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Management of nutrients and water in rainfed arid and semi-arid areas

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FOREWORD

Sustainable food security is needed for the arid and semi-arid regions of the tropical, sub-tropical and warm-temperate climatic zones. In these regions the supply of locally grown food is unreliable because much of it is produced in conditions of highly variable rainfall. Even in favourable seasons, these regions are becoming increasingly dependent on imported food.

The arid and semi-arid regions have not benefited from the "green revolution" as much as areas that are well endowed with water resources. High yielding crop varieties express their full potential only when supplied with non-limiting amounts of water, fertilizers and usually large inputs of pesticides. In arid and semi-arid regions, crop responses to inputs such as fertilizers have generally been low and unprofitable to the farmer. Understandably, input levels remain low and yields are not increasing. The problem of increasing crop productivity in these regions is widely recognized as difficult.

There is evidence, however, that yields can be profitably increased, and the variability in food supply decreased, with a combination of careful management of water and judicious use of fertilizers. There is a pressing need for a better understanding of the mechanisms by which nutrients and water interact when both are in short supply, in order that improved management strategies may be developed to ensure sustainable crop yields. Nuclear techniques provide particularly useful tools for such work. The soil-moisture neutron probe in conjunction with isotopes provide the ability to determine how experimental farm-management practices affect soil moisture availability to crops and efficiency of uptake of fertilizers and soil nutrients.

The IAEA's involvement in field studies on soil-water use dates back several years. A five-year Co-ordinated Research Project on "The Use of Nuclear and Related Techniques in Assessment of Irrigation Schedules of Field Crops to Increase Effective Use of Water in Irrigation Projects," involved the participation of scientists in Argentina, Brazil, China, Côte d'Ivoire, Ecuador, France, Hungary, Morocco, Pakistan, Romania, Spain, Turkey and the USA. That project, completed in 1995, laid a solid foundation for future research. Because of a scarcity of water in many developing countries and increasing needs for sustainable food security in the face of increasing populations and lack of funds for irrigation schemes of significant dimension, research must focus on improved management of (i) the modest quantities of fertilizers that are available to farmers, (ii) the natural resources that are available to farmers for increasing soil organic matter content, and (iii) rain water.

The Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture held a Consultants Meeting on Management of Nutrients and Water in Rainfed Arid and Semi-Arid Areas for Increasing Crop Production, 26-29 May 1997. The assistance of J. Angus and A.R.J. Eaglesham in the preparation of this publication is gratefuly acknowledged. The IAEA officer responsible for this publication is P. Moutonnet of the Joint FAO/IAEA Division.

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SUMMARY

Research is needed on the limited number of factors that can be managed in farming systems of rainfed arid and semi-arid zones. Some factors such as fertilizer use have been intensively studied, but less research has been conducted on the farming-systems aspects of cropping sequence and the management of crop residues. There have been even fewer studies of the interaction of the management of crop sequences and residues with inputs of fertilizers. Exploiting this interaction, particularly in relation to the limited inputs of water and fertilizer appropriate for semi-arid regions, is the most promising way of profitably increasing yields. The contributions of the consultants meeting can be summarized as follows:

- The key is to combine nutrient inputs with crop management practices that increase the supply of water to the crop. The steps to maximize water use by the crop are known in principle. Infiltration of rainfall into the root zone should be maximized, water losses by soil evaporation and weeds should be minimized, and extraction of soil water by the crop should be maximized. However, there are few examples of farmers' adoption of water-conserving strategies within the arid and semi-arid regions. Research aimed at improving practices must be conducted within the context of existing farming systems so that there is interaction among farmers, extension services and researchers to ensure that new technology is appropriate.

- Nuclear techniques provide particularly strong tools to understand the mechanisms by which nutrients and water interact. The soil moisture neutron probe provides the most effective means of quantifying the moisture regime in a cropping system. The use of ^{15}N is the most appropriate method of measuring fertilizer-nitrogen use, the input of biologically-fixed N by legumes, and the transfer of fixed N to subsequent cereals. Both ^{13}C and ^{15}N can be used to investigate decomposition of residues. The use of ^{32}P is the most appropriate way to discover the fate and movement of applied phosphatic fertilizers.

- The long-term sustainability of many existing cropping systems in arid and semi-arid environments is questionable because of land degradation. The common practice of removing crop residues is leaving the soil surface exposed to erosion by water and wind. Removal of residues is leading to rapid depletion of soil organic matter and inorganic nutrient reserves. In some environments nutrient removal and leaching are causing soil acidification while the movement of water in the landscape is leading to salinization.

- If crop production can be increased, there are grounds for optimism about the current problems of land degradation. Additional crop production leads to larger quantities of residue that can build up soil organic matter and provide protection from erosion. Moreover, vigorous crops extract more soil water, leaving less for off-site problems such as salinization. However, the environmental benefits will be realized only if the technology is profitable to the farmer. Research should therefore aim to maximize returns to the farmer through practices that will be environmentally sustainable.

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WATER AND NITROGEN IN CROP AND PASTURE SYSTEMS IN SOUTHERN AUSTRALIA

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Abstract

Recent research on water and N for dryland crops in southern Australia has addressed the need for more efficient and sustainable production. Water-use efficiency is well below the potential and N-use efficiency well below optimum on farms. Excess water and N cause on-site and off-site environmental damage. The most effective means of illustrating these inefficiencies to growers is to present simple benchmarks of water and N-use efficiencies with which farmers can assess and improve the performance of their own crops. The practices shown by our recent research that best support the goals of more efficient and sustainable production are those that maximize extraction of soil water and mineral N, and increase biological N_2 fixation. Wheat growing after a brassica break-crop extracts more water and mineral N from the soil than when grown as a continuous cereal, apparently because of a 'biofumigation' effect that reduces the numbers of soil-borne pathogens of wheat and produces a stronger root system. In the case of phased pasture-crop systems, annual pastures do not fully extract subsoil water or mineral N. However, when the grasses are removed from annual pastures with a selective herbicide, the remaining pure clover rapidly decomposes after maturity, leaving a large amount of mineral N for the following crop. Perennial pastures containing lucerne produce more forage and fix more N_2 than do annual pastures, but they dry the soil profile. After removal of the lucerne, the soil may be so dry that mineralization is slow, with the risk of water deficit for the subsequent crop.

1. INTRODUCTION

Temperate crops and improved pastures occupy much of the subhumid plains of eastern, southern and southwestern Australia. The area of this farmland is about 60 M ha, occupied by about 60,000 farms and producing about 20 M tonnes of grain and carrying 75 M sheep and 6 M cattle. The original vegetation over much of the region was woodland, the clearing of which commenced late last century and has continued in some regions until recently. The soils differ widely in terms of fertility, texture, depth and origin, but most are P deficient and there is widespread trace-element deficiencies on the sandy and alkaline soils of southern Australia. There are also widespread toxicities, including those associated with recent surface-soil acidification in the high-rainfall areas of the south-east and south-west, with natural sodicity and excessive subsoil boron in alkaline soils formed on marine sediments in the drier areas of the south. The growing season extends from autumn to late spring in most regions, and the rainfall in this period varies from 150 to 450 mm [1]. The climatic variability is lowest in the south-west and highest in the north-east. An example of the consequence of the year-to-year variability in rainfall in the south-east is that wheat yield varied from 1 t ha^{-1} during the 1994 drought to 7 t ha^{-1} in the following year.

In much of the area, crops and pastures for sheep are grown on the same properties. Since the 1950s, the common rotation has been a phase of cereals (wheat, barley and oats) alternating every 2 to 5 years with a phase of grazed annual pastures [2]. Since the 1970s, crop production has grown relative to animal production, and since the 1980s there has been a greater diversity of crops, in particular lupin, field pea, canola and chickpea. The major industries of grain, wool and meat operate with virtually no government subsidies, and about 80% of production is exported. These industries have suffered severe economic pressures from the protectionist and dumping practices of the EEC and USA since the mid-1980s. To survive financially during this period of reduced commodity prices, Australian farmers have had to increase efficiency of production. The field research supporting these increases has largely been conducted on farms, much of it in a process of co-learning, in which researchers are in frequent contact with groups of farmers. Much of this research has addressed the problems of water and N management, and recent achievements and current research are discussed here.

2. BENCHMARKING WATER AND NITROGEN USE

2.1. Water

A remarkable convergence of research and extension has developed around the concept of water-use efficiency for crops, particularly in the drier parts of southern Australia. The origin was the work of French and Schultz who plotted yield of wheat in many experiments against the seasonal water use (Fig. 1) [3]. They showed that water use by the most efficient crops formed a frontier with a transpiration efficiency for grain production of 20 kg ha^{-1} mm^{-1} and an intercept of 110 mm on the abscissa, representing soil evaporation. The yields of most experimental crops and all regional crops fell below this frontier, suggesting two major conclusions. First, the yields of almost all crops were not limited by water supply but by factors which were mostly under the farmer's control, such as time of sowing, diseases, weeds and soil problems such as toxicities, waterlogging and nutrient deficiencies [4]. Second, the gap between actual and water-limited yields was greatest in wet years. Most farmers understand and apply this concept to their own crops and are now in a position to target the potential water-use efficiency, particularly in the favourable years when most of the income is made in a variable climate. Water-use efficiency is an easily understood concept that provides a benchmark to lead farmers to a more positive attitude towards overcoming problems rather than blaming droughts for all low yields.

There are obvious simplifications in the concept, such as neglecting runoff and deep percolation, the effect of atmospheric vapour-pressure deficit on transpiration efficiency, and the timing of rainfall, for example at the end of the season when it is ineffective [5]. It appears that these are second-order factors, apparently because the humidity is relatively constant and the rain is mostly effective, i.e. it falls during the active growing period and little is wasted to runoff and deep percolation. More recent studies have shown that the 'French and Schultz' constants are remarkably robust for cereals in southern Australia, and can be modified for other crops such as canola, with different yield potentials, and also be modified in relation to sowing date [6].

Water-use efficiency benchmarks are useful in crop improvement as well as in helping to identify management limitations. One aspect involves breeding crops for faster leaf-area expansion leading to faster ground cover by seedlings, a reduction in soil evaporation with the consequence of more water available for transpiration [7]. Another aspect is breeding for higher transpiration efficiency, basing a selection strategy on the discrimination against $^{13}CO_2$ relative to $^{12}CO_2$, by leaves with partially open stomates. A relatively high ratio of the stable isotope ^{13}C to ^{12}C indicates genotypes of high transpiration efficiency [8]. Selecting for rapid ground cover is important in semi-arid environments in which there are large losses of soil water by surface evaporation, for example because the topsoil is kept wet by frequent small rainfall events. On the other hand, higher water-use efficiency is likely to be most effective when a crop grows largely on stored soil water.

2.2. Nitrogen

Establishing a benchmark for N is as important as for water. Nitrogen fertilizer often gives the least profitable returns of the essential nutrients because of the large amounts required and the high price per unit [9]. The simplest benchmark is the N-use efficiency, typically expressed as kg of additional grain per kg of applied N. This number can be compared with the ratio of N-cost to grain price so as to calculate the economic optimum rate of N application. For example, if the cost of fertilizer is \$0.80 kg^{-1} N and the grain price is \$0.20 kg^{-1}, the price ratio is (\$0.80/\$0.20=4.0). Using this approach, the optimum rate of N fertilizer is achieved when the marginal N-use efficiency has diminished to the price ratio. This approach neglects any premiums for grain protein and the response of grain protein to applied N. This is a serious limitation when cereals are grown for their protein as well as for carbohydrate, and benchmarks based on grain are misleading when the grain-protein level changes in response to applied N.

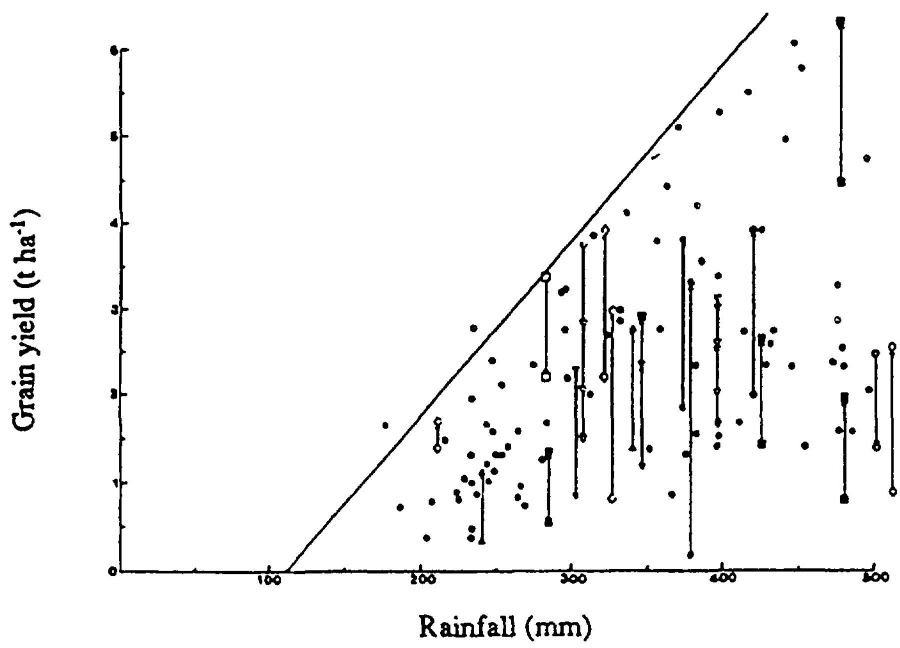

FIG 1. Wheat yield in relation to crop water use during the growing season (after French and Schultz [3]) The line represents a transpiration efficiency of 20 kg ha^{-1} mm^{-1} and the intercept on the abscissa represents soil evaporation of 110 mm The points represent yields of experimental crops and the vertical lines represent gaps between actual and water-limited yields

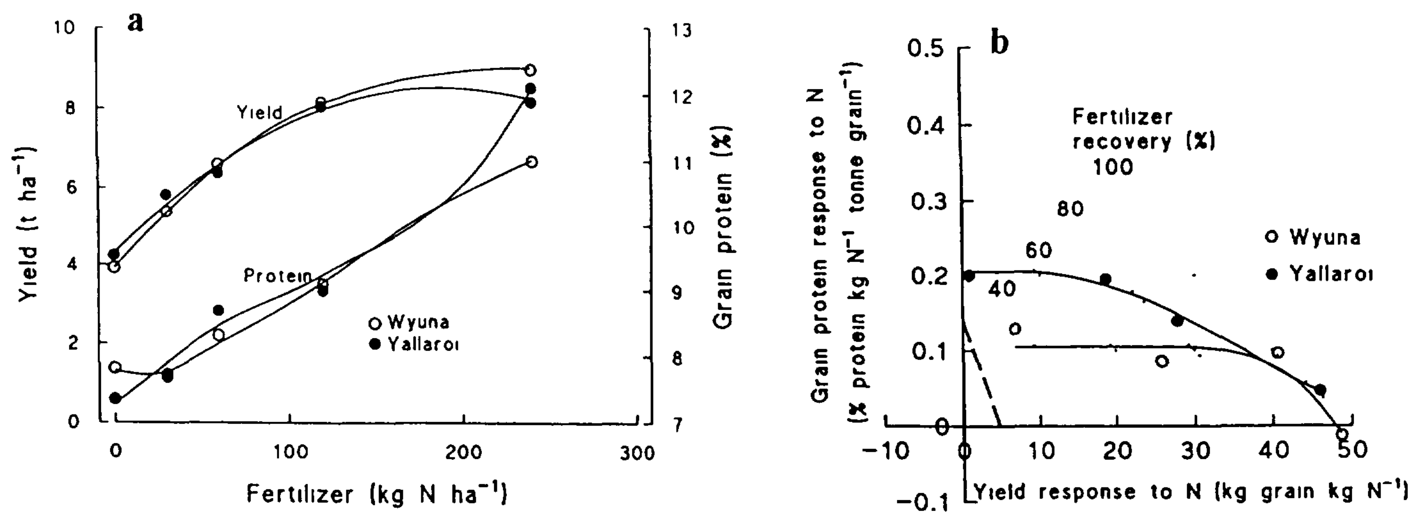

FIG. 2. (a) Responses of yield and grain protein of wheat to applied N (b) The same data expressed as marginal responses The dotted lines represent theoretical maximum responses [9] The dashed line represents an economic break-even line for given costs of fertilizer, price of grain and premium for additional grain protein Responses lying above and to the right of this line represent profitable use of N

Figure 2a presents a typical grain-protein response that accompanies the yield responses to applied N: diminishing returns in yield and increasing returns in grain protein. These data can be analyzed to present the efficiency of N that takes account of grain protein as well as yield. In Fig. 2b, re-analysis of the data shows the marginal returns of yield to applied N on the abscissa and the marginal returns of grain protein to applied N on the ordinate. In this example, there was an apparent fertilizer recovery of 100% when the N-use efficiency approached 50 kg grain kg^{-1} N, but grain protein was unaffected by applied N. At higher levels of applied N, when the apparent fertilizer recovery decreased to 40%, the yield response had plateaued, but grain protein responded at a rate of 0.2% protein kg^{-1} N per tonne of grain. At the prevailing yield level of 8 t ha^{-1}, this was equivalent to 0.025% protein kg^{-1} N. The equations behind this approach were presented by Angus [9].

A controversial comment about crop-N research has been made by Fujisaka [10]. He strongly criticizes research that focuses on losses of fertilizer N and methods to inhibit urease activity and nitrification, while neglecting management research to increase the economic efficiency of low-cost fertilizers. While Fujisaka's comments were made mostly about research on lowland rice, they could equally be applied to dryland crops. The simplest method to boost fertilizer efficiency on farms is to apply the amount of fertilizer that accurately supplements the N-supply by the soil to balance the N-demand by the crop [11]. An important requirement for this approach is a routine tests of soil nitrate, just prior to sowing, to a depth of at least 60 cm. Simple and reliable methods for measuring soil nitrate in the field are now available [12].

Much can be done to increase the efficiency of N fertilizer for dryland crops with innovative placement and timing of application. For example, concentrated bands of ammonia-based fertilizer inhibit nitrification and hence denitrification and leaching. Topdressing as a tactical response to a favourable season or a forecast rain event can greatly increase yield and protein responses compared to the practice of strategic or regular application according to a blanket recommendation. Simulation models of yield response in relation to environmental factors offer ways of quantifying the risks [13]. However, the simplest and most effective means of increasing N-use efficiency in southern Australia is through manipulation of cropping sequences as discussed below.

3. BREAK-CROPS, BIOFUMIGATION AND SOIL WATER AND NITROGEN

3.1. Understanding the effect of break-crops

Rotating crops is a motherhood recommendation made by advisers worldwide, but its justification is not often clearly expressed. Recommendations for crop rotations are often based upon the results of long-term rotation experiments in which the same sequence of crops is grown repeatedly for long enough for results to become statistically significant. Strict rotations are seldom followed on farms and probably should not be. It is more sensible for farmers and advisers to develop flexible crop and pasture sequences based on rules that account for short goals and long-term environmental considerations. For example, such rules could account for product price, cost of production, diversification of income, breaks in the life cycle of pathogens, residual soil water and mineral nutrients, allelopathic effects of stubble, and the constraints imposed by herbicide-carryover and potential herbicide resistance in weed populations.

Research to assist decision-making about crop sequences in southern Australia has focused on the mechanisms by which the individual factors operate. In recent years, the advantages of a *Brassica* species in breaking the life cycle of wheat root diseases have been clarified. Angus et al. [14] showed that wheat growing after different brassicas (canola, *Brassica napus*, and Indian mustard *Brassica juncea*) had different yields and grain-protein levels, and extracted different amounts of soil water and mineral N. Extensive subsequent testing of break-crops indicated that wheat after a brassica typically yielded 25% more than after wheat [15]. The benefit is not simply because soil-borne fungal pathogens are without a host, but also because brassica root exudates have an active suppressive effect [16]. The main functional compounds are isothiocyanates released from the breakdown of glucosinolates (Fig. 3) that are contained in seed, foliage and roots of the *Brassiceae*. The familiar sharp taste of condiment mustard is due to the hydrolysis of glucosinolate on the tongue. The raw product for condiment mustard production is the seed meal remaining after oil extraction of various species of *Brassica*.

The numerous *Brassica* species and genotypes contain glucosinolates with various side-chains that are of differing toxicity to the pathogens [17]. Isothiocyanates also suppress the growth of insects and nematodes, and in some cases inhibit germination of weed seeds [18]. Knowledge of the toxic properties of brassica tissues to fungi has been available for decades [19]. However, only recently has the prospect of breeding specifically for suppressive roots or foliage been promoted. It appears likely that the levels of glucosinolates in the root, foliage and seeds can be modified independently, so there is scope for breeding cultivars with low levels in the seed but high levels in the root. There are challenges in producing dual-purpose brassicas, for example with the seed low, but the root high, in glucosinolates with specific side chains. Another possibility is to develop cover crops designed specifically for disease and pest suppression, with high levels of glucosinolates of known toxicity to target pests. Such cover crops may have a role in controlling pests and disease in subsequent high-value crops, thereby reducing the need for fumigants and synthetic pesticides. An even bigger challenge is extending the biofumigation concept to tropical farming systems, because brassicas are generally not well adapted to high temperatures. It may be that there are botanical taxa other than the *Brassiceae* with analogous mechanisms for pest and disease suppression.

3.2. Soil water and mineral N extraction in relation to break crops

Wheat grown after a break crop extracts more soil water and mineral N than when grown after wheat. The additional amounts extracted have been as much as 40 mm of soil water and 20 kg N^{-1} ha [14,20]. In these experiments, the additional extraction applied over most of the rooting zone, but was not particularly associated with deeper rooting (Fig. 4). The roots of cereals growing after brassicas dried the soil to suctions much greater than the widely recognized limit of 1.5 MPa, whereas after cereals the soil was dried to suctions of about 1.5 MPa.

Two hypotheses have been advanced to explain the greater suction. One is that the brassicas leave channels in the soil through which the subsequent cereal roots are able to penetrate rapidly. The other is that the roots of wheat following the break-crop are healthier and able to function better. Cresswell and Kirkegaard [21] found no evidence for the root-channel hypothesis with annual crops, so it is likely that the main benefit is through reduction in root disease.

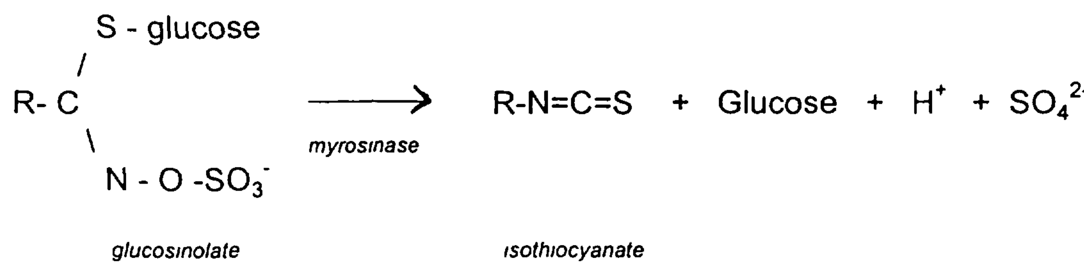

FIG 3. Hydrolysis of glucosinolate leading to formation of isothiocyanate during the breakdown of brassica tissue R represents the side chain common to both the glucosinolate and isothiocyanate

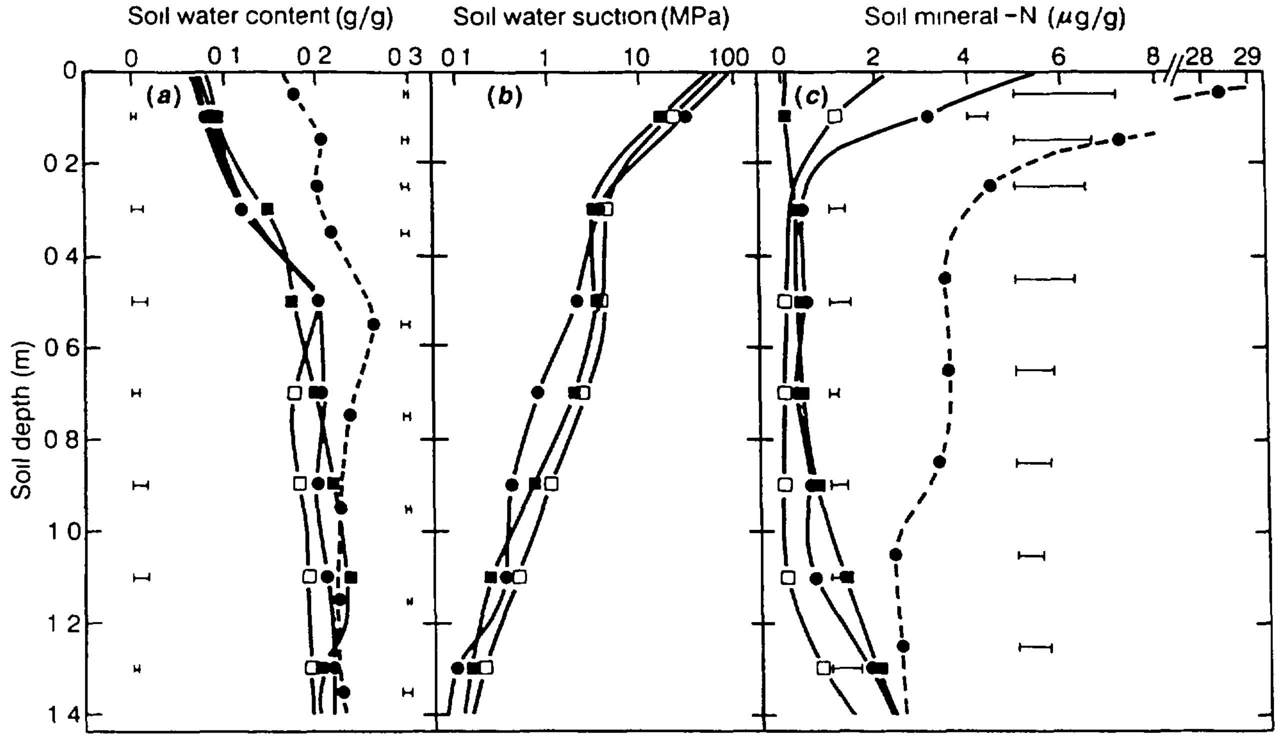

FIG 4 Soil profiles of (a) water content (b) water suction and (c) mineral-N concentration, sampled at maturity (solid lines) of wheat crops following canola (●), Indian mustard (□) and wheat (■) Water content and mineral N at sowing (dashed line) for the wheat following wheat are also presented. Horizontal bars represent standard errors of means [9]

The short-term effects of the additional extraction are increases in yield and protein, but there may be additional environmental benefits. Even in semi-arid environments of southern and eastern Australia there are periods of excess water in the landscape. Reducing the quantity of water stored in the soil increases its capacity to absorb large amounts of rainfall and reduces the incidence of runoff and deep percolation. Consequently there is less soil erosion and accession of water and nutrients to groundwater as well as the associated benefits of reduced salinization of the landscape and reduced acidification associated with nitrate leaching.

4. SOIL WATER AND MINERAL NITROGEN FOLLOWING LEGUMES

Self-regenerating legume-based annual pastures are a traditional part of Australian dryland farming systems, providing animal feed for wool and meat production as well as increasing the supply of soil N for following crops. Figure 6 shows the increases in soil N during a pasture phase and the decrease during a cropping phase. Over the past 25 years, pastures have increasingly been replaced by crops. The reason appears to be a spiral, starting with low prices for animal products, leading to low profitability of pastures, less investment in inputs such as fertilizer and, finally, declining pasture production. While the reduced investment may appear justified when the pastures are considered in isolation, there is a reasonable hypothesis that increased investment is justified when the benefits to the subsequent crops are considered. Research has been started recently to test this hypothesis.

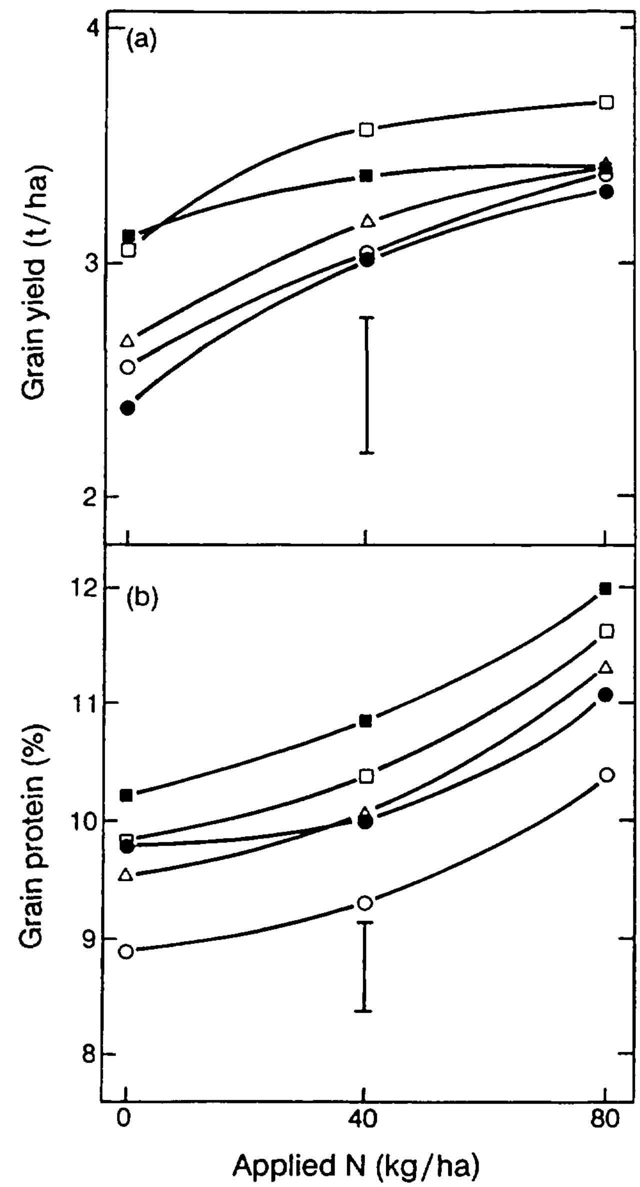

FIG. 5. Responses of applied N of (a) yield and (b) grain protein of wheat following canola (■), linseed (△), Indian mustard (□), oats (○) or wheat (●). The bars represent the LSDs of the species × N interaction [9].

The most obvious symptom in pasture decline is a decreased proportion of legumes, predominantly subterranean clover (*Trifolium subterraneum*) and annual medics (*Medicago* spp.), and an increase in grasses and weedy broadleaf species. The legume proportion can be increased rapidly and inexpensively using grass herbicides. One benefit is the break in the life cycle of cereal root pathogens that are hosted on the pasture grasses. Another is the increased N_2 fixation by the legumes, followed by greatly enhanced N-mineralization [23]. The additional amounts of mineral N for the following crop can be up to 100 kg ha^{-1}, leading to an additional 2 t ha^{-1} of cereal yield [24].

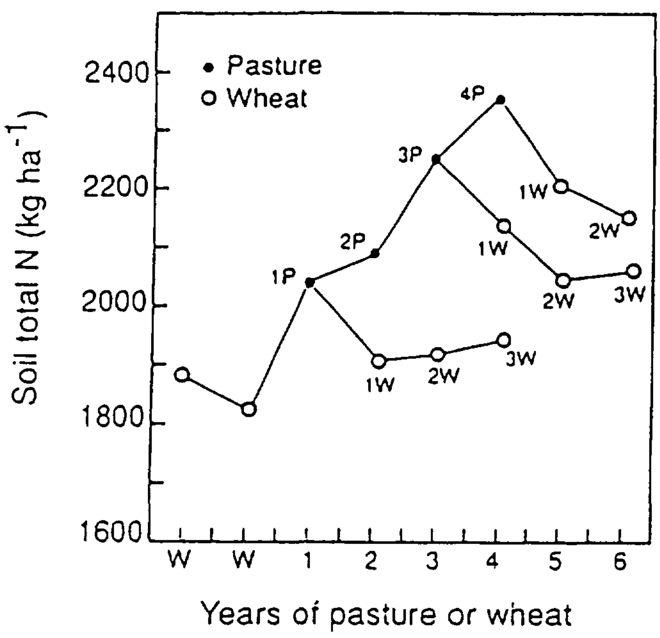

FIG. 6. Changes in the level of total soil N in south-eastern Australia following different numbers of years of legume-based pasture (P) or wheat (W) [22].

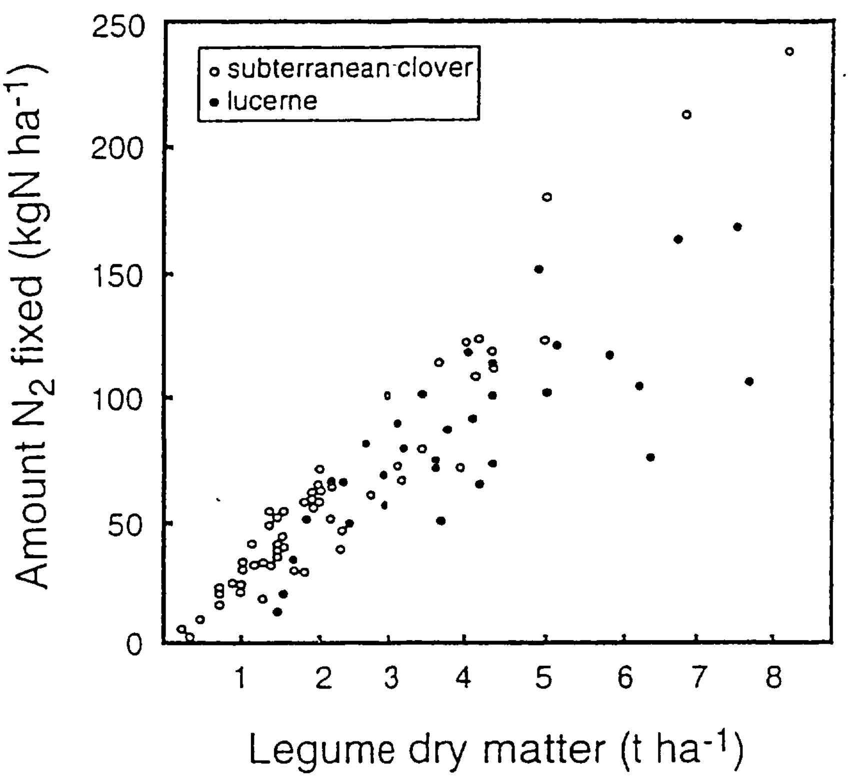

FIG. 7. Amount of N_2 fixed by grazed pastures of subterranean clover and lucerne in relation to the dry-matter production of the legume [23].

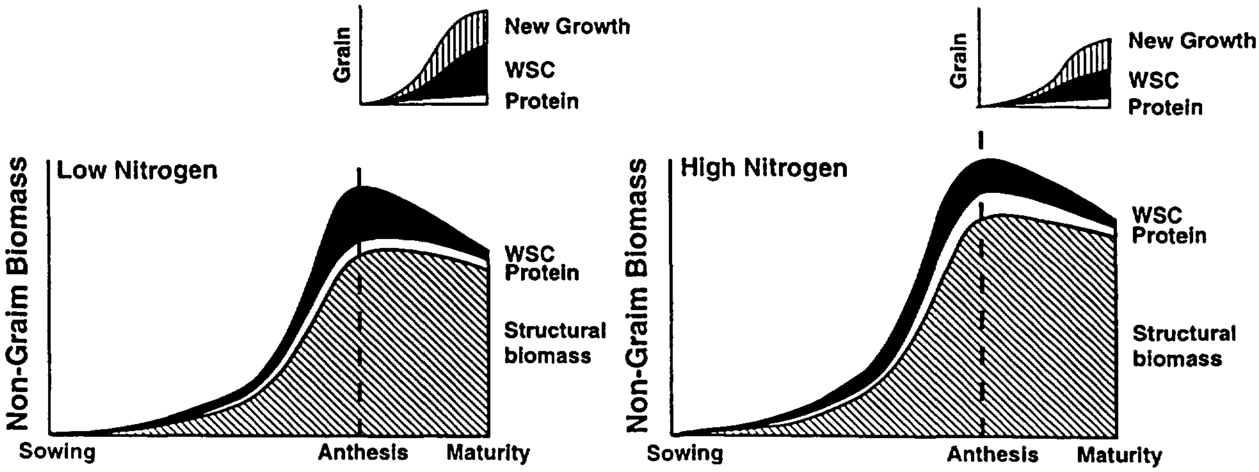

FIG. 8. Comparison of dry-matter production of non-grain and grain biomass of wheat crops at (a) low- and (b) high-N status, in terms of the amounts of structural material, water-soluble carbohydrate (WSC) and protein, during a growing season with a terminal drought.

Perennial pastures containing lucerne (alfalfa, *Medicago sativa*) have advantages because their forage production and N_2 fixation are about twice as high as annual pastures. The greater N_2 fixation is related directly to the dry-matter production for both lucerne- and clover-based pastures; the amount of N_2 fixed by both species is about 25 kg for every tonne of legume biomass (Fig. 7).

High levels of N_2-fixation can be achieved in annual pastures, but there is considerable variability due to extreme shifts in legume composition. For example, about half the N_2 fixed by subterranean clover over a 4-year period was the result of a single favourable season [23]. By contrast, pastures containing lucerne maintain a more stable legume content and continue to grow and fix N_2 when seasonal rainfall patterns are unsuitable for growth of annuals. The average annual input of N_2 fixed by lucerne in this comparison (128 kg N ha^{-1} yr^{-1}) was 90-150% greater than neighbouring subterranean-based pastures (50-66 kg N ha^{-1} yr^{-1}). Therefore, pastures based on lucerne may have greater potential for consistent growth and N_2-fixation than annual pastures. However, the additional lucerne growth also leads to complete exhaustion of water and mineral N throughout the soil profile. The dry soil reduces the rate of mineralization after lucerne removal so that the first subsequent crop may actually be N-deficient, despite a high rate of fixation. It is likely that the soil water will recover after a period of cropping, and the additional fixation will result in faster mineralization than after an annual pasture.

In contrast to the benefits for subsequent crops from pasture legumes, the contribution from crop legumes is relatively small, because most of the fixed N is removed in the grain harvest. The research on both crop and pasture legumes has been based on the fixed N in the above ground parts of the plants, so it is likely that contributions are greater when the fixed N contained in the roots is considered.

5. YIELD DECREASE IN RESPONSE TO EXCESS NITROGEN

Because applied N has such a rapid and cosmetic effect on crops, some farmers are tempted to apply excess. Over-fertilized crops that experience a terminal drought frequently produce lower yields, as much as 25% of a crop yielding 4 t ha^{-1}. The symptoms are early maturity, yield that is low in relation to the amount of vegetative growth and pinched grain of high protein content. The disorder has been widely recognized in Australia for a century and is known as 'haying-off'. Similar symptoms have been reported from many other dryland cropping regions. The presumed cause of the yield decrease is reduced stored soil water at the time of flowering because of extra vegetative growth. The risk of haying-off is a major disincentive for farmers to supply sufficient N for crops to achieve their water-limited yield potential, so that, in a variable environment, crops are under-fertilized in the favourable seasons.

Recently, van Herwaarden et al. [25-27] investigated the reason for haying-off in wheat. Crops of high-N status contained lower reserves of remobilizable carbohydrate at the time of flowering than crops of low-N status. High-N crops therefore suffered the combined stresses of increased water deficit during grain filling, because of additional soil-water extraction, and lack of carbohydrate reserves (Fig. 8). Of these factors, the depletion of carbohydrate was the more important [26]. Surprisingly, high temperature was not found to be a precondition for haying-off, although the association of high temperature with terminal drought had previously led to speculation that it contributed to yield loss [27]. However, it is likely that high-temperature damage increases the loss caused by lack of carbohydrate reserves and water deficit. The new understanding of the mechanism of yield decrease offers leads for overcoming the problem by a combination of genetic change and management techniques to increase soluble carbohydrate reserves.

6. ROLE OF NUCLEAR METHODS

Radioactive and stable isotopes have a potential role in all the examples presented here. Neutron moisture meters can be employed for measuring water use, and ^{13}C can be an indicator of water-use efficiency of crops and pastures. Nitrogen-15 is used in assessing N-use efficiency, tracing N movements and losses in soil and for quantifying N_2-fixation inputs. Carbon-13 or ^{14}C are used in measuring translocation of soluble carbohydrates.

These tools will be most effective if used in testing ways to manage water and N. In our experience in southern Australia, the management of crop sequences and cropping systems has given large economic and environmental benefits. Adoption of new cropping sequences by farmers has been encouraging, and reflects the economic benefits. We suggest that if sustainable practices are to be widely adopted they must be profitable to farmers. Research should therefore focus on systems that are both profitable and sustainable, and are realistic within the farming system.

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THE MANAGEMENT OF NUTRIENTS AND WATER IN THE WEST AFRICAN SEMI-ARID TROPICS

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Abstract

At present, the farming systems in the west African semi-arid tropics are unsustainable, low in productivity, and destructive to the environment. A striking feature of the soils is their inherently low fertility, with negative plant-nutrient balance in many cropping systems. Research in N-use efficiency (NUE) indicated that calcium ammonium nitrate (CAN) significantly outperformed urea on millet. Fertilizer losses, greater for urea (53%) than for CAN (25%) were believed to be due to ammonia volatilization. Continuous cropping resulted in lower yields compared to a cereal grown after cowpea or groundnut, and NUE was improved with crop rotation. Phosphorus deficiency is a major constraint. Phosphate rock (PR), indigenous to the region, e.g. at Tahoua in Niger and Tilemsi in Mali, is suitable for direct application. Partial acidulation of low-solubility PR improves agronomic effectiveness. Long-term soil-fertility management trials indicate that although application of mineral fertilizers increase yields, they alone cannot sustain productivity. When mineral fertilizers are combined with other technologies, such as the return of crop residues and manure, productive and sustainable production systems are possible. Water-use efficiency increased dramatically with the addition of plant nutrients. Technologies for land-surface management and water harvesting, and appropriate cropping systems with careful varietal selection all contribute to the optimization of soil-water use. Future research should focus on water and nutrient interactions and on understanding why presently available improved technologies are not adopted by farmers even when using a participatory approach.

1. INTRODUCTION

The west African semi-arid tropic (WASAT) zone is home to some of the world's poorest people, 90% of whom live in villages and gain their livelihood from subsistence agriculture. Recurrent drought and consequent crop failures in recent years have led to near destruction of the rural economy of the region. Low and erratic rainfall, high soil and air temperatures, soils of poor native fertility, surface crusting and low water-holding capacity, and recurrent water deficits during the growing season are the main abiotic constraints to crop production.

In traditional agricultural systems, when crop yields declined to unacceptable levels, overcropped land was left fallow to restore its fertility, and new areas were then cultivated. Increasing population pressure has decreased the availability of land and resulted in reduced duration of fallow relative to the duration of cropping, to the point that shifting cultivation is losing effectiveness and soil fertility is being lost in many areas. The present farming systems are unsustainable, low in productivity, and destructive to the environment. Plant-nutrient balances are negative for many cropping systems, with offtake greater than input: farmers are mining their soils. In this paper, after a short description of the crop-production environment, we review research on management of plant nutrients and water, and their interactions.

2. THE CROP-PRODUCTION ENVIRONMENT

2.1. Climate

Rainfall in west Africa is controlled by the interseasonal movement of the intertropical convergence zone, north and south of the equator. The amount of rainfall in the semi-arid zone is low, variable and undependable, with a steep north-south gradient representing an additional 1 mm of annual rainfall for every 1 km further south of the Sahara margin. The mean length of the growing period within the zone varies from 75 to 180 days, and the ratio of rainfall to potential evapotranspiration varies from 0.20 to 0.65 [1]. High air temperatures, sometimes exceeding 40°C, can prevent crop-establishment. Sand blasting of the seedlings caused by wind erosion adds to this problem.

2.2. Soil

Entisols, alfisols, and vertisols occupy 26, 33 and 10%, respectively, of WASAT. The entisols are composed mainly of quartz, with low water-holding capacity and nutrient content, and fertilizer efficiency is hampered by severe leaching; they are weakly structured and prone to water- and wind-erosion. The alfisols have a clay accumulation horizon with a low capacity to store nutrients. The vertisols are characterized by a high content of swelling clay with usually high fertility except that P availability is generally low, and high N losses can occur under waterlogged conditions.

The data in Table I show that Sudan-savanna soils in the semi-arid zones have low organic-C and total-N contents because of low biomass production and high rates of organic-matter decomposition. In addition to low reserves of P, the low-activity clay of these soils has a relatively low capacity to fix added phosphate [3]. The textures are predominantly sandy to sandy loams (Table II). The dune soils of the Sahel have a very high hydraulic conductivity (150 to 200 cm day^{-1}) and therefore rapid internal drainage occurs, with high loss of plant nutrients by leaching. In the Sudan-savanna zones, the formation of soil-surface crust reduces internal drainage, and water-erosion becomes a more serious problem than in the Sahel. The sandy soils in the Sahel are prone to wind-erosion, particularly associated with dust storms that occur at the beginning of the rainy season. Crop seedlings are damaged by sand abrasion and may be buried. The soil bulk densities range from 1.4 to 1.7 g cm^{-3}, corresponding to porosities of 36 to 43%, and the available moisture range is as low as 7%.

TABLE I. NUTRIENT RESERVES AND OTHER FERTILITY INDICATORS OF GRANITIC SOILS IN THREE AGRO-ECOLOGICAL ZONES IN WEST AFRICA [2]

Zone	Depth (cm)	$pH_{(H_2O)}$	Org. C (mg kg^{-1})	Total N (mg kg^{-1})	Total P (mg kg^{-1})	CEC[a] (mmol kg^{-1})	B. sat.[b] (%)
Equatorial forest	0-20	5.3	24.5	1.60	628	88	21
	20-50	5.1	15.4	1.03	644	86	16
Guinea savanna	0-20	5.7	11.7	1.39	392	63	60
	20-50	5.5	6.8	0.79	390	56	42
Sudan savanna	0-20	6.8	3.3	0.49	287	93	93
	20-50	7.1	4.3	0.61	285	87	90

[a]Cation exchange capacity.
[b]Base saturation.

TABLE II. TEXTURAL AND CHEMICAL PROPERTIES OF SOME SOILS IN SEMI-ARID REGIONS OF WEST AFRICA

	Sadore (Niger)	Daura (Nigeria)	Gaya (Niger)	Sotuba (Mali)
Annual rainfall (mm)	560	700	824	1,057
Sand (%)	96	97	90	91
Clay (%)	1	1	4	3
Total P (mg kg^{-1})	68	41	96	87
Total N (mg kg^{-1})	123	128	226	142
Organic matter (%)	0.42	0.39	0.52	0.48
pH (KCl)	4.4	5.4	4.3	4.9
Effective cation exchange capacity (cmol(+)kg^{-1})	0.91	1.48	1.37	2.30
Available P (mg kg^{-1}) Bray P1	2.8	4.6	3.9	1.7
Maximum P sorbed (mg kg^{-1})	129	29	101	93

The striking feature of WASAT soils is their inherently poor fertility, which is expressed in low levels of organic matter, total and available N and P, and effective cation exchange capacity (ECEC) (Table II). The accumulation of organic matter is closely related to the total amount of rainfall. The low ECEC is attributable to low organic matter, to low clay content and the kaolinitic mineralogy of the soils. Phosphate sorption maxima, calculated with the Langmuir equation, vary from 29 to 129 mg P kg^{-1} for representative soils from the Sahelian zone. Compared with the oxisols and ultisols of humid tropical regions, these soils can be considered as having relatively low P-fixing capacity, hence small additions of fertilizer increase available P and give significant crop responses.

3. NUTRIENT MANAGEMENT

In Africa, nutrient outputs exceed nutrient inputs. A study commissioned by FAO on N, P, and K balances for thirty-five crops in thirty-eight sub-Saharan countries revealed that the mean annual losses per hectare were approximately 22 kg N, 2.5 kg P, and 15 kg K for the period 1982-1984 [5,6]. There was a net loss of 49 kg ha^{-1} or 9.3 million tonnes of plant nutrient from the system in sub-Saharan Africa in 1983. Furthermore, these quantities of annual nutrient removal are projected to increase to a rate of 60 kg ha^{-1} or 13.2 million tonnes of plant nutrients by the year 2000. The data in Table III show aggregated nutrient budgets in west African countries. In Burkina Faso, current estimates indicate that in 1983, for a total of 6.6 million hectares of land cultivated, soil nutrient mining amounted to a total loss of 95,000 tonnes of N, 28,000 of P_2O_5 and 79,000 of K_2O, equivalent to a value US $159 million as N, P, and K fertilizers. In Mali, van der Pol and van der Geest [7] reported that farmers extract, on average, 40% of their agricultural revenue from soil mining.

TABLE III. LOSSES OF N, P, AND K PER COUNTRY, IN 1983 [5]

Country	Arable area ($\times 10^3$ ha)	Fallow area (%)	N	P	K
			(kg ha^{-1} of cropland)		
Benin	2,972	62	-14	-1	-10
Burkina Faso	6,691	50	-14	-2	-10
Cape Verde	n/a				
Cameroon	7,681	50	-20	-2	-12
Gambia	326	29	-14	-3	-16
Ghana	4,505	24	-30	-3	-17
Guinee	4,182	68	-9	-1	-6
Guinea-Bissau	n/a				
Côte d'Ivoire	6,946	31	-25	-2	-14
Liberia	745	15	-17	-2	-10
Mali	8,015	72	-8	-1	-6
Mauritania	846	79	-7	0	-5
Niger	10,985	47	-16	-2	-11
Nigeria	32,813	18	-34	-4	-24
Senegal	5,235	53	-12	-2	-10
Sierra Leone	1,842	43	-12	-1	-7
Togo	1,503	49	-18	-2	-12

The significance of these figures is alarming when we realize that the productivity of these soils in their native state is already depleted because of inherently low levels of plant nutrients. Sub-Saharan Africa consumes fertilizers at the lowest rate in the world: approximately 10 kg ha^{-1} of nutrients. In the area of structural adjustment, there is intense pressure on governments to remove subsidies on fertilizers without suitable alternative policies to sustain even the current low levels of their use. It is no wonder that improvement and maintenance of soil fertility through application of fertilizers, for example, have become key factors in efforts to sustain food production and to conserve the natural-resource base.

3.1. Nitrogen

Soil N is derived from rain and dust, biological N_2 fixation, organic sources, and fertilizers. About 98% of the soil N is stabilized in organic forms, with the total amounts released for nutrient uptake depending on the organic matter. As a result, fertility is generally equated with organic matter content. Bationo et al. [8] reported that the ECEC is related more to organic matter than to clay content in the Sudano-Sahelian soils, indicating that loss of organic matter will decrease the ECEC and thus nutrient-holding capacity. De Ridder and van Keulen [9] found that a difference of 1g kg^{-1} in organic C results in a difference of 4.3 mmol kg^{1} in ECEC.

As has been noted by several researchers [10-12], the maintenance of organic matter in tropical upland soil is one of the most important practices that influence productive capacity. In many cropping systems, little or no agricultural residue is returned to the soil, which leads to decline in organic matter content, frequently resulting in lower crop yields. In northern Nigeria, Jones [13] found that over 18 years of continuous cropping soil organic matter declined at 3-5% per annum. Continuous cultivation can rapidly deplete soil N (Fig. 1).

For many years, scientists in the Sudano-Sahelian zones conducted research to assess the efficiency of N-fertilizer sources, mode and time of application and other management factors, for increased food production [14-23]; however, there are few reports in the literature of ^{15}N studies. From the results of the work by Ganry et al. [24], Ganry and Guiraud [25], Gigou and Dubernard [18], and Chababalier and Pichot [26,27] the following conclusions can be drawn.

- Loss of ^{15}N-labelled fertilizer to the atmosphere increases with increasing rates of application.
- The estimated losses of N are high regardless of the N source.

Summarizing ^{15}N data from research under the auspices of the International Fertilizer Development Center (IFDC) in semi-arid west Africa, Mughogho et al. [14] found that calcium ammonium nitrate (CAN) significantly outperformed urea on millet. The uptake of N was 37% for CAN and only 20% for urea, which translated into a significant yield differential. Nitrogen losses were greater with urea (53%) than with CAN (25%), believed to be due to ammonia volatilization. Most of the fertilizer N remaining in the soil was in the 0-15 cm layer.

More recently, in field studies to compare N sources and methods of placement, Christianson and Vlek [22] reported that plant uptake of ^{15}N from point-placed CAN was almost three times that of similarly applied urea (Table IV). A 57% reduction in fertilizer N uptake by the plant was found when CAN was broadcast rather than point-placed.

In the Nigerian savanna, Uyovbisere and Lombin [28] found that urea and CAN were equally effective in terms of immediate N-supplying power and effects on crop yields. Soil-acidification has resulted in decreased use of ammonium sulfate, and although urea acidifies the soil more rapidly than does CAN, the attraction of its higher analysis seems to out-weigh any reputation for such deleterious effects.

Better timing of N application can improve N-use efficiency (NUE). In a ^{15}N experiment conducted in southern Niger with sorghum, 8.4% of N applied in the first split was found in the grain compared with 19% from the second application [29]. In northern Nigeria, Uyovbisere and Lombin [28] reported that the efficiency of uptake of applied N was considerably improved by split application. The data in Table V, for two seasons at a site in Bengou indicate that although N had a strong effect on sorghum yield, and, in 1991, NUE varied from 45% for urea to 76% for potassium nitrate, and in 1992 from 37% to 61%, respectively, there was no significant effect of N source. Loss of N from urea due to hydrolysis and ammonia volatilization could be the main reason for the lower NUE values that are found in sandy soils.

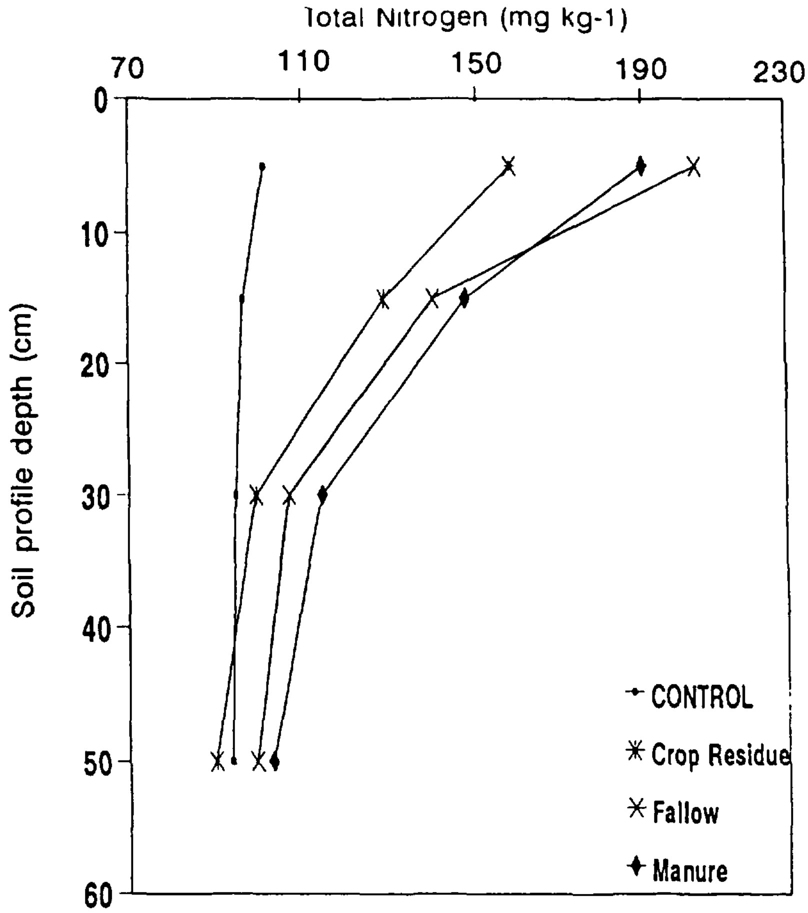

FIG. 1. Effect of 9 yrs. of different management practices on total N in the soil profile, Sadoré, Niger.

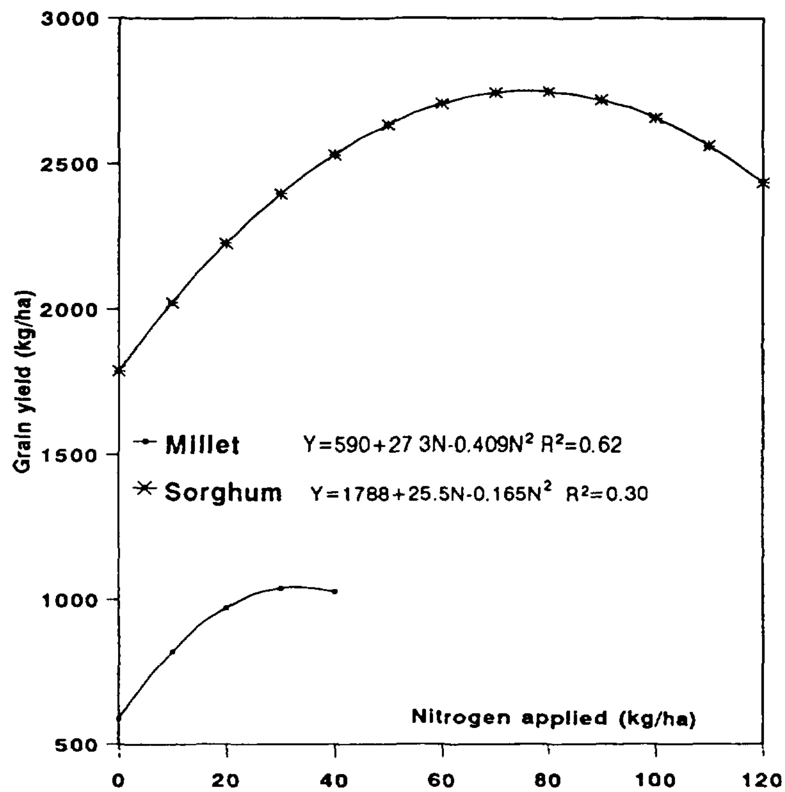

FIG. 2. Average yield response functions for pearl millet and sorghum in the Sudan-Sahelian zone.

TABLE IV. RECOVERY BY MILLET OF ^{15}N FERTILIZER APPLIED AT 3 kg ha^{-1} IN AN EXPERIMENT AT SADORE, NIGER, 1985

N source	Application method	^{15}N recovery (%)			
		Grain	Stover	Soil	Total
CAN	Point incorporated	21	17	30	68
CAN	Broadcast incorporated	11	11	43	65
Urea	Point incorporated	5.0	6.5	22	33
Urea	Broadcast incorporated	8.9	6.8	33	49
Urea	Point surface	5.3	8.6	18	32
SE		1.2	2.0	1.9	2.4

TABLE V. RECOVERY OF ^{15}N IN SORGHUM FROM THREE N-FERTILIZERS, BENGOU, NIGER, 1991 AND 1992 RAINY SEASONS

Treatment	Dry matter yield (t ha^{-1})		N yield (kg ha^{-1})		N from the soil (kg ha^{-1})		NUE[a] (%)	
	1991	1992	1991	1992	1991	1992	1991	1992
Urea[b]	9.95	12.9	83	87	13	64	45	37
Amm. Sulphate[b]	10.69	12.0	100	89	19	53	64	59
Pot. Nitrate[b]	11.0	11.0	96	91	23	54	76	61
SE	0.37	3.45	6	26	1	20	3	15
CV (%)	7	20	13	20	11	25	11	20

[a]Nitrogen-use efficiency.
[b]Applied 60 kg N ha^{-1}.

Groundnut and cowpea are the most widely grown grain legumes in WASAT. They are often intercropped with pearl millet in the Sahelian zone and with sorghum in the Sudanian zone. Continuous cropping of pearl millet resulted in lower yields across all N rates compared to millet rotated with cowpea or with groundnut at three locations in Niger (Fig. 3). Even with an application rate of 45 kg N ha^{-1}, the yield of continuous pearl millet was lower than with no N applied, but rotated with cowpea or groundnut at Tara.

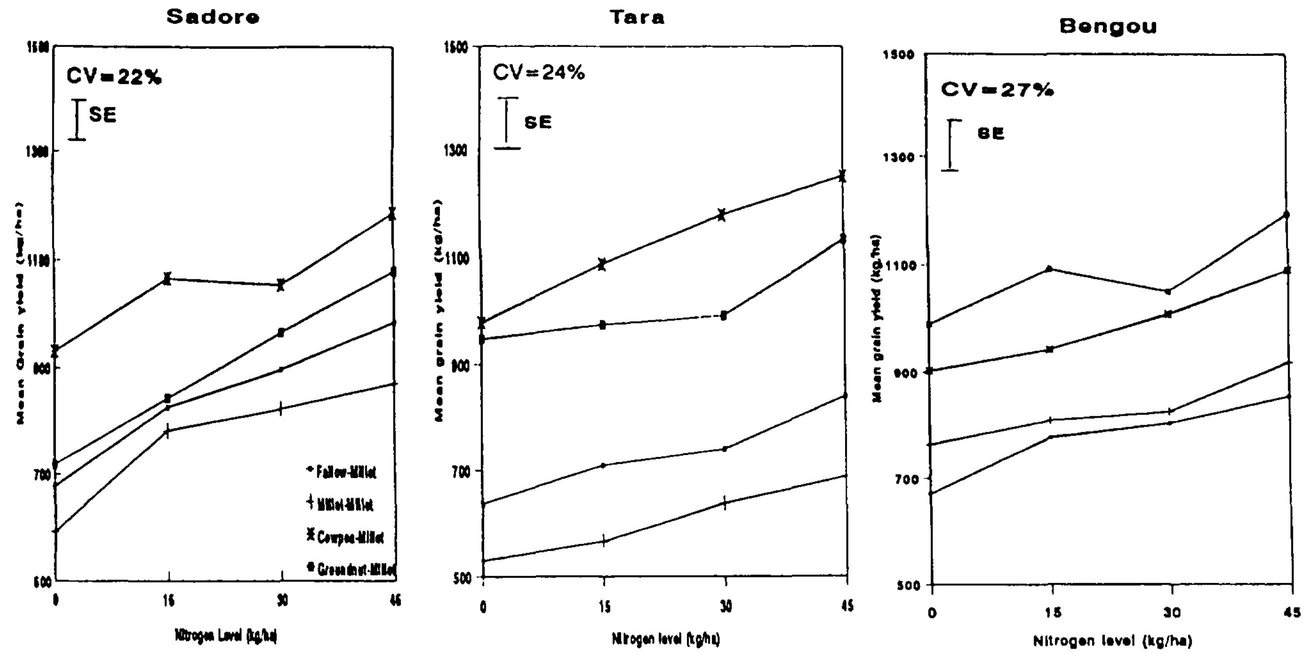

FIG. 3. Effect of N and cropping systems on pearl millet grain yield at Sadoré, Tara and Bengou, Niger over 4 years (1989-1992).

At Bengou and Sadoré, soil N was assimilated more efficiently in rotational systems than with continuous millet. For example at Bengou in 1990, N derived from the soil increased from 39 kg N ha^{-1} in continuous pearl millet to 62 kg N ha^{-1} when rotated with groundnut [30]. And at Sadoré in 1990, NUE increased from 20% in continuous pearl millet to 28% when rotated with cowpea.

3.2. Phosphorus

Phosphorus deficiency is a major constraint to crop production in west Africa [31] and response to N is substantial when moisture and P are non-limiting [32,33]. Sub-Saharan Africa uses 1.6 kg P ha^{-1} of arable land whereas Latin America and Asia use 7.9 and 15 kg P ha^{-1}, respectively. About 80% of the soils in sub-Saharan Africa are P-deficient. Its application is necessary to conserve the resource base as well as to increase short-term production. The conservation of the resource base is an environmental issue and is not only a necessity for Africa but is also a global concern.

For many years, researchers assessed the extent of soil-P deficiency, estimated the requirements of major crops, and evaluated the agronomic potential of various phosphate fertilizers, including phosphate rock (PR) from local deposits [35-42]. Despite widespread and acute P deficiencies in west African soils, very little P fertilizer is used by farmers. Bationo et al. [31] have shown that, for certain crops and soils, direct application of PR indigenous to the region may be an economical alternative to the use of more-expensive imported water-soluble P fertilizers,. When Parc-W and Tahoua PRs, indigenous to Niger, were evaluated, it was found that the former was only 48% as effective as single superphosphate (SSP), whereas the more reactive Tahoua rock was as high as 76% as effective. Further studies by Bationo et al. [42] confirmed that Tahoua PR is suitable for direct application, whereas Parc-W PR has little such potential. The effectiveness of a PR depends on its chemical and mineralogical composition, on soil factors and the crop to be grown [43-45]. The data in Fig. 4 show that Tahoua PR was more suitable for direct application than was Kodjari PR, and rainfall and soil acidity increased efficiency [46]: at Sadore, Gobery and Bengou, the average rainfall is 560, 700 and 800 mm, respectively, and the soil pH values were 5.2, 4.8 and 4.4, respectively.

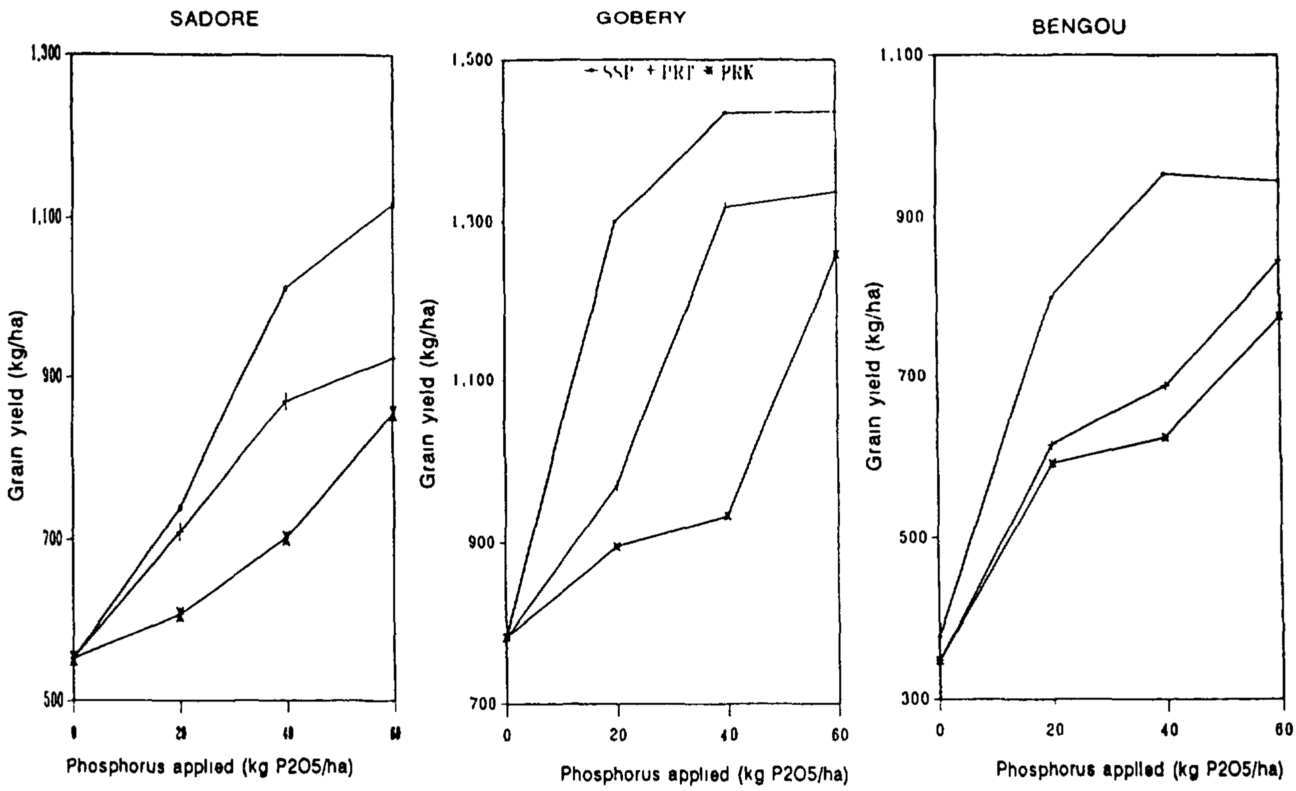

FIG. 4. Effect of different sources and rates of P on pearl millet grain yield in different agro-ecological zones of Niger, 1996. (SSP: single superphosphate, PRT: Tahoua phosphate rock, PRK: Kodjari phosphate rock).

The ineffectiveness of PR of low-reactivity, as compared with SSP, results from low water-solubility. Several studies have shown that partial acidulation of PR (PAPR) increases solubility and agronomic effectiveness at a lower cost than the manufacture of the conventional, fully acidulated fertilizers SSP and triple superphosphate (TSP) [47,48]. In farmer's managed trials, Bationo et al. [49] found Parc-W PAPR was as effective as commercial fertilizers (Table VI).

Farmers' managed trials in three agroecological zones of Mali examined the effects of fertilizer treatments on groundnut, pearl millet, sorghum, maize and cotton (Table VII). Except for millet and groundnut at Tafla in the Sahelian zone, all of the treatments increased crop yields significantly over the absolute-control values. Cotton and cereal yields with Tilemsi PR were as high as those with complex imported fertilizers. Differences in crop yields with annual and one-time (basal) applications of Tilemsi PR were insignificant [49].

Four methods of application of ^{32}P-labelled double super-phosphate were compared for millet-head and -stover yields, and for recovery of applied P. Four types of placement of fertilizer, at 8.7 kg P ha^{-1}, were tested. Except for the head yield in 1990, the broadcast and ridge treatment performed better than the others, and there were no differences among the other placement methods (Table VIII). The recovery of fertilizer P ranged from 10 to 22% in the first year and from 8 to 14% the second. The lower P recovery in 1990 was due to its depleted availability, having been applied in 1989. For both years, P recovery was lowest with hill-placement.

TABLE VI. MILLET GRAIN YIELDS BY TREATMENT (3 YEARS) [21]

Treatment	Yield ($kg\ ha^{-1}$)
Control	261
SSP[a] only	586
SSP + N hill placed	700
SSP + N broadcast	751
PAPR[b] + N broadcast	752
$LSD_{0.05}$	84

[a]Single super phosphate.
[b]Partially acidulated phosphate rock.

3.3. Integrated plant nutrient management from long-term experiments

Long-term experiments allow a practical approach to address the difficult issues associated with quantitative assessment of sustainability in agriculture. Data from twenty-four long-term experiments on soil management conducted in semi-arid Africa (initiated in 1960) have produced unique information on two fundamental processes, soil organic matter decline and soil acidification, which control sustainability under continuous cropping systems [50]. Figure 5 shows responses of pearl millet to fertilizer and fertilizer-plus-manure treatments in southern Niger [51]. Figure 6 presents the result of long-term millet trials with fertilizer and crop-residue applications in the Sudanian zone [52]. Although mineral fertilizers increase yields in arable farming, they alone cannot sustain crop yields in the long run. Only in combination with other technologies, such as the return of crop residues, can productive and sustainable production systems be obtained.

4. WATER

Research on water management attempts to develop principles and techniques for improving rain-water utilization for increasing and stabilizing agricultural production. Only a small proportion of rain water is transpired by the crop. Losses include surface runoff, deep drainage, evaporation from the soil surface, and transpiration by weeds. Techniques have been developed to reduce these losses and increase the proportion of available water transpired by the crop. Common ways of optimizing soil-water use through management of biophysical properties include 1) surface management through tillage and/or residue application, 2) water harvesting, 3) soil amendments, and 4) use of appropriate cropping systems and varieties.

4.1. Soil-surface management and techniques for optimizing water use

Indigenous water-conservation can be divided into engineering, agroforestry and agronomic practices. In WASAT, prominent indigenous methods include stone bunds on slopes, contour stone bunds, stone lines, earth bunding, and planting pits with dung ("zay" in Burkina Faso and "tassa" in Niger, etc.) [53-56]. Vlaar and Wesslink [57] reported sorghum-yield increases of up to 1,500 kg ha^{-1} due to permeable rock dams. The data in Table IX show the effects of rock bunding on sorghum grain yields in two agroclimatic zones of Burkina Faso.

TABLE VII. EFFECT OF MANAGEMENT PRACTICE AND FERTILIZERS ON THE YIELDS OF GROUNDNUT, MILLET, SORGHUM, MAIZE AND COTTON IN DIFFERENT AGRO-CLIMATOLOGICAL ZONES OF MALI, 1989-92

Location/ Crop/ Year		Absolute control	Farmers' practice	Recomm'd practice	Tilemsi PR annual	Tilemsi PR one-time	LSD	CV
				(kg ha^{-1})				(%)
Sougoumba								
Sorghum	1989	993	979	1,279	1,325	1,464	156	18
	1990	955	1,103	1,224	1,365	1,216	215	25
	1991	866	1,134	1,264	1,165	1,210	271	33
	1992	1,036	1,289	1,923	2,207	1,785	162	25
Cotton	1989	1,121	1,923	1,645	1,610	1,691	190	17
	1990	731	1,013	1,223	1,044	1,142	174	23
	1991	1,245	1,428	1,544	1,614	1,564	152	14
	1992	931	1,120	1,307	1,354	1,514	288	18
Tafla								
Grndnut	1989	775	885	844	825	775	112	19
	1990	283	334	361	338	370	67	27
	1991	499	746	591	609	577	107	26
	1992	556	583	695	564	660	109	24
Millet	1989	718	746	894	960	1,039	132	21
	1990	742	995	969	774	914	161	25
	1991	535	664	788	859	1,324	156	28
	1992	254	360	411	349	337	101	40
Tinfounga								
Maize	1989	1,014	1,818	2,296	1,877	2,204	331	25
	1990	723	2,046	2,725	2,069	2,174	374	26
	1991	1,043	2,193	2,725	2,865	2,509	304	19
	1992	670	2,087	2,712	2,190	2,529	418	28
Cotton	1989	866	1,462	1,595	1,410	1,571	165	16
	1990	1,178	1,997	2,236	2,001	1,982	201	15
	1991	436	761	1.103	954	1,116	160	25
	1992	826	1,461	1,515	1,463	1,479	194	20

The multiple advantages of soil tillage include increased water infiltration, reduced runoff and less evaporative loss. Nicou and Charreau [58] have extensively reviewed research on tillage at the Institute de Recherche Agronomique Tropicale (IRAT, Montpellier, France). Table X shows the effect of tillage on the yields of crops of major importance. In Niger, pre-sowing tillage led to better seedling establishment, thereby improved crop water-use efficiency and grain yields [29]. Use of a shallow cultivating hoe on sandy soil immediately after rainfall has also been shown to reduce evaporation such that cumulative water conservation increased by up to 70 mm in a 2.5-m profile, due to changes in the surface energy and water balance [59]. Residue application to the surface increased infiltration by dissipating the energy of falling raindrops on degraded lateritic soils and attracted termites, which then formed macropores thereby increasing infiltration [60].

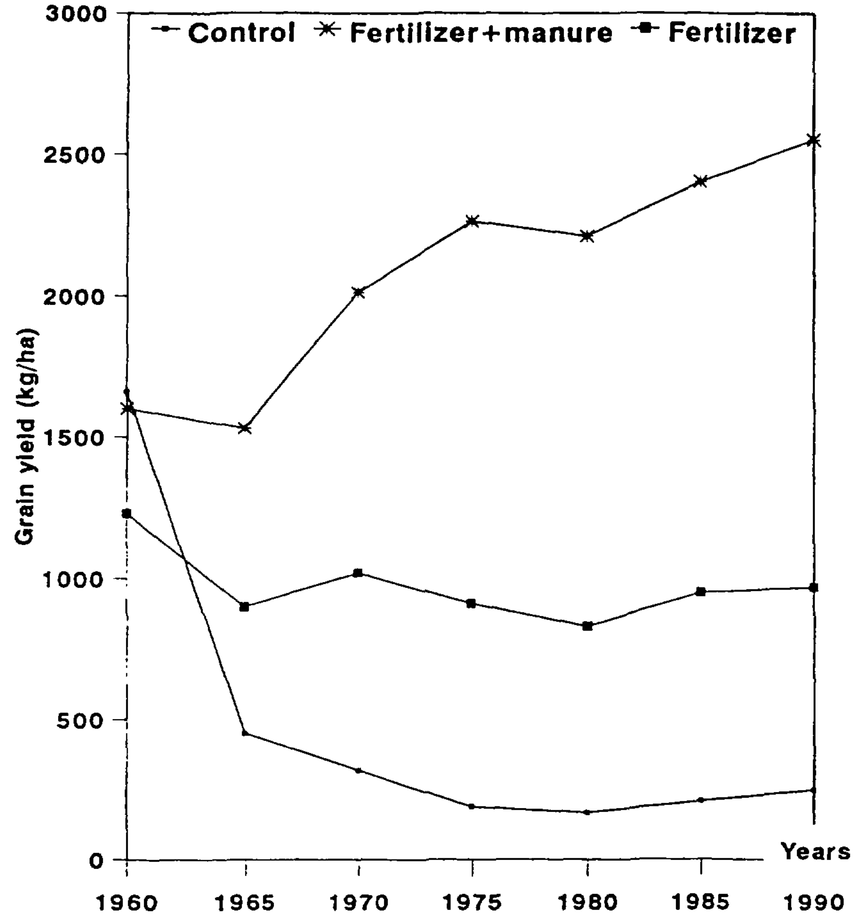

FIG. 5. Pearl millet total dry matter yield as affected by different management practices in a long-term experiment.

In Niger, windbreaks of neem trees increased millet yields by approximately 20% by controlling wind erosion as well as reducing evaporative loss (K.Michels, personal communication).

Rodriguez [61 reported strong maize responses to tied ridges along the toposequence, except with low-lying hydromorphic soils (Fig. 7). Roose [55] reviewed the results of 30 years of research by scientists of the Institut Francais de Recherche Scientifique pour le Developpement en Cooperation, (ORSTOM, Montpellier, France) and the Centre de Cooperation Internationale en Recherche Agronomique pour le Developpement (CIRAD, also Montpellier) and concluded that the major factors for soil and water conservation are vegetation cover (mulching), appropriate cultural practices, and slope management.

4.2. Appropriate cropping systems and varietal choices

In Mali, intercropping cereals with groundnut offered a more than 50% yield advantage [64]. Breeding for drought resistance also offers yield improvements. For example, the breeding strategy at the Sahelian Center of the International Center for Research in the Semi-Arid Tropics (ICRISAT, Niamey, Niger) is to develop short-duration genotypes that can either escape terminal drought or, with delayed sowing, can avoid early-season drought. Drought-resistant pearl-millet germplasm currently being tested and/or released in west Africa includes SOSAT (from IER/ICRISAT), GB-8735 (ICRISAT), ICMV IS 85333 (ICRISAT), and EBMA (Institut National de Recherche Agronomique du Niger, INRAN, Niamey, Niger).

5. WATER AND NUTRIENT INTERACTION

In WASAT, although it is recognized that water and nutrients dictate crop production, few studies have been conducted on their interactive effects.

5.1. Fertilizer application and water-use efficiency

From multilocation water-balance studies in Niger, it was shown that an important consequence of the use of fertilizer is increased water-use efficiency (Table XI). Crop production is limited often more by low soil fertility than by moisture deficiency [65,66].

In other long-term rotation experiments at ICRISAT's Sahelian Center, fertilization increased seasonal crop-water use (evapotranspiration, ET) modestly, but due to the high response of pearl millet, its water-use efficiency increased dramatically, from 5.4 to 14.4 kg mm^{-1} (Table XII). From the data of Experiment 2, the measured crop-water use was almost the same in 1986 and 1987, but water-use efficiency was lower in 1987 due to insect attack and poor stand establishment.

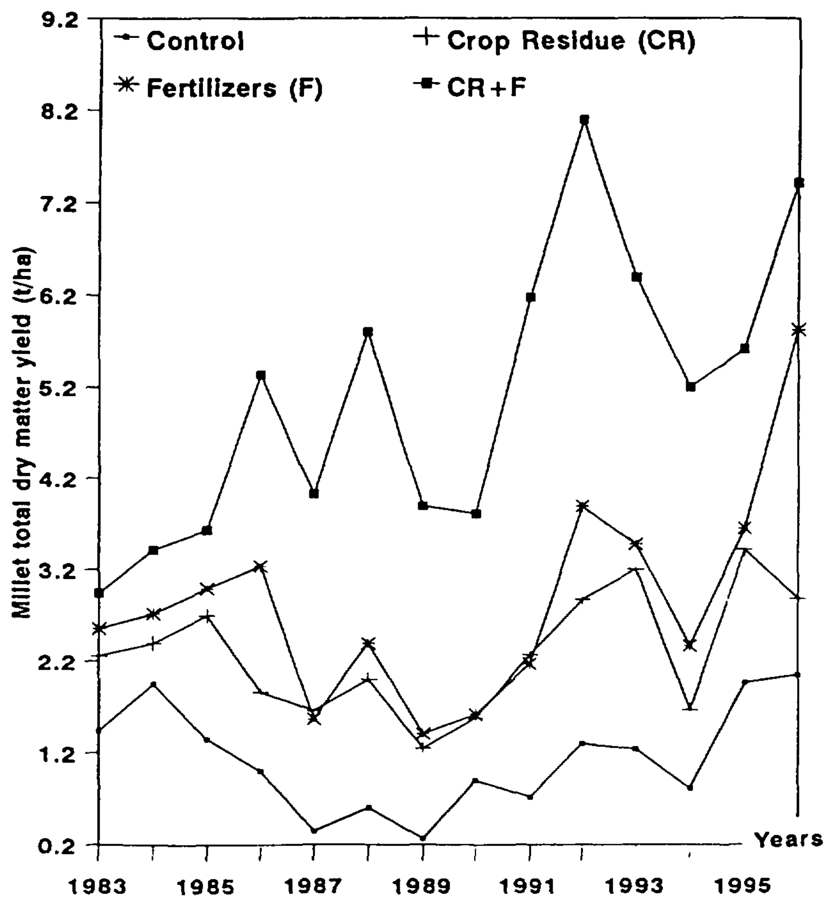

FIG. 6 Millet grain yield as affected by mineral and organic fertilizers over time [52].

TABLE VIII. RECOVERY OF ^{32}P WITH DIFFERENT METHODS OF FERTILIZER-P APPLICATION TO PEARL MILLET, SADORÉ, NIGER, 1989 AND 1990 RAINY SEASONS

Treatment	Yield (t ha^{-1})				Total uptake (kg ha^{-1})		P derived from fertilizer (%)		Total P derived from fertilizer (kg ha^{-1})		Fertilizer P utilization (%)	
	Head		Stover									
	1989	1990	1989	1990	1989	1990	1989	1990	1989	1990	1989	1990
Broadcast	1.04	1.40	2.00	1.97	7.55	7.40	46	34	3.36	2.45	15	12
Broadcast and incorporated	1.13	1.58	2.39	2.13	8.10	7.91	53	34	4.37	2.70	22	14
Broadcast and ridged	1.21	1.55	2.56	2.23	9.12	7.62	46	38	4.14	2.78	21	14
Hill-placed	0.85	1.35	2.00	1.83	4.93	5.55	43	28	2.02	1.53	10	7.8
SE	±0.10	±0.07	±0.29	±0.14	±0.77	±0.44	±3.4	±0.7	±0.45	±0.27	±2.0	±3.6
CV(%)	23	11	33	16	26	16	18	20	32	28	29	28

TABLE IX. EFFECTS OF ROCK BUNDING AND SORGHUM VARIETY ICSV 1002 ON GRAIN YIELD IN FARMERS' FIELDS IN FOUR VILLAGES IN TWO AGROCLIMATIC ZONES, BURKINA FASO, 1985

	Agroclimatic zone			
	Sudanian		Guinean	
	Kolbila	Ononon	Koho	Sayero
	(kg ha^{-1})			
Number of fields	8	7	8	8
Rainfall in 1985 (mm)	514	487	922	715
Fields receiving heavy runoff	5	1	0	1
Fields receiving moderate runoff	2	5	2	1
Sorghum grain yield (kg ha^{-1}) with bunding and ICSV 1002	730	350	670	1,010
Control	230	160	650	600
SE	±118	±67	±206	±233

TABLE X. EFFECT OF TILLAGE ON THE YIELDS OF THE MAJOR CROPS CULTIVATED ANNUALLY IN SEMI-ARID WEST AFRICA

	Number of annual results	Control yield (kg ha^{-1})	Tillage yield (kg ha^{-1})	Gain from tillage (%)
Millet (grain)	38	1,558	1,894	+22
Sorghum (grain)	86	1,691	2,118	+25
Maize (grain)	31	1,893	2,791	+50
Rainfed rice (paddy)	20	1,164	2,397	+103
Cotton (grain)	28	1,322	1,550	+17
Groundnut (pods)	46	1,259	1,556	+24

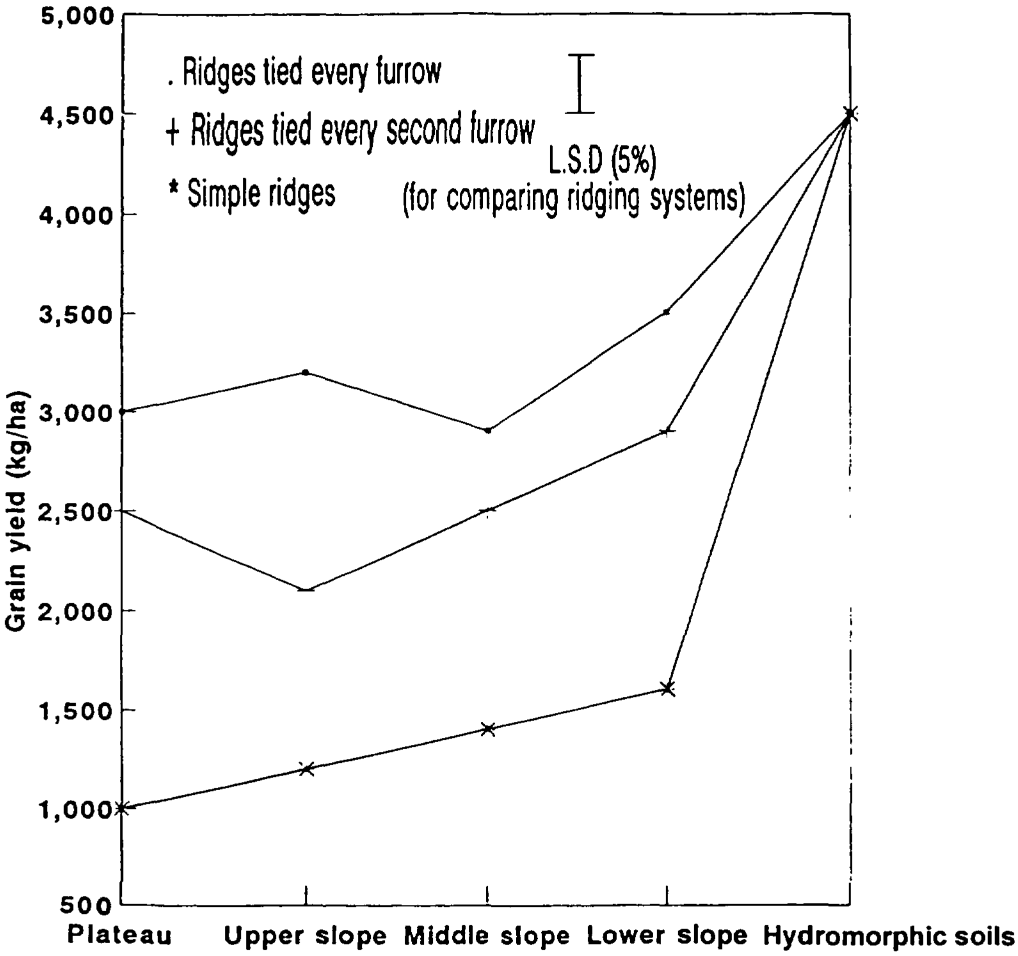

FIG. 7. The effect of position on a toposequence and ridging on maize yield, Kamboinse 1981 [61].

5.2. Effect of rainfall on response to fertilizer

The efficiency of N-fertilizer use depends on the rainfall received by the crop. If it is optimal during the entire growing season, the response to N will be strong. Conversely, in years of poor precipitation, there will be little or no effect of N application. Bationo et al. [16] developed a model relating yield of pearl millet to mid-season rainfall (45 days from mid-July to end of August). This model predicts that N responses in dry years will be limited, with little benefit to the farmer from the investment in N fertilizer. However, in years of average mid-season rainfall, 30 kg N ha^{-1} applied in the presence of adequate P will result in a yield increase of 430 kg ha^{-1} (14 kg grain per kg N). In a year of optimal rainfall, it is essential to use N to gain maximum yields and 30 kg N ha^{-1} will result in a fertilizer efficiency of 25 kg grain per kg N (Fig. 8).

Increased root growth due to P application is associated with greater rooting depth and deeper extraction of moisture during dry spells (W.A. Payne, personal communication).

TABLE XI. EFFECTS OF N, P AND K FERTILIZERS ON WATER USE (WU), GRAIN YIELD AND WATER-USE EFFICIENCY (WUE) FOR PEARL MILLET GROWN AT THREE SITES IN NIGER, RAINY SEASON 1985

Site	Rainfall (mm)	Treatment	WU (mm)	Yield (kg ha^{-1})	WUE (kg ha^{-1} mm^{-1})
Sadore	543	Fertilizer	382	1,570	4.14
		No fertilizer	373	460	1.24
Dosso	583	Fertilizer	400	1,700	4.25
		No fertilizer	381	780	2.04
Bengou	711	Fertilizer	476	2,230	4.68
		No fertilizer	467	1,440	3.08

TABLE XII. EFFECT OF FERTILIZER ON WATER USE EFFICIENCY. RESULTS FROM TWO EXPERIMENTS, ICRISAT SAHELIAN CENTER, RAINY SEASONS 1986 AND 1987.

	Fertilizer	Evapo-transpiration (mm)	Drainage (mm)	Rainfall (mm)	Total biomass (kg ha^{-1})	Water use efficiency (kg mm^{-1} ha^{-1})
Experiment 1						
1986 Pearl millet	No	211	207	440	1,140	5.4
1986 Pearl millet	Yes	268	147	440	3,850	14.4
Experiment 2						
1986 Pearl millet	Yes	298	105	431	4,030	13.5
1987 Pearl millet	Yes	303	65	361	2,170	7.2
1986 Cowpea	Yes	276	115	339	3,760	13.6
1987 Cowpea	Yes	265	57	319	660	2.5

The effects of P cannot be separated from those of water upon root and leaf growth, which in turn determine the plant's supply of, and demand for, water [67]. A major consequence of P-fertilizer use for pearl millet is not only increased growth but also improved water-use efficiency [68].

Early growth results in more complete ground cover early in the season, which reduces the proportion of water lost through soil evaporation to some extent, thus facilitating effective and efficient use of rainfall.

6. CONCLUSION

In WASAT, nutrients and water both dictate crop production. The present farming systems are unsustainable, low in productivity and destructive to the environment. Plant-nutrient balances are negative and farmers are mining their soils. Several technologies have been developed for soil and water conservation, but few of these technologies have reached the small-scale farmer.

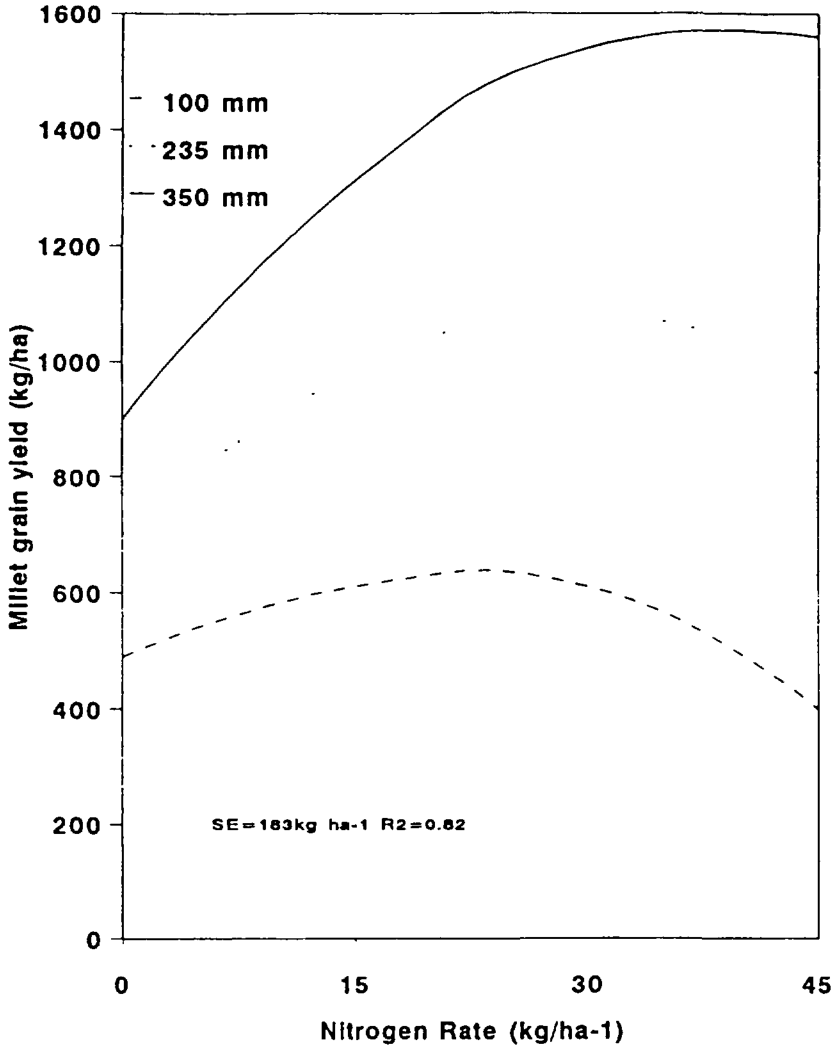

FIG. 8. Grain yield of pearl millet as related to N rate and midseason rainfall at Sadoré, Niger.

Future research must focus on the efficiency of plant-nutrient use to redress distorted nutrient budgets, which implies the development of integrated plant-nutrient management systems, conceptualized as the judicious manipulation of the nutrient-input and -output processes. There is also a need for more basic research on water management in viable cropping systems and the interaction between water and plant nutrients at the village and watershed levels. Future research must involve farmers, researchers, extension agents, non-governmental organizations and government-policy makers in order to foster the efficient transfer of existing knowledge on nutrient and water management to the small-scale farmer.

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MANAGEMENT OPTIONS TO INCREASE SOIL ORGANIC MATTER AND NITROGEN AVAILABILITY IN CULTIVATED DRYLANDS

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Abstract

Cropping of dryland soils in marginal regions with an emphasis on economic rather than ecological sustainability has generally led to decline in soil organic matter reserves and hence nutrient availability. Outputs commonly exceed inputs, with degradation of soil structure, reduction in infiltration and increase in runoff. Biological productivity is severely affected, leading to a vicious cycle of events usually culminating in decreased N release, excessive soil loss and ultimately desertification. Reducing the incidence of bare fallow, increasing crop-residue retention, strategic N-fertilizer application and shifting to cereal-legume rotations (as opposed to monocultures) and intercropping can slow the spiral. Simulation models such as DSSAT and SOCRATES provide suitable and easy-to-use platforms to evaluate these management strategies in terms of soil organic matter accumulation and yield performance. Through the linkage of these models to global information systems and the use of spatial-characterization software to identify zones of similarity, it is now possible to examine the transportability and risk of a particular management strategy under a wide range of climatic and soil conditions.

1. INTRODUCTION

The abundance and formation of soil organic matter in dryland agro-ecosystems has, within the last decade, assumed increasing importance within the context of crop production and resource sustainability, and the impact thereupon of global climate change and shifting rainfall patterns. Enhancing native soil fertility in the cropping systems of the major semi-arid regions of the developing world, such as sub-Saharan Africa, have come under the closest scrutiny, as population and production costs (particularly fertilizers) increase. The area of rainfed croplands has been estimated as 457 M ha, which is approximately 10% of the world's total dryland area as classified by UNEP in 1992. Of this area, nearly half is listed as degraded to some extent, with an additional 4 M ha being lost each year, the result either of erosion or urbanization.

There are essentially two approaches to managing soil fertility: by application of fertilizers and by manipulating biological processes to optimize nutrient availability [1]. The latter minimizes the use of external purchased inputs while maximizing organic inputs; it is the more complex approach, but can lead to a more readily sustainable, self-perpetuating system because it relies on the gradual transformation of organics to inorganics, as opposed to the immediate availability of chemical-based nutrients. The chemical fertilizer approach has the greater potential for inefficiency and loss of inorganic N from the system, critical factors in low-input cropping systems of the semi-arid regions.

Abiotic influences on soil organic matter dynamics, such as moisture, temperature, aeration and composition of plant residues are reasonably well understood [2]. However, in rainfed arid and semi-arid environments, superimposed on these properties and processes is the fact that most soils are deficient in both N and P, as a direct result of inputs not meeting outputs, reduced ground cover and increased losses of nutrients by erosion. This cycle of events is difficult to reverse without a dynamic and informed management approach (as opposed to decisions made haphazardly or for historical reasons).

Further complicating these issues is the fact that farm holdings in the developing regions are small and rely on family resources. Although many resource-management options are potentially available, few are actually accessible to farmers. Human labour and some animal traction are used to prepare lands, incomes are low, with production barely subsistent at the best of times, hence little or no money is available for external inputs such as fertilizers, and chemicals for weed and disease management. Blanket recommendations are also usually made that ignore climatic variation in the areas farmed by small-holders. For example, of 32% of farmers in Zimbabwe who followed fertilizer recommendations for the 1990-91 maize crop, nearly half failed to recover the outlay costs [3].

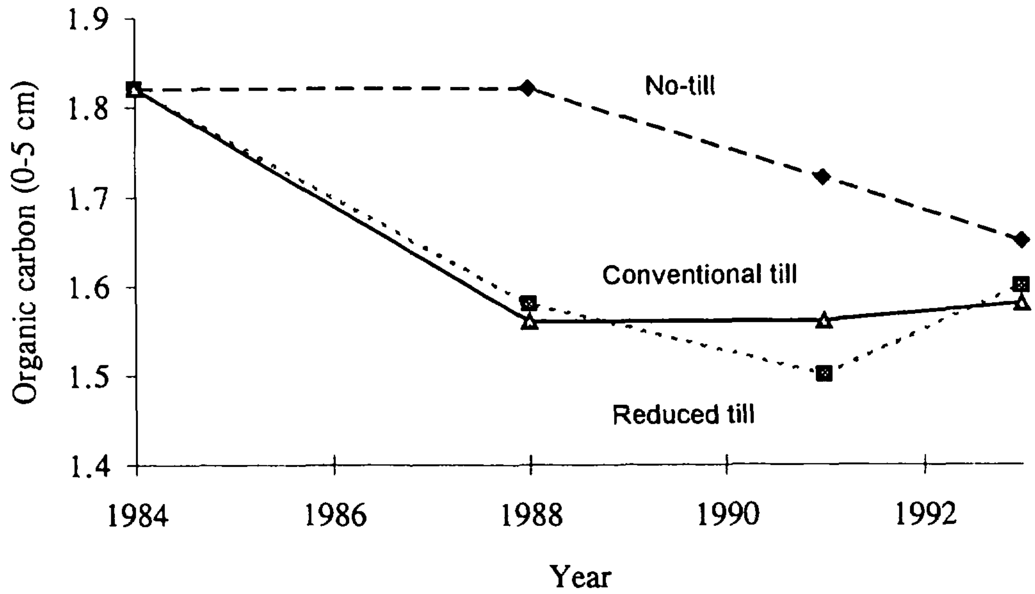

FIG. 1. Soil organic C (0-5 cm) in a wheat-lupin rotation on a sandy loam at Kapunda, south Australia.

Also, many of the solutions for increasing production, which have been generated in countries where mechanization is widely available and farms are much larger with suitable monetary return (e.g. USA and Australia), may not be directly applicable in the non-commercial holdings of semi-arid Africa, Asia, and South and Central America. However, the lessons learned from the impact of some technologies, particularly reduced and no-tillage, residue retention, rotation management, strategic N applications and intercropping, in combination with simulation techniques, can be valuable in providing site-specific management options.

2. MANAGEMENT OPTIONS

2.1. Tillage and residue retention

Reduced-tillage and no-till management practices tend to concentrate crop residues and associated micro-organisms in the surface layer [4], resulting in distinct profile stratification that may greatly improve surface-soil aggregation, increasing infiltration rates and water-use efficiency, critical factors in dryland cropping. Reduced and no-tillage systems also tend to have slower rates of organic-matter degradation compared to conventionally tilled systems [5,6,7]; however, this is not always the case in drylands, where increases in soil organic C in no-till systems may be transient [8] (Fig. 1). There was no conclusive evidence of yield benefit in no-till systems in a detailed survey of twenty-eight long-term cropping trials in the semi-arid regions of Australia [9]. This would suggest that the improvement in aggregate stability and infiltration associated with no tillage after a number of years produces a more favourable environment for microbiological activity in the longer term, causing increases in the rate of decomposition of organic matter and release of simple C substrates that have been linked to increased incidence of root pathogens.

Because crop-residue amounts from semi-arid monocultures are typically low (0.5-5 t ha^{-1}), there is little opportunity for long-term increases in soil organic matter (and subsequent benefits in fertility and water storage). As livestock plays an integral role in many African cropping systems, most crop residues are used as feed. The traditional practice of fallowing (i.e. set asides with volunteer growth) used in semi-arid east Africa to replenish soil fertility is rapidly decreasing due to limited availability of land [10]. Also, in many cases, this practice, which resembles bare fallowing, reduces the risk of crop failure through water stress and increases yield-residue production to meet both livestock and management needs, and the increase in water availability significantly hastens organic-matter degradation. However, the advantages are short term, and it is ultimately self-destructive in terms of sustainable crop production.

The quality as well as the quantity of the residual material has a significant affect on the potential for soils to accumulate organic matter. Improved short fallowing, with the use of annual legumes such as *Sesbania sesban* as organic manure, has been found to increase maize yields three-fold in Zambia [11]. Synchronizing the release of nutrients (e.g. through the use of slow-release organic manures) can also increase N-cycling efficiency [12]. Green manures were heavily researched in Zimbabwe in the 1920s [13], and, until fertilizer prices fell in the 1950s, green manuring was widely practiced by commercial farmers. The rising cost of fertilizers and concern over the sustainability of current cropping systems in east Africa have resulted in a resurgence in the use of this option on small-holdings. The attractiveness of green manures in terms of N-use efficiency is clearly demonstrated in a Tanzanian study where a sunnhemp (*Crotalaria*) green manure was found to be four times more effective than inorganic fertilizers [14].

Evaluation studies of velvet bean (*Mucuna*), sunnhemp and fish bean (*Tephrosia*) productivity in Zimbabwe and Malawi [15] indicate that biomass accumulation is highly dependent on initial soil fertility. Velvet bean appeared to be the most promising candidate as a green manure in these semi-arid regions, provided additional P was applied to the poorer soils. Farmers in central America have successfully used velvet bean for decades [16], and promising results in east Africa are similar to those being found in the high rainfall tropics of Veracruz in Mexico [17]. Little information is available, however, on N cycling and water availability in these systems; for example, is removal of soil water during the green-manure phase sufficiently offset by N credits to the following maize? Such questions can be addressed through the use of nuclear techniques.

2.2. Rotation management

Crop selection in the rotation sequence has a direct impact on residue production and organic matter storage in subsequent years, particularly the N benefit of including grain legumes or the impact of "break" crops such as *Brassica* spp. to control cereal-root diseases [18]. In semi-arid areas of Australia, legume-dominant pastures (*Medicago* spp.) still play a significant role in crop production. Increases in soil organic C were reported for wheat rotations that included 2-4 years of annual sown pasture [19] with associated increases in improvements in soil structure [20,21] and water-holding capacity.

Annual pastures also contribute a large amount of C in root production. As a proportion of C in above-ground production, input below ground may range from 0.40 to 0.97 [22], with subsequent rapid increases in native soil organic matter levels. The residual N made available may boost dry-matter production of subsequent crops. In contrast, immobilization of mineral N accompanying the decomposition of grass-dominant pastures may lead to a reduction in crop production. Grass-dominant pastures also tend to provide suitable hosts for pathogens, e.g. *Gaeumannomyces graminis* pv. *tritici*, that may affect the roots of subsequent crops [23].

Because of the necessity for small-scale food production, annual pastures are not really a viable option in semi-arid regions of the developing world. On large holdings, the potential exists for taking some fields out of food production for periods of 1-2 years, but such luxury is absent in communal farming. Most small-holders in east Africa do practise some form of crop rotation, whether it be maize-groundnut-cotton-soybean or maize-groundnut-sunflower-soybean [24]. The amount of N returned depends on whether the legume is harvested for seed, used for forage, or incorporated as a green manure. Soybean generally sequesters more N in its seed than it contributes to the cropping rotation, even when all stover is incorporated [25]. This may not be the case, though, with locally adapted varieties that are usually leafier and have a lower N-harvest index compared to more highly bred genotypes. In Malawi, N credits of up to 110 kg ha^{-1} from pigeon pea with a 2.8 t ha^{-1} yield advantage in the following maize crop have been reported [26]. Nitrogen-15 natural-abundance techniques can be used to gain a better understanding of the site-specific cycling of N in these rotations, and the potential for wider adoption.

2.3. Fertilizer application

Water use in nutrient-deficient plants is similar to that of nutritionally balanced plants [27], however the precursor to this is sufficient moisture to actually produce a healthy plant. The majority of semi-arid cropping systems are characterized by erratic rainfall, in terms of both intensity and amount. Soils are usually poorly developed due to inherently low organic-matter levels, and subject to degradation and structural decline. In many cases there is either too little or too much rain for the soils to efficiently deal with. Thus, fertilizer-use efficiency in crops of these regions is usually less than 25% and highly inconsistent. Small-holders in Malawi and Zambia using current recommendations can expect 9.5-16 kg of maize per kg of nutrient for local varieties with 17-19 kg for hybrids [28], which is essentially half the fertilizer-use efficiency of crops in tropical west Africa [29]. Such poor return, combined with the fact that fertilizer costs are prohibitive, make inorganic fertilizers an extremely risky option for both yield and biomass production.

Strategic application of fertilizers may improve use efficiency of the supplement with significant gains in both yield and biomass production possible, however, losses of inorganics from the rooting zone may be high at any time. Consistent rains immediately after a dry spell can lead to a flush of inorganic N from the native organic pool, which may be then lost as a result of denitrification if transient waterlogging occurs (provided labile forms of C are available in the profile). Significant losses of nitrate through leaching are possible also in coarse sands and cracking clays. These losses and the dynamics of the soil organic mater pool can be accurately quantified through the use of ^{15}N-labelled fertilizers [30] and the effectiveness of split applications assessed. These data form some of the crucial process information to validate simulation models for a wide range of management options. Versions of the internationally recognized CERES-Maize model have been modified to accommodate isotopes to facilitate the calibration of N and C transfers through the soil-plant-water system [31,32].

There is growing evidence, however, that the best option to improve inorganic fertilizer efficiency in small-holder systems is by adding high-quality organic matter [33,34]. Where high-quality organic manures are employed, fertility is usually at a higher level than the additive benefits of the individual components [35]. Yield increases ranging from 19-60% have been reported [36]. The relative success of green manures in terms of nutrient carryover in the semi-arid environment allows the most limiting requirement of high-quality inputs (i.e. high N concentration) to be met. The application of high-quality organic residues also tends to increase the labile and slowly decomposable organic matter fractions, easily identified as particulate organic matter (POM), a handy indicator of the sustainability of a particular cropping system. Unfortunately, when a green manure is being grown it also means the field is not producing an edible product during that time. Application of animal dung can overcome the need for green manuring, but it tends to be of lower quality with less potential to maintain soil fertility and yield, even though it may release nutrients for sustained periods of time.

2.4. Intercropping

Intercropping of cereals and pulses is a traditional practice in developing countries. In Africa and Latin America it forms a major part of small-holder agriculture. The practice tends to have a stabilizing effect on food security and enhances the efficiency of land use [36]. Its impact is most significant in low-fertility, N-depleted soils [37], such as those found in many rainfed semi-arid zones. Growth characteristics and planting densities contribute to success or failure. The yield advantages with intercropping are usually less than for grain-legume/cereal rotations [38]. However, this is not always the case: cowpea-maize intercrops in the wetter regions of Zimbabwe yielded better than their sole crops on a land-equivalent basis [39].

The amounts of N transferred from the legume to the cereal vary greatly and are difficult to decipher and compare due to the variety of methodologies used for quantification. The standard N-difference method indicated greater amounts when compared to isotope-dilution data [37]; in the case of the latter, the majority of experiments have failed to demonstrate an agronomically significant transfer of N. Intercrop biomass is usually less than that of a solecropped cereal, however, the material applied to the soil from the former is of higher quality, thus enhancing the supply of readily available nutrients. The mixture of high- (legume) and low-quality (cereal) residues can provide a continuous N supply and improve nutrient-release synchrony [40]. Little information is available on this interaction, however, intercropping provides the small-holder with food and a better overall quality of organic matter for sustained cropping, provided that sufficient water is available or the planting strategies are carefully adjusted for the climatic conditions of that year. The complex interactions between water and N in the intercropping system are difficult to unravel, but nuclear techniques offer valuable approaches. Fortunately, some empirical simulation models do exist to investigate intercropping [41], allowing various planting strategies to be tested against a range of climatic conditions.

3. SIMULATION MODELS

Whilst the majority of studies would indicate the success of reduced tillage and rotations in improving a soil's ability to accumulate organic matter and be more productive, the exceptions rather than the norm may tell us more about the long-term consequences of such management practices. Strategies to improve soil fertility and ecological sustainability are definitely soil- and environment-dependent. Single indicators of soil quality or health are of questionable value, considering the complexity of the soil-plant system. The full potential of the effects of management on nutrient cycling in agro-ecosystems can be accurately assessed only in the context of whole-system simulation models. These allow the integration of the many basic empiricisms describing the processes and properties in organic-matter decomposition and nutrient availability, and allow feedbacks of crop production, disease and climate to be fully coupled.

A vast array of models exist that deal with crop production at various levels of complexity. Few deal with short- and long-term concepts of sustainability in terms of both crop production and the soil resource, and few operate at a level whereby data requirements are not excessive and also provide accuracy. These characteristics are important when trying to develop useful long-term management strategies for a wide range of environments under a common framework. It also does not isolate the experimentalist from the model user, an important interaction in developing suitable, but also very practical, management strategies. This is particularly important in the semi-arid regions where climatic variability makes essential a flexible approach to sustainable production.

SOCRATES and CENTURY are models that specifically deal with soil organic matter dynamics, fertility and yield performance, offering great flexibility in terms of management options and the impact of climate. CENTURY [42] has been widely used, but has slowly increased in complexity and experience is now needed to make full use of it. On the other hand, SOCRATES [43], although based on a similar conceptual structure, is extremely simple to use. Its strength lies in being easily modified for any environment, and it can be used by researchers and extension personnel. It was recently selected by researchers in Canada, after comparisons with CENTURY and other models, as the best option to look at long-term changes in soil C and to develop sustainable rotations in their farming systems.

SOCRATES, Soil Organic Carbon Reserves And Transformations in agro-EcoSystems, is a robust simulation model encapsulating our current knowledge for promoting soil organic matter storage and reducing degradation in semi-arid agro-ecosystems. To make the model applicable to the decision-makers from the farm to regional levels, it emphasizes the use of easily accessible input data. Users also have access to a simple utility that changes some key parameters, thus allowing re-calibration of the model to a particular environment. SOCRATES was designed specifically to estimate changes in surface soil organic C as influenced by crop, pasture and legume rotations, N fertilizer addition, disease, grazing intensity and climate. It runs on a monthly timestep, and simulations can range from 5-100 years.

SOCRATES contains a simplistic plant-growth model that is essentially a means of producing either leguminous or non-leguminous dry matter. This calculation is based on the relationship between growing-season rainfall (including an estimate of stored water) and productivity, after adjustments are made for water-use efficiency in the system [44]. A linear regression is specified for each crop or pasture for the potential yield in a certain environment, and the yield is then adjusted for crop/soil water-use efficiency (a function of run-off and evaporation). As a strong relationship exists between C accumulation, aggregate stability and infiltration [21], the water-use efficiency in the model also changes in response to annual fluctuations in C reserves. Nitrogen-fertilizer-use efficiency in SOCRATES varies as a function of annual rainfall. The individual crops considered (but not restricted to) in the model are canola, barley, wheat, oats, maize and grain legume, with the model also capable of estimating annual pasture productivity and simulating green manures. SOCRATES, like CENTURY, has been tested across a wide range of environments, including east Africa.

The major drawback of models such as SOCRATES and CENTURY is that the monthly timestep for climate can mask major changes in yield performance in the highly variable rainfed systems common in semi-arid regions. To gain a more accurate assessment of yield variation due to strategic fertilizer amendments and in intercropping systems, we need to use a daily timestep model to capture the transient changes in water availability that are the primary limiting factor in drylands. For this reason, the DSSAT model, Decision Support System for Agrotechnology Transfer [45], is considered the best equipped and most easily usable platform for analyzing the impact of more detailed management decisions (e.g. sowing dates, N-fertilizer rates, residue management, rotation selection) on yield and grain quality in response to the physical and climatic characteristics of the environment. Simulations can be made for many consecutive years.

DSSAT is actually a set of validated crop models for simulating the growth and development of specific cultivars in response to soil water and N. The cornerstone of the package are the CERES cereal [46] and CROPGRO grain-legume [47] models, which have been validated and used extensively around the world. DSSAT also contains a database-management scheme to store and retrieve the minimum data set required for running the models. This database also contains generic soil profiles and a weather-generating option to facilitate problem solving. Its decision-support strength is its applications program for analyzing "what if" scenarios or management questions frequently asked by farmers and advisors concerned with sustaining economically sound and environmentally productive agriculture. This includes risk and gross-margin analysis for a single season or for long-term rotations. The model requires daily inputs of air maximum and minimum temperature, rainfall and solar radiation, or a weather generator option can be employed to give a wide variety of scenarios. Simulations require initial values of organic C, soil water and nitrate, but these can be estimated. Soil physical characteristics are available in the database supplied with the model.

4. THE POTENTIAL ROLE OF CIMMYT

Up to recent times, the Centro Internacional de Mejoramiento de Maiz y Trigo (CIMMYT) was recognized as chiefly a "plant breeding" institute dealing with germplasm improvement for increased production of wheat and maize predominately in third-world countries. More than 70% of the developing world's wheat lands have been sown to CIMMYT-derived varieties. Just over 50% of the maize area in developing countries is planted to CIMMYT cultivars [48]. It has become abundantly clear over the past decade that improved germplasm does not in itself produce the yield increases required to feed the rapidly expanding global population. The organization has always been at the international forefront in combining the physiological, agronomic and economic aspects of agriculture in the quest for sustainable productivity increases in wheat and maize production. However, at current population densities and production levels, the degradation of both soil and water resources in agricultural lands of both the developed and undeveloped countries is becoming critical.

Within this context of agro-ecosystem management, CIMMYT has recently formed the Natural Resources Group (NRG) to aid in the development of robust cropping strategies to sustain production of wheat and maize systems whilst maintaining the natural resource-base on small farm holdings. The NRG's holistic approach to agro-ecosystem sustainability as a means of enhancing crop production is underpinned with specific expertise in the use of isotopes in the soil and plant sciences, farming-systems research, simulation models and geographic information systems (GIS).

With the effectiveness of natural-resource management often hindered by the inability to "scale up," the NRG is also using advanced methodologies for geographical extrapolation of possible strategies. Both DSSAT and SOCRATES are process models dealing with information from one point in space over a specified time-period - historically or predicted. What happens when we require its application at a local, regional, national or world-wide scale? To develop these models, and others of similar nature, as powerful tools for planning and management purposes of areas rather than individual points, requires the integration of appropriately geographically referenced data sets with the model. Such data sets in this instance are rainfall, temperature, soil type, land zone and chemical-analysis data (e.g. cation exchange capacity and initial soil organic C values). In most instances, these data sets exist only as point-in-space information, and interpolation methodologies must be employed to convert them into a "spatial data set" to make the models usable over the landscape. Spatial variability within the data sets is a critical issue,and, in our on-going work to convert DSSAT and SOCRATES from strictly process models into those that have a strategic spatial approach, we are employing a variety of techniques to produce accurate spatial data sets from the original point data.

One of the means by which management strategies can be evaluated across a wide range of climate zones is through the use of the Spatial Characterization Tool (SCT), which is a GIS application that accesses gridded environmental data, point data and vector-based information (polygons) [49]. The tool provides a suite of querying capabilities that allow the characterization of agricultural and agroecological environments. The tool enables the rapid construction of simple empirical models of conditions at a site or a zone for the purpose of supplying decision-makers with broad-scale environmental information (climate, available water-holding capacity of soil and topographic characteristics). Databases currently exist for Africa and Latin America, with a global dataset being released shortly. As an example of its use, zones of similarity can be identified where the growing season is defined by the five consecutive months that maximize the precipitation to potential evapotranspiration ratio. Probability distributions of rainfall and other climate variables can be made. This information identifies target domains for management strategies developed at one particular site with a defined climate. Simulation models can then be used for risk assessment by evaluating the spatial variation in crop production as a function of soil type and climatic variation.

CIMMYT is involved also in a collaborative effort to combine vertical dimension water-flow simulations from a crop model with a terrain analysis. Having a water balance on a landscape scale should permit more realistic assessment of the effects of tillage practices and other factors on crop-production sustainability. The same analyses should have direct application to precision agriculture and crop improvement under variable edaphic conditions.

5. CONCLUSIONS

Specific experiments should involve the use of ^{15}N-labelled fertilizers and organic materials to examine N-use efficiency in defined treatments as well as prospects for sustained release of N from soil organic matter. As soil-water availability plays the dominant role in semi-arid farming systems, it is important that a complementary assessment of water-use efficiency be made in these treatments to evaluate possible tradeoffs between water and N. These data then allow the refinement of simulation models. Even without this information immediately available, a large-scale simulation modelling exercise should be undertaken using the DSSAT model linked to a GIS to identify site-specific management strategies to maximize yield and reduce resource-degradation.

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SOME CIRAD ACTIVITIES AND PERSPECTIVES IN WATER AND NUTRIENT MANAGEMENT IN ARID AND SEMI-ARID REGIONS USING NUCLEAR TECHNIQUES

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Abstract

The Centre de Cooperation Internationale en Recherche Agronomique pour le Developpement has conducted collaborative research with national agricultural research services in several semi-arid regions that has led to a general understanding of the relationship between water consumption and growth, and crop responses to fertilizers However, farmers' adoption of practices arising from the research has been minimal Current effort is directed at overcoming limits to adoption, firstly by understanding the interaction of fertilizer response and water supply, especially through modelling, in order to quantify risk criteria from the farmer's point of view Secondly, research now takes account of the whole cropping system, including labour availability, access to credit, livestock management, etc, with a multidisciplinary approach Approaches that offer sustainability are improved intercropping systems, retention of crop residues, increased plant cover, and agroforestry There are important technical gaps in understanding of how these systems should operate The allocation of nutrients and water among the components of intercropped or agroforestry systems is not understood and solutions could lead to improved spatial arrangements The integrated effects of residues on runoff, soil evaporation, crop transpiration and N mineralization are not quantified In these and other problems, the full range of risks as well as benefits need to be evaluated

1. INTRODUCTION

The Annual Crops Department of the Centre de Cooperation Internationale en Recherche Agronomique pour le Develeppement (CIRAD-CA) has been involved in a large number of research projects in cooperation with national agricultural research services (NARS) in the Sahelian and Sudano-Sahelian zones of Africa, and more recently in Latin America and Asia. Based on intensive use of water-balance measurements and modelling [1], these activities have led to regional syntheses [2,3], and conclusions that:

- the relationships between water consumption of crops and yield are well known,
- the responses of crops to fertilizer are also well known.

However, the observation that few farmers adopt recommendations derived from scientific knowledge lead to the following questions.

- Are the recommendations technically correct?
- Have they been validated in farming conditions?
- Are they compatible with the biophysical and socioeconomic constraints affecting the whole farming system?
- Do the recommendations involve risk that farmers are prepared to accept?

In order to provide scientific answers, CIRAD, in partnership with NARS, is conducting farming-systems research and is developing tools to provide specific understanding of on-farm limitations by:

- modelling the coupled effects of water and fertilization on yield, in conditions of low water supply,
- taking into account the whole cropping system, including labour availability, access to credit, risk limitations, etc., in order to prepare conditions for a *multidisciplinary* study of the conditions of applicability of the technical recommendations.

2. COUPLED STUDIES

In the Sahelian zone, it is necessary to broaden these aspects and to develop accurate methodologies instead of following isolated studies on water and/or nutrients. Affholder [4] reached the following conclusions in a recent study.

"In many developing countries, yield increases obtained through intensification of agriculture seem necessary to face the high population growth rate. In the case of rainfed agriculture of semi-arid regions, the effect on yield of some intensive farming practices is highly variable, however, due to interactions with rainfall distribution and amount. This paper presents a model (SARRA) to perform regional comparisons of the risk associated with intensive practices in semi-arid environments. The model, built for this specific and restricted objective, is suitable for crops and regions where few data are available. The intensification level of a given crop situation is assumed to be the potential yield that would be obtained without any water constraint. The model was calibrated and validated for millet in Senegal and then run for three locations in that country, using long-term sequences of climatic data from wet and dry periods. Three potential yield levels and two runoff loss levels were tested for each location and period. At one site, the study revealed that using management to increase potential yield is highly risky. In a location only 200 km south of the former, the risk associated with intensive practices is much less, provided that all rainfall infiltrates. Considering a 25% rainfall loss by runoff, which was reported to be common in this region, however, the risk associated with high yield potential increases. This case study highlighted the extent to which the risk faced by farmers in semi-arid regions can vary spatially and with management practices. The approach proposed in this paper appears suitable for use in designing agricultural development strategies in semi-arid regions.

The model described here, due to its simplicity, is not suitable for detailed analysis of cropping techniques that could minimize risks for farmers, such as split nitrogen applications or reducing plant population during the crop cycle according to the rainfall conditions. The model is of interest, however, for making regional comparisons and assessing the impact of time changes in rainfall conditions. When used to analyze situations at three different sites in the Senegalese Bassin Arachidier, it highlighted the extent to which the water/fertility ratio can vary spatially. In the northern part of the Bassin Arachidier, the model simulations indicated that it is not worth trying to increase fertility when yields range from 500 to 1,000 kg ha^{-1} annually, because the rainfall situation will not support increased production. On the other hand, just 200 km further south, at Nioro-du-Rip, when all rainfall is infiltrated in the soil and the phytosanitary conditions are satisfactory, achievement of yields less than 1,500 kg ha^{-1} is a definite sign that fertility is a limiting factor. Hence, in the Sahel, more than anywhere else, the environmental crop-production conditions have to be fully defined before designing agricultural development strategies. In this respect, the present model would be a highly useful contribution, as it helps locate areas where there is a strong interaction between climatic conditions and intensification levels. Efforts to calibrate and validate mechanistic models could then focus on such areas, in order to optimize management techniques, taking into account climatic risk.

Actually, the risk faced by farmers does not directly result from yield variability, but rather from the way this yield variability and the variability of inputs and product prices interact with the farmers' social and economic objectives. Strategies to reduce such risk can be designed by linking crop models with socio-economical models. That would require multi-disciplinary work, which would enable researchers not only to design specific management techniques but also to test alternative price policies."

A review of the Sudanian zone shows that its cropping systems are similar to those in the Sahelian zone, and suggests that similar agronomic approaches should be taken with both. However, fewer biophysical limitations exist in the former, and there are more possibilities for exploring innovative cropping systems that may offer significant increases in farmers' yields and income, and at the same time provide more-sustainable farming systems. The current cropping systems are increasing soil erosion and lowering fertility, illustrated by decreasing organic matter content, decreasing pH, decreasing porosity of the soil, and degradation of hydrodynamic properties. In these conditions, intercropping, crop-residue retention, increased plant cover, and agroforestry are systems that could be encouraged to offer greater sustainability.

For these cropping systems, there remain important deficiencies in our comprehension of the relationships between a set of techniques and the yield, which cannot be resolved by direct experimentation. Before proposing innovative systems, mechanisms have to be better understood, and some basic questions must be resolved, as follows.

- How to partition correctly the specific water and nutrient demand of two associated crops?
- How to rationalize spatial arrangements between trees and annual crops in agroforestry systems for optimum water and N-use efficiency?
- What are the simultaneous effects of crop residues on run off, soil evaporation, crop transpiration, and N mineralization?
- What are the thresholds in terms of slope, soil type, and fertility, beyond which innovative cropping systems may or may not present more inconvenience than advantage?

3. SPECIFIC STUDIES

The first example concerns a study in Mexico of direct sowing rainfed maize after mulching with crop residues on the plant-available water supply, in areas with irregular rainfall [5].

"In tropical areas with low and/or irregular rainfall, good use of precipitation is often primordial for the success of rainfed crops. Soil preparation techniques play an important and complex role. The study analyzes the advantages of direct sowing with crop residue mulch to ensure production of maize in the V. Carranza region in Mexico. A combined, structured test design was set up. A controlled experimental procedure was performed to examine the relations between soil-preparation techniques and plot water fluxes and an agronomic survey of farmer's fields was carried out to examine the regional diversity of all the other production conditions which may affect water supply and successful cropping. In spite of the small amount of residue available (about 2 tons dry weight per hectare), the direct sowing + mulching technique resulted in better storage of rainfall in the soil. More water was available during dry periods, enabling greater water consumption by the crop and longer maintenance of photosynthesis. Root spread appeared to be less discriminatory under local soil-climate conditions; the differences between different types of soil preparation were small in all cases with little effect on water uptake. However, the extra water available is not always used to the full soil profile under field conditions. High water uptake by a strong weed population may reduce the advantage for the maize crop. Likewise, better water availability must be accompanied by equivalent crop demand. Farmers must manage plant cover population and growth and the factors affecting them for optimal use of the available water. Finally, the amount of grain formed must not be reduced by another limiting factor with a too strong effect on the functioning of plant cover during the critical flowering period. The study shows the difficulty of satisfactory application of direct sowing with mulching. The procedure proposed can provide the information required for the design of new cropping procedures incorporating direct sowing with mulching for a region such as V. Carranza. The crop management sequences proposed should enable better management of rainfall and remain acceptable for farmers."

The second example concerns analysis of agroforestry systems in a region of southern Senegal with irregular rainfall. In this study, N'Diaye [6] reported the use of prunings of N_2-fixing trees as an alternative source of nutrients:

"Low rates of chemical fertilizer applied on cereals in West Africa and lack of manure have led agronomists to look for other nutrient sources for cereal crops. This study was conducted within the framework of the development of an agroforestry system in which prunings of nitrogen-fixing trees were used as an alternative source of nutrients.

The scientific approach followed has three main steps: (i) diagnosis of nitrogen fixation by tree legumes growing under natural conditions using the natural isotopic ^{15}N abundance technique (ii) *characterization of nitrogen supply by tree prunings and their contribution on nitrogen uptake by maize (iii) in the field, quantification of contributions of soil, prunings and fertiliser on nitrogen uptake by maize, using the ^{15}N labelling technique.*

The diagnosis on nitrogen-fixing tree legumes growing under natural conditions reveals a rainfall threshold below which the nitrogen fixation is limited. Two hypotheses were made to explain the low level of the nitrogen fixation : (i) native Bradyrhizobium *strains develop and express themselves only when host plants are grown for a long period in a given zone (ii) negative interaction between soil/climatic conditions do not allow good survival of native* Bradyrhizobium *in the soil. Two characteristics of prunings: capacity of nitrogen supply and kinetics of biodegradation (half-life time) are measured in laboratory and validated under field conditions; they allow the set up of a predicting model of nitrogen supply by tree prunings. Optimal sowing date of maize and pruning period of tree legume are modelized to adjust nitrogen supply to nitrogen uptake by maize. To do so, the following parameters are taken into account (a) indicators of prunings (b) rainfall series on a long period of time (c) characteristics of cereal variety (d) soil characteristics. Contributions of mineral fertilizer, soil and tree prunings to nitrogen uptake by cereal are evaluated. Among those, the contribution of nitrogen fixation in tree prunings accounts for the role of nitrogen fixation in the durability the cereal based-agroforestry system. The Land Equivalent Ratio (LER) in alley cropping, is 0.90 and 1.6, respectively, when the maize pure crop is fertilized and unfertilized; this indicates the good biological efficiency of the agroforestry system.*

The agroforestory system performance is high and requires few expensive inputs. So, in theory it presents advantage in regions with high demographic pressure as the Peanut Basin of Senegal. However, farm diversity and socio-economic constraints of farmers should be considered before the agroforestry system is adopted.

4. CONCLUSION

We could ask a long list of questions about water and nutrient use in semi-arid cropping systems for which the current scientific literature offers only partial and sometimes contradictory answers. However, unless correct answers are given to these questions for each region, there is no probability that farmers will accept the risk of changing current cropping systems for a proposed but hazardous replacement. So agronomic research is obliged to face the challenge of developing improved and sustainable systems. *There are no simple solutions to complicated problems.*

Responses to the agronomic questions must include the disciplines of bioclimatology, physical, chemical, and biological soil science and crop physiology. The simultaneous use of nuclear techniques, neutron probes and labelled fertilizers are essential, for measuring water and nutrient behaviour. The results can be integrated in models to exploit innovative cropping systems. Such methods can contribute significantly to the implementation of high-quality research with southern-country partners, as shown in the presented examples.

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REVISED FAO METHODOLOGY FOR CROP-WATER REQUIREMENTS

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Abstract

In the early 1970s, the Food and Agriculture Organization of the United Nations (FAO) developed a practical procedure to estimate crop-water requirements that has become a widely accepted standard, in particular for irrigation studies. Since its publication as FAO Irrigation and Drainage Paper, new concepts and advances in research have revealed shortcomings in the methodology and made necessary a review and revision. A consultation of experts organized by FAO recommended the adoption of the Penman-Monteith combination method as a new standard for reference evapotranspiration, and advised on procedures for calculation of the various parameters. By defining the reference crop as hypothetical with an assumed height of 0.12 m, a surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evaporation of an extensive surface of actively growing and adequately watered green grass of uniform height, the FAO Penman-Monteith method was developed, overcoming previous deficiencies and providing values more consistent with actual crop-water-use data worldwide. Furthermore, recommendations have been developed for the use of the FAO Penman-Monteith method with limited climatic data, largely eliminating the need for any other reference evapotranspiration methods and creating a consistent and transparent basis for a globally valid standard for crop-water-requirement calculations.

1. INTRODUCTION

As part of FAO's mandate to assist its member countries to increase and sustain agricultural production, the Land and Water Development Division has been instrumental in the development of a globally accepted methodology for the prediction of crop-water requirements. The methodology published first in 1974 as No 24 in the FAO Irrigation and Drainage Series, and revised in 1977 [1] has become an international standard, extensively used worldwide.

Advances in research and the more accurate assessment of crop-water use have revealed weaknesses in the FAO No-24 methodologies [2,3,4]. The FAO Penman method was found frequently to over-predict reference evapotranspiration (ET_o) while the other FAO-recommended ET_o equations, namely the FAO Radiation, the FAO Blaney-Criddle, and the FAO Pan Evaporation methods, showed variable adherence to the reference-crop evapotranspiration standard of grass. Furthermore, the problem of using grass as a reference crop resulted in inconsistencies under different climatic conditions.

A consultation of experts and researchers was organized by FAO in May 1990 in Rome, in collaboration with the International Commission for Irrigation and Drainage and with the World Meteorological Organization, to review the FAO No-24 methodologies and to advise on the revision and updating of procedures. The panel recommended the adoption of the Penman-Monteith method and revised the definition and calculation procedures for estimating reference evapotranspiration. The report of the consultation presents the results of the review and recommendations as well as the detailed procedures for the calculation of the FAO Penman-Monteith method [5].

To follow up on the recommendations, a working group was established to carry out additional studies directed at further validation of the Penman-Monteith method and to improve or replace the original radiation and temperature methods when insufficient climatic data are available. Furthermore, a review and update were undertaken of the crop coefficients in light of the newly defined concept for the reference crop.

This paper provides a summary of the review of the various ET_o methods, presents the new recommended standard of the FAO Penman-Monteith method as a consistent and globally valid standard for crop-water-requirement calculations, and indicates how to apply the method when limited climatic data are available.

The results of the review of crop coefficients of the original FAO No-24 Manual have been consolidated into a single system of coefficients with procedures to adjust for crop height and various climatic conditions. The revised crop coefficients are reported [6] under the same topic area.

2. REVIEW OF REFERENCE EVAPOTRANSPIRATION METHODS

A large number of more or less empirical methods has been developed over the last 50 years by numerous scientists and specialists worldwide, to estimate evapotranspiration from different climatic variables. Relationships were often subject to rigorous local calibrations and proved to have limited global validity.

Based on the available research results and recommendations of experts in 1971 and 1972, four evapotranspiration methods were adopted in the FAO No-24 method to be used according to the availability of climatic data, as indicated in Table I.

- The FAO modified Penman was an adaptation of the original Penman method and included a revised wind function, derived from lysimeter data at various locations worldwide.
- The FAO radiation method was based on the Makkink method, developed originally for the humid conditions in the Netherlands. By introducing a correction coefficient for wind and humidity conditions, its validity was extended to a wider range of climatic conditions.
- The Blaney-Criddle method, introduced in the early 1950s in the arid western United States, found broad application in irrigation studies and was adapted as the FAO Blaney-Criddle method for a wider range of climatic conditions by introducing a correction factor that can be determined from estimates of humidity, wind and sunshine conditions.
- The pan evaporation method has been widely adopted on agro-meteorological stations; the measured evaporation of water in a standardized container has been extensively used as an ET_o parameter and is applied in many irrigation studies and in real-time irrigation scheduling. A pan factor is required, however, to correct the evaporation from a free water surface to the evapotranspiration of a green-grass cover. The method has been consolidated in FAO No-24 by standardization of the pan factor for various climatic conditions and environments.

A key element in the procedures for determining crop-water requirements (ET_{crop}) was the introduction of the crop coefficient standardized for the various growth stages. These coefficients were given for a large number of crops with detailed calculation procedures, providing an easy and uniform method that has become the accepted standard.

The large number of ET_o-estimation methods with various locally adapted or modified parameters has become confusing for the common user. To evaluate the performance of the various estimation procedures under different climatological conditions, a major study was undertaken under the auspices of the Committee on Irrigation Water Requirements of the American Society of Civil Engineers (ASCE).

The ASCE study reported by Jensen et al. [4] analyzed the performance of twenty different methods, using detailed procedures to assess the validity of the methods compared to a set of carefully screened lysimeter data from eleven locations with variable climatic conditions. The study proved to be revealing and showed the widely varying performance of the methods under different climatic conditions. Table II shows their performance, classified for humid and arid conditions.

TABLE I. Climatic data required for the FAO evapotranspiration methods [1]

Method	Temperature	Humidity	Wind Speed	Sunshine	Evaporation
FAO Blaney Criddle	*[a]	O[b]	O	O	
FAO Radiation	*	O	O	*	
FAO Penman	*	*	*	*	
Pan Evaporation		O	O	O	*

[a]Measured data essential.
[b]Estimation required.

In a parallel study commissioned by the European Community, a consortium of European research institutes evaluated the performance of various evapotranspiration methods using data from various lysimeter studies in Europe [7]. It confirmed the overestimation by the Modified Penman method introduced in FAO No-24, and the variable performance of the other methods depending on the degree of adaptation to local conditions. The comparative studies may be summarized as follows.

- The Penman methods require local calibration of the wind function to achieve satisfactory results.
- The Radiation methods provide good results in humid climates where the aerodynamic term is relatively small, but performance in arid conditions is erratic and underestimates evapotranspiration.
- Temperature methods remain empirical and require local calibration in order to achieve satisfactory results. A possible exception is the Hargreaves method [8], which has shown reasonable ET_0 results with global validity.
- Pan evapotranspiration methods clearly reflected the shortcomings of predicting crop evapotranspiration from open-water evaporation. The methods are susceptible to the micro-climatic conditions under which the pans are operating and their performance proves erratic.
- The excellent performance of the Penman-Monteith approach both in arid and humid climates was convincingly shown in the ASCE and the European studies.

3. THE FAO PENMAN-MONTEITH EQUATION

The comparative studies and much other research have confirmed the superior performance of the Penman-Monteith approach. By introducing aerodynamic and canopy resistance in the combination method, better simulation of wind and turbulence effects and of the stomatal behavior of the crop canopy was achieved [9]. Earlier difficulties related to the estimation of the resistance values have been largely overcome by progress in research and reliable estimates of the two parameters for a range of crops including the reference crops, grass and alfalfa.

The FAO experts reached unanimous agreement in recommending the Penman-Monteith approach as the best-performing method to estimate evapotranspiration of a reference crop, and adopted the estimates for bulk surface and aerodynamic resistance as elaborated by Allen et al. [2] as standard values for the reference crop.

TABLE II. Performance of various ET_o methods [4]

Method	Humid			Arid		
	Rank no.	Over est.[a]	Stand error[b]	Rank no.	Over est.[a]	Stand error[b]
Combination						
Penman-Monteith	1	+4%	0.32	1	-1%	0.49
FAO-24 Penman (c=1)	14	+29%	0.93	6	+12%	0.69
FAO-24 Penman (corrected)	19	+35%	1.14	10	+18%	1.1
FAO -PPP-17 Penman	4	+16%	0.67	5	+6%	0.68
Penman (1963)	3	+14%	0.60	7	-2%	0.70
Penman 1963, VPD #3	6	+20%	0.69	4	+6%	0.67
1972 Kimberley Penman	8	+18%	0.71	8	+6%	0.73
1982 Kimberley Penman	7	+10%	0.69	2	+3%	0.54
Businger-van Bavel	16	+32%	1.03	11	+11%	1.12
Radiation						
Priestley Taylor	5	-3%	0.68	19	-27%	1.89
FAO-Radiation	11	+22%	0.79	3	+6%	0.62
Temperature						
Jensen-Haise	12	-18%	0.84	12	-12%	1.13
Hargreaves	10	+25%	0.79	13	-9%	1.17
Turc	2	+5%	0.56	18	-26%	1.88
SCS Blaney-Criddle	15	+17%	1.01	15	-16%	1.29
FAO Blaney-Criddle	9	+16%	0.79	9	0%	0.76
Thornwaite	13	-4%	0.86	20	-37%	2.4
Pan evaporation						
Class A Pan	20	+14%	1.29	17	+21%	1.54
Christiansen	18	-10%	1.12	16	-6%	1.41
FAO Class A	17	-5%	1.09	14	+5%	1.25

[a]Over- or under-estimation as percentage from eleven lysimeter data locations, corrected for reference type.
[b]Weighted standard error of estimates, mm/day.

The adoption of fixed values for crop-surface resistance and crop height required an adjustment of the concept of reference evapotranspiration that was redefined as follows.

Reference evapotranspiration is the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height (12 cm), a fixed crop surface resistance (70 s m^{-1}) and albedo (0.23), closely resembling the evapotranspiration from an extensive surface of green grass-cover of uniform height, actively growing, completely shading the ground and with adequate water.

Thus defined, the Penman-Monteith equation used for 24-h calculations of reference evapotranspiration and using daily or monthly mean data can be simplified as follows,

$$ET_o = \frac{0.408\Delta(R_n-G)+\gamma\frac{900}{T+273}U_2(e_a-e_d)}{\Delta+\gamma(1+0.34U_2)}$$

where

ET_o is the reference crop evapotranspiration (mm d^{-1}),
R_n is the net radiation at the crop surface (MJ m^{-2} d^{-1}),
G is the soil heat flux (MJ m^{-2} d^{-1}),
T is the average air temperature (°C),
U_2 is the wind speed measured at 2 m height (m s^{-1}),
(e_a-e_d) is the vapour pressure deficit (kPa),
Δ is the slope of the vapour pressure curve (kPa $°C^{-1}$),
γ is the psychrometric constant (kPa $°C^{-1}$), and
900 is the conversion factor.

Full details of the FAO Penman-Monteith method and procedures for determining the various parameters, algorithms, recommended values and units are already published [10,11].

The FAO Penman-Monteith equation can be adapted to hourly ET_o calculations, of relevance in detailed research studies and for automatic weather stations, by replacing the conversion factor 900 in the equation by 37, equal to 900/24. Net radiation and soil heat flux are determined for hourly values by adjusted formulas for incoming radiation and heat flux. Comparison of hourly measured and calculated values and summations of hourly and 24-hour calculations showed good agreement [11].

A key element in the development of the FAO Penman-Monteith equation is the assumption of the reference crop as hypothetical, with a fixed surface-resistance value. Many studies on various crops have shown, however, that the resistance factor, which represents stomatal behaviour, is affected by climatic conditions. Solar radiation, air temperature, vapour-pressure deficit, day-length and wind affect the crop resistance to different degrees and in different directions. The study commissioned by the European Community showed increasing resistance values for lower latitudes and recommended a variable factor [7].

Further studies have been undertaken by the FAO working group to evaluate this aspect [12,13]. Results have not been conclusive and often contradictory. The original recommendation made by the FAO expert panel of a surface resistance of 70 s m^{-1} for a hypothetical grass crop is therefore maintained as a valid and standardized approximation.

4. USE OF FAO PENMAN-MONTEITH WITH LIMITED CLIMATIC DATA

A main reason to recommend the use of different ET_o methods has been the limited availability of full climatic data, in particular, sunshine, humidity and/or wind data are often lacking. To further standardize the use of the FAO Penman-Monteith method, additional studies have been undertaken to provide recommendations when limited meteorological data are available, as outlined below.

4.1. Wind data

Measured wind data are often lacking, or prove unrepresentative for the crop because of different microclimatic conditions at the agro-meteorological station. Such wind-speed differentials can be large on a day-to-day basis, whereas mean monthly values may be more consistent.

If no wind data are available, estimates can be made of average wind-speed values for ET_o calculations from global values on a monthly basis. Wind-speed data from the nearest station can be used for that purpose. The FAO CLIMWAT database [14] contains mean monthly readings from more than 3,200 stations, and allows estimates on wind data for many locations worldwide. In a further simplification, a worldwide average can be taken, based on CLIMWAT data, as follows.

$$U_2 = 2\ m\ s^{-1}$$

For windy conditions, wind speed can be approximated by an average value of 260 km day^{-1} or 3 m s^{-1} and, for low-wind conditions, values of 90 km day^{-1} or 1 m s^{-1} can be taken.

4.2. Humidity data

The radiation method was introduced in FAO No-24 to accommodate users in humid climates with measured data on temperature and radiation and with estimates for wind and humidity. Other studies [15,16] have shown that daily minimum temperature, which is more commonly available, allows reasonable estimates of the dew-point temperature. Under more arid climates greater deviations may occur, with minimum temperature 1 to 3 degrees above dew point when the weather station is surrounded by well-watered or irrigated vegetation, representing the reference condition. Actual vapour pressure (e_d) can be estimated [17] from the minimum daily temperature (T_{min}) using the following relationship.

$$e_d = 0.611 \exp\left(\frac{17.27\ T_{min}}{T_{min} + 237.3}\right)$$

ET_o values determined according to the FAO Penman-Monteith method using humidity estimates from minimum temperatures and standardized wind values (2 m s^{-1}) were improved over those made using a standard temperature formula [16].

4.3. Radiation data

Temperature methods, such as Blaney-Criddle, Turc, and Hargreaves, have remained popular because of their lack of radiation data and relatively easy calculation procedures. Studies have been undertaken by the FAO working group to correlate radiation and sunshine duration with minimum and maximum temperatures [15,18] and with rainfall [19]. Analogous to the relationship established in the Hargreaves method [8], radiation can be approximated [16] for inland stations from incoming extraterrestrial radiation (R_a) and the temperature deficit ($T_{max} - T_{min}$), using the following relationship.

$$R_s = 0.17 \frac{P}{P_o} (T_{max} - T_{min})^{0.5}\ R_a$$

For higher elevations, a barometric correction (P/P_o) needs to be applied, where P_o is the barometric pressure at sea level. For coastal stations, a coefficient of 0.19 proved better, while for island stations a simple relationship could be established as follows.

$$R_s = (-4 + 0.7 R_a)$$

The correlations proved to be weak on a global basis and better ET_0 estimates were obtained when using R_s data from the nearest station with comparable climatic conditions.

5. CONCLUSIONS

The FAO-Penman-Monteith equation is recommended as the standard method for estimating reference and crop evapotranspiration. The new method has been proven to have global validity as a standardized reference for grass evapotranspiration and has found recognition by the International Commission for Irrigation and Drainage and by the World Meteorological Organization.

Procedures have been established to estimate missing climatic data that allow the FAO Penman-Monteith method to be used under all conditions. This eliminates the need for any other methods and will increase the transparency and consistency of reference and crop-water requirement studies.

The change of ET_0 definition to a hypothetical crop with fixed parameters has, to a large extent, eliminated problems related to the previous requirements in measuring a living reference ET_0, and will further facilitate the calibration of crop coefficients for the estimation of crop-water use.

It is hoped that the new FAO publication on revised procedures for crop-water requirements, which will shortly be published, will indeed become a globally accepted reference .

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