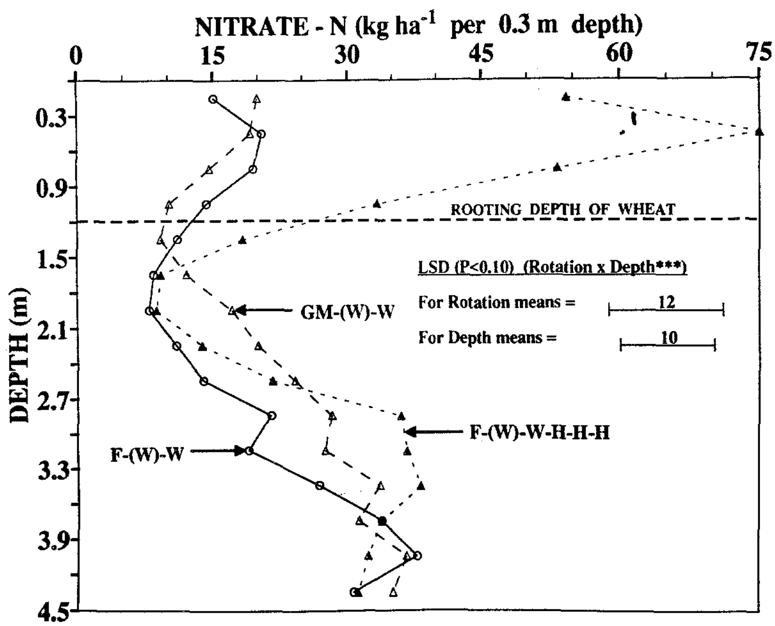

Fig. 9. Effect of legume green manure and legume-grass hay crops on nitrate-leaching in rotations after 34 years at Indian Head, Saskatchewan. The rotation phase in parenthesis was the one sampled [17].

inant N gas produced during nitrification in aerated soils [78].

Nitric oxide, which is the dominant component of the so-called NO_X, has no direct effect on the earth's radiation balance, but it is very active chemically and plays a critical role in its interaction with such oxidants as ozone [31]. Because NO_X is eventually oxidized to nitric acid it will also contribute to acid precipitation.

Nitrification is believed to be the major source of NO in soils with moisture content in the available range [49]. In such soils, NO evolution was an order of magnitude greater than N_2O evolution. Because nitrification is a common occurrence in prairie soils whenever ammonium fertilizers are applied, one can assume that most ammonia-based fertilizers do contribute to evolution of NO_X to some extent. However, the amount of N fertilizers used on the Canadian prairies is small compared to the more humid regions of Canada, the USA, or Europe; therefore, our contribution to the evolution of these noxious gases is, presumably, relatively small.

Tropics - Predominantly subsistence farming

Background

Nitrogen fertilizer use in the tropics has increased more slowly than in more developed countries in Europe and North America. Nitrogen is mainly used on lowland rice (*Oryza sativa*) and on the high value crops, such as sugarcane (*Saccharum officinalis* L.), cotton (*Gossypium hirsutum*) and irrigated wheat. Historically, fertilizer use was encouraged by artificially low cost of fertilizer, but subsidies have tended to decrease with time. Because of the prevalence of subsistence farming, economics is the main concern and environmental questions are incidental. Because of limited resources, there has been minimal long-term research on N cycling in soils of the tropics [46]. In fact, tropical agriculture has mainly relied on results of research from temperate regions. This seems reasonable since the principles involved apply in all climates, varying only in degree as dictated by climate, especially precipitation and temperature [4,5].

Sustainable agriculture production - The problem

The definition of sustainable agriculture used earlier for the developed countries is applicable to the tropics. As stated earlier, economics is the main concern and, as shown later, many farmers cannot afford to buy fertilizers, while wastes such as cow manure may be more valuable as an energy source or for industrial purposes (India) than for building soil organic matter. The second part of this paper will deal more with nitrogen use efficiency than on environmental impact of N.

Impact of N on yields and economics

Many experiments have been conducted on N management of crops in the tropics. Most have been aimed at evaluating N fertilizers and have been directed to lowland rice, the most important crop. In recent years, there has been an increase in the research effort directed at the use of green manures and other organic inputs for both lowland rice and upland crops. Generally, the responses to N have paralleled those obtained in temperate climates. Field experiments in Puerto Rico, Brazil and Ghana showed that the response of maize (*Zea mays* L.) to N was remarkably similar to that obtained on similar soils in the USA [46]. Further, apparent N recovery in the above-ground crop (measured by difference method) was almost identical for tropical and temperate locations, with mean recovery ranging from 60–120 kg ha^{-1} being 56% [46]. On the Canadian prairies mean recoveries of fertilizer N for cereals is 53% [29].

Nitrogen use efficiency

Lowland Rice

Asia uses 39% of the world's N fertilizer and about 60% of this is used on lowland rice [33]; thus, most research has been conducted on this crop. Research, together with favourable fertilizer prices has ensured widespread use of N fertilizer on lowland rice. However, whereas farmers have been quick to adopt practices aimed at optimizing yields, there is still a problem with respect to NUE by rice. Generally, less than 40% of N applied to rice is used by the crop [33]. Loss has been mainly through ammonia volatilization, although leaching and denitrification also contribute to inefficient utilization. Because of the nature of these processes, attempts to reduce losses and improve NUE have focused on water management. In the case of ammonia volatilization, loss is closely related to concentration of ammonium in the floodwater. Estimates of total losses of N as ammonia are between 36–44% [40]. This loss was reduced to 22% by use of urease inhibitors [40], but the cost is prohibitive [10]. Two approaches to reducing loss by reducing floodwater concentration of ammonia have been (a) to drain the floodwater and apply the fertilizer to the soil surface, and (b) to place the fertilizer below the soil surface. It was confirmed that losses were less when fertilizer was applied to the drained soil surface than when it was broadcast on the floodwater [32]. It was shown that utilization efficiency could be raised to more than 60% by placing the fertilizer below the surface of the soil (deep point placement) [34]. Banding it was also effective, but combinations of various split applications, including that favoured by the farmers, gave the poorest efficiency. The latter observation was confirmed by others [50,72]. For example, lowland rice took up 25–34% of urea applied as split application, but 50–61% from deep placed urea supergranules [72].

Reviewing a series of experiments in Indonesia, Myers [62] concluded that there were technical solutions to increasing NUE of lowland rice. Various split applications for example, resulted in improved NUE (Table 4). Placement of fertilizer below the soil surface also consistently gave high yield and NUE. However, generally the improved technology merely improved N concentration in the grain rather than grain yield. In the absence of any price incentives for grain protein, farmers are justifiably unwilling to adopt these technologies. One byproduct of this research is a clear indication of the need for accompanying study of economic and social factors. In the Philippines, similar research led to revised recommendations on N placement which were similarly rejected by farmers.

Upland crops

Because most farmers in the tropics are subsistence farmers, many cannot afford to buy fertilizer; consequently, upland crops receive less fertilizer than lowland crops. Fertilizers are mainly used on higher value crops, such as sugarcane and cotton, or in special situations, such as on irrigated wheat in Zambia; little is used on crops such as corn. Response of these crops to N is widespread (46,55); however, because precipitation is uncertain, farmers need to be aware of the risk of receiving no response from inputs.

Upland crops in the humid tropics are grown on substantial areas where the land is either acidic or often sloping or steep. The high precipitation results in considerable loss of N by denitrification, leaching and runoff. The major crops include cassava, rice, corn and some pulse; such as peanut. Nitrogen deficiency is general, especially in the aridic soils, and deficiencies of nutrients such as P, K, Ca, Mg, B and others is common. Thus, responses to N may be limited unless these other deficiencies are also addressed. Although NUE here, as in the temperate climates, is directly related to crop production (N uptake) and thus precipitation, excessive precipitation will reduce N availability. Thus, NUE was found to be lowest where rainfall was highest [74]. For upland rice grown in Sumatra in the rainy season (900–1300 mm) NUE was 9–18% while for corn grown in the dry season (410–840 mm) NUE was 32–40%.

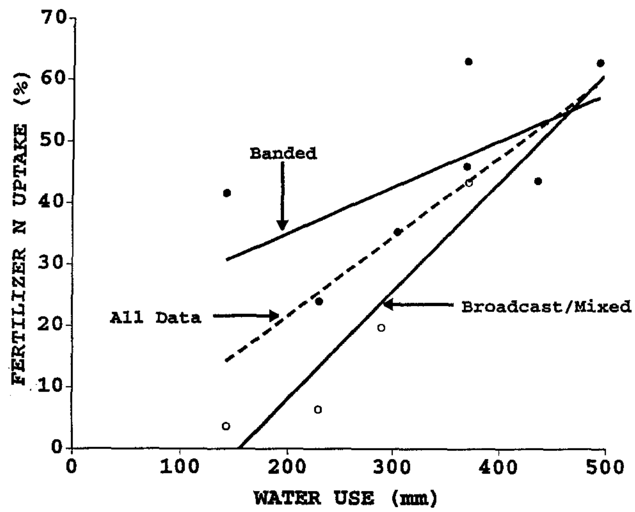

Fig. 10. Fertilizer N uptake in relation to available water and method of application (•banded, ○broadcast/mixed) (From Myers and Hibberd, unpubl. data).

In the subhumid and semiarid tropics where there are substantial areas of Vertisols and soils are less acid, restriction to upland crop response to N is mainly due to water deficiency. Here we find interactions between water and available soil N and crop response to fertilizer N similar to that reported for temperate climates [27,63,76,77). As soil fertility declines and available water increases, the frequency and magnitude of response of cereals to N usually increases. Because extremes of water supply are part of the normal climatic variation in subtropical and tropical regions, this demonstrates the risk of using N fertilizer. Under rainfed conditions in India, sorghum took up 29–56% of N applied as urea on a Vertisol where the seasonal rainfall was 695 mm [60]. In an Alfisol, 47–64% crop recovery of N was observed where 830 mm rain was received, compared with 54-67% when 610 mm was received [61]. With these weather-related risks with which to contend, it is not surprising that subsistence farmers hesitate to spend scarce cash on fertilizers. Myers and Hibbard (unpubl. data) found that crop recovery of applied N by sorghum on a Vertisol ranged from 0–60% depending on the amount of water available for use by the crop (Fig. 10).

Sugarcane and cotton, two major upland crops of the subhumid and semiarid tropics, are usually grown

Table 4. Percentage utilization and net uptake of fertilizer applied to flooded rice at different times and different rates determined by ^{15}N [1]

Time of application	Fertilizer applied (kg N ha^{-1})					
	25		50		75	
	Uptake (kg N ha^{-1})	Recovery (%)	Uptake (kg N ha^{-1})	Recovery (%)	Uptake (kg N ha^{-1})	Recovery (%)
Transplanting	6.2	25	13.0	26	–	–
21 d.a.t.	5.1	21	9.4	19	13.5	18
btn 21 d.a.t., PI	5.3	21	11.8	24	17.5	23
7 d.b.PI	8.5	34	–	–	–	–
PI	–	–	20.8	42	29.2	39
FL	–	–	–	–	22.7	30

d.a.t. - days after transplanting, PI - primordial initiation, d.b. - days before, FL - flag leaf emergence.

under irrigation and both crops generally make poor use of N. In the case of sugarcane, N is often lost by volatilization when urea is broadcast onto the trash on the soil surface [41]. In this environment the Australian sugarcane grower is prepared to accept these losses and apply additional N rather than undergo increased expenses in placing the N below the soil surface. However, if irrigation can be scheduled efficiently, it should be possible to increase N uptake and minimize N losses [19]. Care must be taken when using furrow irrigation to ensure that N is not pushed into the tops of ridges where it will be unavailable when the soil dries out [81]. This problem can be circumvented by placing the N deeper in the soil.

In summary, crop response to N, and N use efficiency, are very similar for similar types of crops in tropics and temperate climates [46]. Further, the same factors influence efficiency. Thus. greatest efficiency of N use is obtained when N is placed (e.g., in a band) rather than broadcast, when N is applied to the plant near to seeding time (not long before it's required), and when N availability is in synchrony with N requirements by the crop. The influence of N source on N use efficiency is less clear because workers in Puerto Rico and Brazil reported that, in contrast to expectations, maize used urea-N more efficiently than sulfur-coated urea or lime-coated ammonium nitrate in well-drained acid soils [46].

Green manures and crop residues

The use of organic amendments in tropical soils can provide several benefits, the main one being to supply nutrients. However, they can also be effective in assisting in weed control, reducing erosion, reducing soil temperature, conserving water and increasing soil aggregation and thereby improving soil structure. The major nutrient supplied is N and the effectiveness of this role is variable. In the developing countries where economic margins are so nebulous at times, producers will not apply any new technique unless they are sure it is going to lead to almost immediate direct economic benefits; that is, they will rarely institute some new management in order to reap some possible future advantage *per se*.

In Australia, rapid acceptance of trash retention for sugarcane production was due to reduction in production costs associated with reduced tillage, not due to perceived improvements in the soil organic matter or N cycling. In the 1920s and 1930s, the West Indies Sugar Co. at Frome, in Westmoreland, Jamaica, started applying organic manures such as bagasse, bagassed-under-compost, filterpress mud, and fly-pen manure (bedding from pens of cows that transport the cane), to the cane fields. Previously only N, P and K fertilizers had been applied. The organic manures (plus N, P, K as determined by tissue testing), resulted in tremendous yield increases and markedly prolonged the productive life of the ratoon cane fields (Fig. 11). At the same time, this allowed the sugar factory to recapture space which had been used to store these byproducts and it reduced the practice of contaminating rivers with toxic dunder. In Indonesia, farmer acceptance of green manuring was partly due to the perceived N inputs, but also because farmers found that seeds of the green manure crop could be used for food (R. Sutanto and

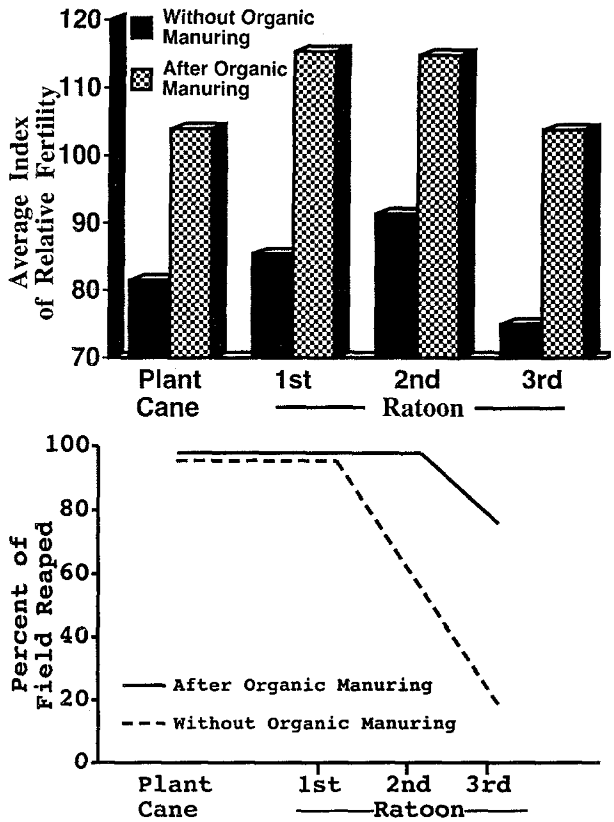

Fig. 11. Influence of organic manuring with sugarcane waste products on yields (top) and on ratooning powers (bottom) of sugarcane fields at Frome Estate, West Indies Sugar Co., Jamaica [51].

A: Supriyo, personal communication). In Vietnam and the Philippines, farmers accept leguminous hedgerows because they provide soil erosion control rather than for the N inputs that farmers cannot see. Nevertheless, there are increasing numbers of examples of substantial fertilizer substitutions provided by leguminous inputs in tropical environments.

Several workers have demonstrated that, in the humid tropics, green manures can be a very effective fertilizer substitute [36,65]. For example, 47 to 49% of the N in *Sesbania rostrata* or *Aeschynomene afraspera* was taken up by lowland rice in the wet season, compared with 23–71% uptake from urea fertilizer [36]. In the dry season, 40–42% was taken up from legume N, compared with 31–54% from urea. For upland crops grown on an Ultisol in Sumatra, N in cowpea residues was found to be more available than N applied as urea [74]. For upland rice, green manure was found to be equivalent to 66 kg N ha^{-1} of fertilizer, and residues left after harvest were equivalent to 70 kg N ha^{-1} [53]. Also, for upland crops there is interest in the degree to which prunings from hedgerow species in alley-cropping systems can substitute for N fertilizer. Maize was found to only obtain 9% of the N contained in Leucaena prunings whereas 43% of fertilizer N was taken up [82,83]. Applying Leucaena prunings containing 300 kg N ha^{-1} was found to be equivalent to applying 64 kg N ha^{-1} of fertilizer [71]. Variable results with these materials have prompted an interest in gaining an understanding of the processes and this has led to the idea that effectiveness of organic inputs depends on weather-related factors (moisture and temperature) and quality-related factors (chemical and physical). Thus, rapid release of N from organic inputs has occurred mostly in humid conditions. Research into the importance of quality factors has centred on three components – N concentration (for C:N ratio), lignin concentration and polyphenol content.

There is concern that some high quality crop residues or green manures may release N too rapidly so that losses of N may occur. The concept of synchrony of supply of N with the crop's demand has resulted. Thus, an organic material of the right quality may release N at approximately the same rate as required by the crop (Fig. 12). If this happened, there should be less opportunity for N loss by denitrification or leaching. The principle of synchrony has been described in detail and evaluated recently [64]. Some other organic inputs which would supply some N to crops are of potential importance in the tropics. Included are the waste products from milling of palm oil,, municipal wastes, etc. So far, these products have been little researched.

Socioeconomic factors

In the tropics, most farmers either do not have the cash or the access to credit to invest in fertilizer; or, the prices for farm products are too low to make fertilizer use attractive. In some countries there are, or have been, subsidies on certain fertilizer products which have encouraged the use, and occasionally overuse, of fertilizer. As these subsidies have been removed, there has been a reduction in the profitability of fertilizing. There is a contrast between farmer attitude to N fertilizing in developing versus developed countries. For example, sugarcane growers in Thailand tend to apply less than the recommended rates of fertilizer whereas their Australian counterparts tend to apply more than recommended rates (P Pramanee, pers. commun.). This is probably due to a different risk factor – the Australian farmer is managing the risk of losing yield

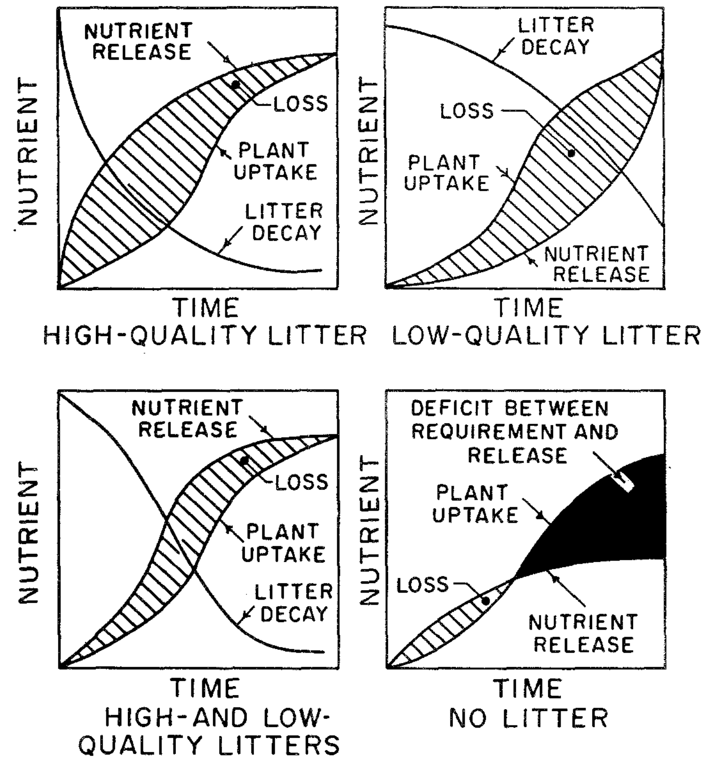

Fig. 12. Hypothetical patterns of nutrient availability in four treatments of an experiment to test the synchrony principle [64].

because of higher than usual N losses, whereas the Thai farmer is managing the risk of not getting the maximum return per unit of investment. Such attitudes create different opportunities for environmental impact. For example, the Australian approach would increase the likelihood of negative environmental impacts through N moving from the field into waters, whereas the Thai farmer's system, which is more conservative, could lead to soil degradation. There are other ways that economics may force farmers to use strategies with potentially poor environmental impact. Where deep point placement of N for lowland rice was recommended to farmers in the Philippines the recommendation was sound in agronomic and environmental terms, because the N was used more effectively by the rice than was N applied according to farmers' practice; however, farmers refused to adopt the improved practice because of the labour cost and inconvenience [42]. They preferred to add a larger amount of N and accept the poorer utilization efficiency. Fujisaka *et al.*, [42] concluded that the farmers were correct in rejecting the official recommendation. There are examples of legislation affecting nutrient management, as in the case of rubber replanting schemes in Malaysia. Here, farmers must sow legume ground covers between the rows of trees to control erosion and to supply N to the system. Unfortunately, such legislation does not ensure success of the legume ground cover, consequently there are many cases where the cost of seed and sowing is wasted because of careless management. Of course, similar situations occur in developed countries as well [12].

Impact of N on environmental quality

There are few long-term trials in the tropics (except some on lowland systems at the International Rice Research Institute) to allow systematic monitoring of the influence of N on environmental quality.

Impact on soil quality

Although organic matter and organic N have been measured on numerous occasions, there appears to be lack of agreement on the amounts of organic matter in tropical soils compared to temperate soils. For example, while some [5] suggest that organic matter is low in tropical soils, others (9) say that many well-drained tropical soils have greater organic matter content than do comparable temperate soils. Sixteen randomly selected soils among four major soil orders in the USA, Brazil and Zaire showed no difference in organic matter [69,70]. In a review paper, Grave [46] reported that organic N in Oxisols and Ultisols in Brazil, Puerto Rico and Zaire ranged from 0.07 to 0.3% in the plow layer while in temperate soils the range was 0.08 to 0.4%.

Some lowland rice systems have been in existence for so long that it might be assumed that the organic matter is in equilibrium so that fertilizer either has no impact on soil quality or that it merely helps to maintain quality. In a 7-yr fertilizer study conducted in Brazil, it was reported that the concentration of soil organic nitrogen in the surface soil of unfertilized plots did not change significantly during the experiment, even though 384 kg of N was removed in above-ground dry matter [46]. Apparently, the amount of organic nitrogen mineralized was sufficiently small, relative to experimental error, that changes in soil organic N were undetectable. Annual fertilization did not influence soil organic C either. Mean concentration of soil organic N (0.124%) in fertilized treatments (sampled in 1975 and 1976) was similar to that in check plots.

As in temperate soils, moisture and temperature are the main factors influencing N mineralization. Because temperature is well above freezing all year, N mineralization can occur all year. Consequently, if water is available, the amount of N mineralized annually should be greater in a tropical soil than in a temperate soil [52]. As well, when a soil is disturbed so that the organic matter level changes towards a new steady state, this rate of change should be more rapid in the tropical system [46]. It is known that N mineralization can occur even in dry soils and nitrate will accumulate in dry seasons [73], then at the onset of rainy reasons, large flushes of N mineralization can occur [7,8]. Such flushes are much greater under conditions of alternate wetting and drying than when moisture is steady [7]. This was also observed in temperate climates [11]. Thus, minor droughts during rainy seasons will enhance mineralization. In the 7-yr study conducted in Puerto Rico, Brazil and Ghana, net N mineralization during a growing season for maize was found to be very similar to that produced in New York and Nebraska, being typically about 60 to 80 kg N ha^{-1} [46].

Ammonium-containing fertilizer is known to acidify soils. However, in flooded rice where highest N rates are used persistently, the system seems to be buffered against acid conditions, provided it is maintained in the flooded condition where N is primarily in the ammonium form. In upland systems, N fertilizer use is generally low in the tropics thus soil acidification from fertilizer should be minimal, except in certain high input systems such as sugarcane and cotton., Similarly, legumes in the tropics may not be fixing sufficient N to provide a positive N balance,, consequently their impact on soil acidification and maintenance of soil organic matter may be less dramatic than in temperate climates.

Impact on water quality

Conditions in well-drained tropical soils are conducive to N loss through leaching, which occurs most rapidly in soils of coarse, sandy texture during the rainy season [39], when rainfall often exceeds evapotranspiration. High correlations between rainfall and N movement have been reported in tropical soils of Australia [80], and in West African Ultisols [28]. Leaching losses of 65 percent of applied N have also been reported in Costa Rican alluvial soils planted to maize [43].

In the tropics, as in other environments, the key to reducing the possible negative impact of N on the environment is to synchronize N availability with crop requirements. Nitrate will move with water thereby entering ground water and streams. The potential for perturbation of watersheds from nitrate addition is particularly significant in the tropics. The N/P ratios in Central American lakes were observed to be lower than in temperate zones by a factor as great as 5 [35]. This suggests that nitrogen deficiency may be general in the tropics and that eutrophication may result from increased nitrogen addition. Thus, proper timing and level of fertilization will reduce potential environmental damage.

Because of its mode of culture, lowland rice must impact on water quality downstream. As well, water quality could be important in respect of waterways downstream of heavily fertilized sugarcane. In the tropics this could impact on reefs. However, only the more wealthy amongst the farmer community can be expected to modify their system to address this problem.

Impact on air quality

The significance of N loss by denitrification in tropical soils is not well documented. Denitrification losses from cultivated, grassland, and forest soils was studied in Ghana and N losses found to be insignificant at field capacity [44]. Significant losses occurred only in waterlogged conditions. Significant denitrification losses were reported for waterlogged surface soils in Puerto Rico, but here glucose had been added to provide adequate supply of energy [37]. Losses from samples of surface and subsurface soils at field capacity were found to be insignificant [37]. Thus, it appears that denitrification loss in humid tropical soils is not likely to be large under field conditions.

It is known that the rice system is a major producer of methane. It must also be responsible for production of some N_2O. While this must be a matter of concern, there can be no expectation that low-income farmers will modify their practices to reduce environmental problems unless there is some other rewarding reason for doing so.

Conclusions

We have clearly demonstrated that, when fertilizers are used responsibly, they will increase crop production, contribute to economic survival, and maintain or improve the physical, biochemical, and biological quality of soils in the temperate/boreal climates. Under such circumstances, fertilizers will not have significant detrimental effect on soil, water, or air quality. On the contrary, failure to apply adequate fertilizer may be uneconomical and may eventually lead to soil degradation. The inclusion of legumes, such as green manure, and hay crops, in cereal- based crop rotations will improve yields, economics, and soil quality for some time; however, because legumes do not supply P, cereal yields in such systems may gradually decline and such systems may eventually become unsustainable.

In tropical climates, most of the same principles observed for the behaviour of N in temperate climates are applicable. The main differences are that much less N fertilizer is used because most producers are subsistence farmers who can rarely afford to buy fertilizer and only lowland rice and higher value upland crops such as sugarcane, cotton and irrigated wheat are likely to receive much fertilizer. Legumes are rarely used just to provide extra N, they must provide other benefits such as erosion control. Even when used, legumes often provide less N than they remove. Despite low use of fertilizer N for upland crops in the tropics, the humid conditions, year-round high temperatures, steep terrain in many instances, and flushes in N mineralization that occur when dry soils are wetted, will likely result in sizeable N losses through leaching, runoff and denitrification, and eventually cause soil degradation. In contrast to temperate climates, however, only limited research on these factors has been conducted because of limited resources of most tropical countries.

While governments in developed countries, located mainly in temperate and boreal climates, are able to use incentives and/or deterrents to entice farmers to adopt and implement measures that will promote sustainable crop management, in most tropical countries subsistence farming predominates and economics will be the main motivator, thus compliance regarding environmental issues will depend mainly on the incentives that are offered.

References

1. Abdullah N, Sisworo WH & Prawirasamudra A (1980) Pengaruh cara-cara pemberian pupuk nitrogen terhadap hasil dan komponen hasil serta distribusi N-pupuk di daiam tanaman padi pelita I/1. Majalah BATAN 13: 20
2. Aulakh MS, Rennie DA & Paul EA (1983) The effect of various clover management practices on gaseous N losses and mineral N accumulation. Can J Soil Sci 63: 593–605
3. Aulakh MS, Rennie DA & Paul EA (1984) Acetylene and N-serve effects upon N_2O emissions for NH_4^+ and NO_3^- treated soils under aerobic and anaerobic conditions. Soil Biol Biochem 16: 351–356
4. Bartholomew WV (1972) Soil nitrogen and organic matter. In: Drosdoff M (ed) Soils of the Humid Tropics, pp 63–81. Natl Acad Sci, Washington, DC, USA
5. Bartholomew WV (1973) Soil nitrogen in the tropics. In: Sanchez PA (ed) A Review of Soils Research in Tropical Latin America, pp 68–89. N.C. State Univ Agr Exp Sta. Tech Bull. 219
6. Bauder JW, Sinclair KN & Lund RE (1993) Physiographic and land use characteristics associated with nitrate nitrogen in Montana groundwater. J Environ Qual 22: 255–262
7. Birch HF (1958) The effect of soil drying on humus decomposition and nitrogen availability. Plant Soil 10: 9–31
8. Birch HF (1959) Further observations on humus decomposition and nitrification. Plant Soil 11: 262–286
9. Buol SW (1973) Soil genesis, morphology, and classification. In: Sanchez PA (ed) A Review of Soils Research in Tropical Latin America. pp 1–38. N. C. State Univ Agr Exp Sta Tech Bull 219
10. Buresh RJ, DeDatta SK, Padilla JL & Samson MI (1988) Effect of two urease inhibitors on floodwater ammonia following urea application to lowland rice. Soil Sci Soc Am J 52: 856–861
11. Campbell CA (1978) Soil organic matter, nitrogen and fertility. In: Schnitzer M Khan SU (eds) Soil Organic Matter Developments Soil Sci 8, pp 173–272. Elsevier Scientific Publ. Co., Amsterdam, the Netherlands
12. Campbell CA (1992) Adoption of sustainable agriculture in cereal production on the Canadian prairies. Paper presented at Organization for Economic Cooperation and Development

(OECD) Workshop on Sustainable Agriculture, Paris, France, Feb. 1992. 11 p (Mimeo)
13. Campbell CA, Biederbeck VO, Zentner RP & Lafond GP (1991) Effect of crop rotations and cultural practices on soil organic matter, microbial biomass and respiration in a thin Black Chernozem. Can J Soil Sci 71: 363–376
14. Campbell CA, Bowren KE, Schnitzer M, Zentner RP & Townley-Smith L (1991) Effect of crop rotations and fertilization on soil organic matter and some biochemical. properties of a thick Black Chernozem. Can J Soil Sci 71: 377–387
15. Campbell CA, DeJong R & Zentner RP (1984) Effect of cropping, summerfallow and fertilizer nitrogen on nitrate-nitrogen lost by leaching on a Brown Chernozemic loam. Can J Soil Sci 64: 61–74
16. Campbell CA, Lafond GP & Zentner RP (1993). Spring wheat yield trends as influenced by fertilizer and legumes. J Prod Agric 6: 564–568
17. Campbell CA, Lafond GP, & Zentner RP (1994) Nitrate leaching in a Udic Haploboroll as influenced by fertilizer and legumes. J Environ Qual 23: 195—201
18. Campbell CA, Moulin AP, Curtin D, Lafond GP & Townley-Smith L (1993) Soil aggregation as influenced by cultural practices in Saskatchewan. I. Black Chernozemic soils. Can J Soil Sci 73: 579–595
19. Campbell CA & Paul EA 1978 Effect of fertilizer N and soil moisture on mineralization, N recovery, A-values under spring wheat grown in small lysimeters. Can J Soil Sci 58: 39–51
20. Campbell CA, Schnitzer M, Lafond GP, Zentner RP & Knipfel JE (1991). Thirty-year crop rotations and management practices effects on soil and amino nitrogen. Soil Sci Soc Am J 55: 739–745
21. Campbell CA & Zentner RP (1993) Soil organic matter as influenced by crop rotations and fertilization. Soil Sci Soc Am J 57: 1034–1040
22. Campbell CA, Zentner RP, Dormaar JF & Voroney RP (1986) Land quality, trends and wheat production in western Canada. In: Slinkard AE & Fowler DB (eds) Wheat Production in Canada - A Review, pp 318–353. Proc. of the Canadian Wheat Production Symposium, Saskatoon, SK, Canada.
23. Campbell CA, Zentner RP, Janzen HH & Bowren KE (1990) Crop rotation studies on the Canadian prairies. Canadian Gov't. Publ. Centre, Supply Services Canada, Hull, P.Q. Publ. No. 1841/E. 133 p
24. Campbell CA, Zentner RP & Lafond GP (1991) Legumes in cereal-based rotations: Influence on profitability and soil quality. Better Crops with Plant Food. Spring, 1991. pp 28–30
25. Campbell CA, Zentner RP, Selles F & Akinremi OO (1993) Nitrate leaching as influenced by fertilization in the Brown soil zone. Can J Soil Sci 73: 387–397
26. Campbell CA, Zentner RP, Selles F, Biederbeck VO and Leyshon AJ (1992) Comparative effects of grain lentil-wheat and monoculture wheat on crop production, N economy and N fertility in a Brown Chernozem. Can J Plant Sci 72: 1091–1107
27. Campbell CA, Zentner RP, Selles F, McConkey BG & Dyck FB (1993) Nitrogen management for spring wheat grown annually on zero-tillage: yields and nitrogen use: efficiency. Agron J 85: 107–114
28. Charreau C (1972) Problems poses par l'utilization agricole des sols tropicaux par des cultures annuelles. Agron Trop (France) 27: 905–929
29. Cowell LE &Doyle PJ (1993) Nitrogen use efficiency. In: Rennie DA, Campbell CA & Roberts TL (eds) Impact of Macronutrients on Crop Responses and Environmental Sustainability on the Canadian Prairies - A Review, pp 49–109. Can Soc Soil Sci Ottawa, ON, Canada
30. Cowell LE & Doyle PJ (1993) Crop nutrients and the environment. In: Rennie DA, Campbell CA & Roberts TL (eds) Impact of Macronutrients on Crop Responses and Environmental Sustainability on the Canadian Praires - A Review, pp 474–527 Can Soc Soil Sci, Ottawa, ON, Canada
31. Curtin D, Selles F, Campbell CA & Biederbeck VO (1993) Role of agriculture as a source and sink of the greenhouse gases carbon dioxide and nitrous oxide. Final report, Greenhouse Gases Initiative Project. Research Branch, Agriculture Canada, Research Station, Swift Current, SK. Publ. No. 379M0082. 72 p
32. DeDatta SK, Fillery IRP, Obcemea WN & Evangelista RC (1987) Floodwater properties, nitrogen utilization, and nitrogen-15 balance in a calcareous lowland rice soil. Soil Sci Soc Am J 51: 1355–1362
33. DeDatta SK & Buresh RJ (1989) Integrated nitrogen management in irrigated rice. Adv Soil Sci 10: 143–169
34. DeDatta SK, Trevitt ACF, Freney JR, Obcemea WN, Real JG & Simpson JR (1989) Measuring nitrogen losses from lowland rice using bulk aerodynamic and nitrogen-15 balance methods. Soil Sci Soc Am J 53: 1275–1281
35. Deevey ES (1957) Limnologic studies in middle America with a chapter on Aztomnology, Conn Acad Arts Sci Trans 39: 213–328
36. Diekmann KH, DeDatta SK & Ottow JCG (1993) Nitrogen uptake and recovery from urea and green manure in lowland rice measured by ^{15}N and non-isotope techniques. Plant Soil 148: 91–99
37. Dubey HD & Fox RH (1974) Denitrification losses from humid tropical soils of Puerto Rico. Soil Sci Soc Am Proc 38: 917–920
38. Eichner MJ (1990) Nitrous oxide emissions from fertilized soils: Summary of available data. J Environ Qual 19: 272–280
39. Engelstad OP & Russel DA (1975) Fertilizers for use under tropic;al conditions. Adv Agron 27: 175–208
40. Fillery IRP & DeDatta SK (1989) Ammonia volatilization from nitrogen source applied to rice fields. I. Methodology, ammonia fluxes and nitrogen-15 loss. Soil Sci Soc Am J 50: 80–86
41. Freney JR, Denmead OT, Wood AW, Saffigna PG, Chapman LS, Ham GJ, Hurney AP & Stewart RL 1992 Factors controlling ammonia loss from trash covered sugarcane fields fertilized with urea. Fert Res 31: 341–349
42. Fujisaka S Guino R & Obusan L 1993 Could farmers recommending a recommendation be right? The question of nitrogen at transplanting for irrigated rice. ASIALAND workshop on interpreting data from field experiments on upland soils. IBSRAM Technical Notes No. 6 (*In press*)
43. Gamboa J, Paez G & Blasco M 1971 Unmodelo para describir los procesos de retencian y lixiviacio en los suelos. Turrialba 21: L 312–316
44. Greenland DJ (1962) Denitrification in some tropical soils. J Sci 58: 227–33
45. Greer KJ (1989) Evaluating the soil quality of long-term crop rotations at Indian Head, M.Sc. Thesis, Univ. of Saskatchewan, Saskatoon, SK.
46. Grove TL (1980) Nitrogen fertility in Oxisols and Ultisols of the humid tropics. Cornell Int Agric Bull 36: 3–27
47. Hedlin RA & Cho CM (1974) Fertilizer use and other soil management practices in relation to contamination of ground and surface water with nitrogen and phosphorus. In: Allocative Conflicts in Water Resource Management, pp 303–323. Agassiz Centre for water studies, Univ. of Manitoba, Winnipeg, Man

48. Henry JL & Meneley WA (1992) Nitrate in the Environment. In: Ed. by John L. Havlin, Kansas State Univ., Manhatan, KS pp 1–14 Great Plains Soil Fertility Conference Proc., Denver, Colorado. March 3–4, 1992. pp 1–14
49. Hutchinson GL, Guenzi WD & Livingston GP (1993) Soil water controls on aerobic soil emission of gaseous nitrogen oxides. Soil Biol Biochem 25: 1–9
50. Ingram KT, Dingkuhn M, Novero RP & Wijangco EJ (1991) Growth and CO_2 assimilation of lowland rice in response to timing and method of N fertilization, Plant Soil 132: 113–125
51. Jamaica Agricultural Society (1954) The Farmer's Guide. The Univ. Press, Glasgow. Scotland
52. Jenny H (1949) Comparative study of decomposition rates of organic matter in temperature and tropical regions. Soil Sci 68: 419–432
53. John PS, Buresh RJ, Pande RK, Prasad R & Chua TT (1992) Nitrogen-15 balances for urea and neem coated urea applied to lowland rice following two cowpea cropping; systems. Plant Soil 120: 233–241
54. Juma NG (1993) The role of fertilizer nutrients in rebuilding soil organic matter. In: Rennie DA, Campbell CA & Roberts TL (eds) Impact of Macronutrients on Crop Responses and Environmental Sustainability on the Canadian Prairies - A Review, pp 363–387. Can Soc Soil Sci, Ottawa, ON
55. Keating BA, Godwin DC & Watiki JM (1991) Optimising nitrogen inputs in response to climatic risk. In: Muchow RC & Bellamy JA (eds) Climatic Risk in Crop Production: Models and Management for the Semiarid Tropics and subtropics, pp 329–358. CAB International, Wallingford, UK
56. Kowalenko CG, Ivarson KV & Cameron DR (1978) Effect of moisture content, temperature and nitrogen fertilization on carbon dioxide evolution from field soils. Soil Biol Biochem 10: 417–423
57. Lueken H, Hutcheon WL & Paul EA (1962) The influence of nitrogen on the decomposition of crop residues in the soil. Can J Soil Sci 42: 276–288
58. Malhi SS & Nyborg M (1983) Field study of the fate of fall-applied ^{15}N-labelled fertilizers in three Alberta soils. Agron J 75: 71–74
59. McGill WB, Campbell CA, Dormaar JF, Paul EA & Anderson DW (1981) Soil organic; matter losses. In: Agriculture land: Our disappearing heritage. A. symposium, pp 72–133. Proc. Ann. Alberta Soil Sci. Workshop, Edmonton. 24–25 Feb. 1981 Alberta Soil and Feed Testing Lab., Edmonton, AB
60. Moraghan JT, Rego TJ, Buresh RJ, Vlek PLG, Burford JR, Singh S & Sahrawat KL, (1984) Labeled nitrogen fertilizer research with urea in the semi-arid tropics. II. Field studies on a Vertisol. Plant Soil 80: 21–33
61. Moraghan JT, Rego TJ & Buresh RJ (1984) Labeled nitrogen fertilizer research with urea in the semi-arid tropics. III. Field studies on Alfisol. Plant Soil 82: 193–203
62. Myers RJK (1992) Management of nitrogen in cropping systems in Indonesia - a review of studies using ^{15}N. Soil Manage Abstr 4: 109–137
63. Myers RJK & Hibberd DH (1986) Effect of water supply and fertilizer placement on use of nitrogenous fertilizer by grain sorghum on cracking clay soils. Proc. Aust. Sorghum Conf 5. 82–5.92
64. Myers RJK, Palm CA, Cuevas E, Gunatilleke IUN & Brossard M (1994) The synchronisation of nutrient mineralisation and plant nutrient demand. p 81–116. In: Woomer PL and Swift MJ (eds) The management of Tropical Soil Biology and Fertility, pp 81–116. John Wiley and Sons
65. Palm O, Weerakoon WL, De Silva MA & Rosswall T (1988) Nitrogen mineralization of *Sesbania sesban* used as green manure for lowland rice in Sri Lanka. Plant Soil 108: 201–209
66. Rennie DA, Campbell CA & Roberts TL (1993) Impact of macronutrients on crop responses and environmental sustainability on the Canadian prairies - a review. Can Soc Soil Sci, Ottawa, ON, Canada. 527 p
67. Ryden JC, & Lund LJ (1980) Nature and extent of directly measured denitrification losses from some irrigated vegetable crop production units. Soil Sci Soc Am J 44: 505–511
68. Sahrawat KL & Keeney DR (1986) Nitrous oxide emission from soils.
Adv Soil Sci 4: 143–148
69. Sanchez PA (1976) Properties and Management of Soils in the Tropics. John Wiley and Sons, New York
70. Sanchez PA & Buol SW (1975) Soils of the tropics and the world food crisis. Science 188: 598–603
71. Sanginga N, Mulongoy K & Ayanaba A (1988) Nitrogen contribution of *Leucaena/Rhizobium* symbiosis to soil and a subsequent maize crop. Plant Soil 112: 137–141
72. Savant NK, De Datta SK & Craswell ET (1982) Distribution patterns of ammonium nitrogen and ^{15}N uptake by rice after deep placement of urea supergranules in wetland soil. Soil Sci Soc Am J 46: 567–573
73. Semb G & Robinson JBD (1969) The natural nitrogen flush in different arable soils and climates in East Africa. East Afr Agric For J 34: 350–370
74. Sisworo WH, Mitrosuhardjo MM, Rasid H & Myers RJK (1990) The relative roles of N fixation, fertilizer, crop residues and soil in supplying N in multiple cropping systems in a humid, tropical upland cropping system. Plant Soil 121: 73–82
75. Stanford G (1973) Rationale for optimum nitrogen fertilization in corn production. J Environ Qual 2: 159–166
76. Thompson CH (1974) Fertilizing dryland grain sorghum on upland soils in the 20- to 26- inch rainfall area in Kansas. Kansas State University Agricultural Experiment Station Bulletin 579
77. Thompson CH (1975) Fertilizing dryland wheat on upland soils in the 20–26-inch rainfall area in Kansas. Kansas State University Agricultural Experiment Station Bulletin 590
78. Tortoso AC & Hutchinson GL 1990 Contributions of autotrophic and heterotopic nitrifiers to soil NO and N_2O emissions. Appl Environ Microbiol 56: 1799–1805
79. van Kessel C, Pennock DJ & Farrell RE (1992) Temporal denitrification at the landscape scale in a Black soil. In: Proc Soils and Crops Workshop, pp 280–289. Published by Univ. of Saskatchewan, Saskatoon, SK
80. Wetselaar R (1962) Nitrate distribution in tropical soils. Plant Soil 16: 19–31
81. Wright GC & Catchpoole VR (1985) Fate of urea nitrogen applied at planting to grain sorghum grown under sprinkler and furrow irrigation on a cracking clay soil. Aust Agric Res 36: 677–684
82. Xu ZH, Saffigna PG, Myers RJK & Chapman AL (1993) Nitrogen cycling in Leucaena (*Leucaena leucocephala*) alley cropping in semi-arid tropics. I. Mineralization of nitrogen from Leucaena residues. Plant Soil 148: 63–72
83. Xu ZH, Myers RJK, Saffigna PG & Chapman AL (1993) Nitrogen cycling in Leucaena (*Leucaena leucocephala*) alley cropping in semi-arid tropics. II. Response of maize growth to addition of nitrogen fertilizer and plant residues. Plant Soil 148: 73–82

84. Zentner RP, Campbell CA, Brandt SA, Bowren KE & Spratt ED (1986) Economics of crop rotations in western Canada. In: Slinkard AE & Fowler DB (eds) Wheat Production in Canada - A Review, pp 254–317. Proc Can Wheat Prod Symp 3–5 March 1986, Saskatoon, SK

85. Zentner RP, Ukrainetz H & Campbell CA (1989) The economics of fertilizing bromegrass in Saskatchewan. Can J Plant Sci 69: 841–859