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Nutrient and water management practices for increasing crop production in rainfed arid/semi-arid areas

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FOREWORD

The world's population is expected to reach eight billion by the year 2025, putting greater pressure on world food security, especially in developing countries where major population increases is expected to occur. In meeting the increasing demand for food, rainfed agriculture will continue to play a major role. More than 65% of cereal croplands worldwide are rainfed, accounting for 58% of world cereal production. Moreover, with the decreasing availability of irrigation water for agriculture, there is an increased need for enhancing crop productivity under rainfed conditions. Currently, irrigation accounts for around 70% of water withdrawals worldwide and 90% in low-income developing countries, but due to rapidly increasing domestic and industrial demands for water in many developing countries, serious limitations to irrigated agriculture are foreseen.

Increasing crop productivity in arid and semi-arid areas is widely recognized as difficult. This is mainly due to highly erratic and low rainfall as well as degraded soils deficient in plant nutrients. To meet the increasing demand for food, farmers in many developing countries have expanded rainfed agriculture into marginal lands that are susceptible to environmental degradation, particularly soil erosion. Nutrient mining is a common application of adequate amounts of fertilizers to replenish nutrient uptake by crops and losses but is not a viable option for most resource-poor farmers in these regions. As a result, crop productivity of rainfed regions is low. For example, cereal yields in rainfed areas of developing countries rarely exceed 1.5 t ha^{-1}, less than half those of rainfed cereals in developed countries. Nevertheless, there is some evidence that crop yields in these regions can be profitably increased and yield variation decreased with a combination of careful management of natural resources and low inputs of chemical fertilizers. Since nearly two-thirds of the rural population of developing countries live in these less-favoured areas, there is an increasing demand for exploring such management practices for improving soil fertility and increasing crop production. In this regard, isotopes and nuclear techniques play a crucial role in providing valuable quantitative information on nutrient release from crop residues and fertilizers and uptake of nutrients and water by crops for identification of promising management practices for optimising crop production under rainfed conditions.

Based on the recommendations of a consultants meeting organized by the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, 26–29 May 1997, a Coordinated Research Project on Management of Nutrients and Water in Rainfed Arid and Semi-Arid Areas for Increasing Crop Production was implemented between 1997 and 2002 with the overall objective of increasing crop production through improved management of nutrients and water in rainfed arid and semi-arid areas.

Eleven contract holders from Argentina, China, India (two), Jordan, Kenya, Morocco, Niger, Pakistan, Senegal and Zimbabwe, and five agreement holders from Australia, France, TSBF-Kenya, ICARDA-Syria and ICRISAT-Zimbabwe participated. The first research coordination meeting (RCM) was held 6–10 July 1998 in Vienna, the second RCM was held in Tunis, 6–10 March 2000 and the final RCM convened in Vienna, 24–28 September 2001. P. Moutonnet and G. Keerthisinghe/L. Heng were the Project Officers from December 1997 to June 2001 and from July 2001 to December 2002, respectively.

This publication contains the manuscripts prepared by the project participants and A.R.J. Eaglesham, Ithaca, New York. The IAEA Officers responsible for this publication are G. Keerthisinghe and L. Heng of the Agency's Laboratory, Seibersdorf.

EDITORIAL NOTE

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SUMMARY

This coordinated research project (CRP) supported national efforts in eleven Member States to identify improved nutrient- and water-management practices for increasing crop production in rainfed arid and semi-arid areas. Various options for utilizing organic manures and fertilizers, recycling crop residues, inclusion of legumes in rotations and conservation of water that are sustainable and economically attractive to farmers were examined using isotopic techniques. The specific objectives were to:

- investigate management strategies that optimize and sustain the productivity of rainfed farming systems by increasing the efficiency of utilization of water and nutrient,
- define appropriate technologies to enhance crop water use and nutrient uptake, and to ensure their applicability at the farm level,
- test crop responses to water and nutrients in relation to crop sequence and surface management in field experiments using nuclear techniques,
- promote collection of minimum sets of data in all experiments, store the data in a common data base, test and apply simulation models and use the data and models in training national staff.

The field experiments of this CRP covered a wide range of arid and semi-arid regions and cropping systems, such as wheat–maize systems on the loess plateau of China (Cai et al., p. 77), sorghum–castor rotations (Ramana et al., p. 139) in Andra Pradesh, India, maize-based systems in the Machakos District of Kenya (Sijali and Kamoni, p. 209) and in the Senegal peanut basin (Sene and Badiane, p. 197), and wheat–vetch rotations in the Safi-Abda region of Morocco (El Mejahed and Aouragh, p. 89). Most of the study sites were characterized by low rainfall (< 300 mm) during the growing season with frequent dry spells and soils low in organic matter (<1% organic carbon) and plant nutrients, especially nitrogen (N) and phosphorus (P).

The use of stable isotope ^{15}N provided valuable quantitative information on the fate of N inputs through fertilizers, manures, crop residues and biological N_2 fixation, enabling identification of appropriate N management practices best suited to local conditions. It was observed from all the studies that irrespective of the management practices, 20 to 60% of applied fertilizer N was lost, and under alkaline (pH 7.7-8.0) soil conditions, N losses at the beginning of the vegetative period were as high as 80%, while the residual value of applied N available to subsequent crops was extremely low, and rarely exceeding 9% of the crop N requirement. These results highlighted the importance of investigating fertilizer-management practices to minimize losses, especially during the early part of the cropping season. Split application is one option which can increase fertilizer use efficiency; experiments conducted at Changwu Experimental Station in the southern part of the Chinese Loess Plateau (Cai et al., p. 77) showed that split application of 60 kg N ha^{-1} during the dry season was adequate to increase wheat yields by 80% compared with no fertilizers, however, no further increase in crop yields was observed at higher levels of N. The amount of N to be applied at each split needs to be based on the soil N status and crop demand for N.

Participants investigated a number of options to reduce fertilizer-N inputs by substituting a proportion of the required N with manure, crop residues and biological N_2 fixation. The selection of management options depended mainly on the availability of the resources and farmers' practices. Results indicated that manure combined with mineral fertilizers in correct proportions could provide 10 to 15% of the crop-N requirement and increase yields. Studies conducted at the Regional Agricultural Research Station (RARS), in Andhra Pradesh, India (Ramana et al., p. 139) demonstrated that application of 1.5 t ha^{-1} farmyard manure (FYM) to sorghum did not increase the grain yield but combined with 45 kg N ha^{-1} of urea, it produced a grain yield equivalent to 60 kg N ha^{-1}. Similarly, studies conducted at the Nioro Agricultural Research Station in the Senegal peanut basin (Sene and Badiane, p. 197) showed that by application of 5 t ha^{-1} of manure every two years, corn yields can be increased by almost 100% compared with no organic or inorganic inputs. However, the manure option is dependent on supply and will not be viable for all regions.

The participants demonstrated various ways of utilizing biological nitrogen fixation to improve the N nutrition and yields of crops. Intercropping cereals with grain legumes showed positive results in increasing overall system productivity. For example, intercropping sorghum with pigeon pea in India (Ramana et al., p. 139) or wheat with lentil around Peshawar in Pakistan (Mohammad et al., p. 107) significantly increased crop yields per unit area compared with sole crops. Moreover, legumes produced over 2 t ha^{-1} of crop residues, which supplied over 10 kg N ha^{-1} to subsequent crops. Crop residues also play an important role as animal fodder.

Using ^{15}N techniques, legume species efficient in biological N_2 fixation were identified for inclusion in crop rotations. For example under Sahelian conditions, cowpea fixed more than twice the amount of atmospheric N compared with groundnuts, and inclusion of cowpea in millet-based cropping systems increased N-use efficiency by about 30% (Bationo et al., p. 53). Isotope techniques were also useful in assessing intercropping systems. Studies conducted in Andhra Pradesh, India, showed that a sole pigeon-pea crop obtained 57% of its N from the soil, whereas when intercropped with sorghum it took only 35% of its N from the soil. The researchers were thus able to quantify the value of different N inputs and formulate management options accordingly.

In all studies, the amount and variation in precipitation during the growing season had a strong impact on yield and the utilization of applied N. Both grain yield and N use efficiency by crops increased with increasing amount and timely distributed rainfall, which provided adequate soil moisture for uptake of nutrients. This was demonstrated in the studies conducted at Maru Agricultural Research Station in Jordan (Rusan et al., p. 155), and at Jemaa Riah and Jemaa Shaim Agricultural National Research Institute (INRA) experimental stations in Morocco where fertilizer application under adequate moisture condition increased crop yields (El Mejahed and Aouragh, p. 89), however, addition of nutrients during periods of drought led to decreased yields. This was also demonstrated in the studies conducted at the Indian Agricultural Research Institute farm in New Delhi with better performance of both wheat and mustard in the first year primarily due to higher and timely winter rainfall (Sachdev, p. 179).

The use of soil moisture neutron probe has provided quantitative measurements of soil moisture and allowed water use efficiency (WUE) to be calculated. The WUE is the ratio between grain yield and evapotranspiration (ET) and is considered to be an important parameter defining the productivity of crops in water limiting environments. In general, application of N increased the WUE of crops due to improved groundcover and hence reduced evaporation from the soil. Up to 50% improvement of the efficiency of water use by crops could be achieved by changing the management practices according to the pattern of rainfall during the growing season (Mohammad et al., p. 107). The result was better overall crop productivity (by approximately 50%) and profitability and improved conservation of scarce water resources. The results demonstrated that understanding the interactive effects of N and water on nutrient uptake and crop yields is important to identify management practices for cost-effective crop production (Asseng and Turner, p. 43).

The project also compared various soil- and water-conservation practices. In general, mulching techniques using crop residues or polythene covers improved water infiltration and reduced soil-water evaporation. However, the effects of mulching on crop yields were not consistent. For example, the experiments conducted in China showed that corn yields increased due to mulching but similar effects were not observed in wheat, mainly due to differences in soil-water content at sowing (Cai et al., p. 77). Other practices such as ridging over flat cultivation and zero tillage over conventional tillage did not exhibit any significant effects on crop yields, especially under very low soil-moisture levels (Sijali and Kamoni, p. 209). These results highlight that, if the soil moisture is extremely low during the vegetative period due to low or erratic rainfall, expected benefits of soil moisture conservation methods cannot be achieved.

One means of coping with dry environments is to exploit genotypic differences in plants for drought tolerance. The carbon-isotope discrimination (Δ) technique was assessed as a diagnostic tool for predicting water-use efficiency (WUE) and yield (Mohammad et al., p. 107; Sachdev, p. 179). While there were significant relationships between Δ and wheat grain yield, they were not consistent, being variously positively and negatively correlated (Heng et al. b, p 15). The variable data imply that studies specifically designed to separate out confounding factors are needed before the efficacy of the Δ technique can be verified.

The above studies indicated that low soil fertility and drought are the main factors affecting the productivity and sustainability of rainfed agriculture. To improve crop productivity in drought-prone areas, farmers, extension workers, researchers, and policymakers need to identify best-suited management options to optimize the use of natural resources. Simulation models can provide valuable information to researchers and farmers to evaluate a wide range of cropping system options (e.g. crop rotations and intercropping; planting dates, fertilizer-management practices) and examine the long-term climatic risks. One such model is APSIM (Agricultural Production Systems Simulator Model), developed by the Agricultural Production Systems Research Unit (APSRU) in Australia, which can accommodate interactions among climate, soil fertility, and crop- and residue-management practices. In this CRP, APSIM-N wheat was successfully used to simulate wheat-grain yield and grain-N content using field experimental data collected in Morocco and Jordan (Heng et al. a, p. 5). It was subsequently used to analyse the long-term effect of soil type, rate and timing of N fertilizer application, initial stored soil water, different cultivars (early versus late) and supplemental irrigation in optimizing wheat production The simulation results indicate that yields were mainly limited by the amount and timing of rainfall. While nitrogen fertilizer improved grain yields in wet years; the effect was minimal or detrimental in dry years. Tactical N management to improve and sustain yield can be achieved through early sowing, having stored soil moisture at the start of the season and a small amount of supplemental irrigation at sowing. Similarly, APSIM's sorghum, pigeon pea modules were successfully used to examine options for improving productivity in smallholder farming in semi-arid lands in India and Zimbabwe (Myers, p. 127), by setting of low-rate fertilizer recommendations for resource-poor farmers.

In conclusion, there is potential in increasing crop production in rain-fed agriculture to sustain food production, if rainwater, crop and soil fertility can be managed properly and if socio-economic constraints can be overcome. This CRP shows that there are a range of options available for addressing the problems of low productivity in rainfed agriculture, through efficient use of natural resources such as organic manures and fertilizers, the recycling of crop residues, inclusion of legumes in rotations and conservation of water such as water harvesting (collecting of runoff and using it to irrigate crops). The use of improved or high-yielding crop germplasm resistance/tolerance to abiotic stresses (drought and salinity) is another way of sustaining yields in rainfed system. All these can significantly improve yields and the reliability of agricultural production. However, in many parts of the world where water is absolutely limiting, the addition of water through irrigation, supplemental irrigation needs to be considered, as that is the only option to provide the much-needed water by the crops.

OPTIMIZING WHEAT PRODUCTIVITY UNDER RAINFED ENVIRONMENTS OF WEST ASIA AND NORTH AFRICA USING SIMULATION MODEL

L.K. HENG[1], S. ASSENG[2], K. EL MEJAHED[3], M.M. RUSAN[4], G. KEERTHISINGHE[5]

[1] Soil Science Unit, FAO/IAEA Agriculture and Biotechnology Laboratory, Seibersdorf, Austria
[2] CSIRO Plant Industry, Wembley, Australia
[3] Institut National de la Recherche Agronomique, Settat, Morocco
[4] Jordan University of Science and Technology, Irbid, Jordan
[5] International Atomic Energy Agency, Vienna

Abstract

The performance of a crop simulation model (APSIM-Nwheat) was tested using data obtained from two locations in the rainfed environments of West Asia and North Africa: Morocco and Jordan. The experiments covered three seasons in Morocco and one in Jordan, with a range of fertilizer-N treatments. The model was able to simulate wheat-grain yield, grain-N content reasonably well except for one season in Morocco. It was subsequently used to analyse the effect of soil type (water-holding capacity), rate and timing of N-fertilizer application, initial stored soil water and different cultivars (early flowering versus late) in optimizing wheat production using twenty years of historical weather records from Morocco. The simulation results indicate that yield is limited by rainfall. Nitrogen fertilizer can improve grain yield in wet years; however, the effect can be detrimental depending on the timing and distribution of rainfall. Having initial stored soil moisture was beneficial in dryer years, but the effect was minimal in wet years. Simulation models such as APSIM can, therefore, be a useful tool to help identify better nutrient- and water-management practices to increase crop production in rainfed arid and semi-arid areas.

1. INTRODUCTION

The West Asia and North Africa (WANA) region is one of the driest in the world, with low, erratic precipitation and frequent droughts. Water shortage is a major constraint to agricultural production. Cereal production is important in this region; in Morocco it represents more than 80% of the total arable land [1]. However, yields of cereal crops in the rainfed areas are generally low; in Jordan they range from 0.2 to 1 Mg ha^{-1}. The unpredictability of the rainfall also makes it difficult to determine the level and timing of fertilizer needed to attain optimum yield, as it might result in over- or under-application of N depending on the rainfall [2]. Variation in growing-season precipitation, therefore, has strong impact on yield and utilization of applied N.

In order to develop suitable and appropriate crop-production strategies for increased and sustained yields, and to understand the links between climate variability, water availability and use, and agricultural productivity, a crop-simulation model, APSIM-Nwheat, was used to evaluate field experimental data collected in Morocco and Jordan between 1998 and 2002 [1,2]. Simulation models can be useful when appropriately applied, as they allow study of outcomes over many seasons in parallel with minimal computing time and with control over unwanted factors; they also allow the evaluation of alternative farm-management options and overcome the limitations of field experiments: length of time, locations, soil types and management options and initial conditions. Using information from long-term simulation experiments and by characterizing production systems, it is possible to extrapolate the results from these experiments to other similar agro-ecological zones, and explore the implications of various improved cropping systems in farmers' fields.

The Agricultural Production Systems Simulator Model (APSIM) [3] for wheat (APSIM-Nwheat version 1.55s), developed by the Agricultural Production Systems Research Unit (APSRU), Toowoomba, Queensland, Australia, is a model capable of simulating crop development, growth, water and N dynamics and interactions among climate, soil fertility, and crop- and residue-management practices. It runs on a daily time-step using daily weather information based on rainfall, maximum and minimum temperatures and solar radiation. It calculates the potential yield, which is the maximum yield reached by a crop in a given environment, and is limited only by temperature, solar radiation, water and N supply. APSIM-Nwheat has been rigorously tested against various field measurements under a range of growing conditions [4,5].

2. MATERIALS AND METHODS

The first field trial reported here was conducted between 1998 and 2002 in Jemaa Riah (JR) at the Agricultural National Research Institute (INRA) Experimental Station, located 60 km south of Casablanca in the Chaouia region of Morocco, as described in Ref. [1]. The soil was classified as a fine montmorillonitic, thermic Palexerollic chromoxerert with a IIe capability subclass. It has a petrocalcic horizon below 50 to 60 cm. The properties of the soil were described by El Mejahed and Aouragh [1]. The measured physical and hydraulic properties used in APSIM simulation are given in Fig. 1a. The plant-available water-holding capacity (PAW) of JR soil is approximately 70 mm, which is the water content between the drained upper limit (DUL) and plant-available lower limit (LL). The DUL is the soil water retained after gravitational flow, sometimes referred to as “field capacity” (FC) SAT is the saturated water content and LL15 in Figs. 1a and b refers to the 15-bar lower limit of soil-water content in the upper layers. It is approximately the least water content achievable by plant extraction.

The second study was carried out in the 1998–1999 and 1999–2000 seasons at Maru Agricultural Research Station, 100 km north of Amman, Jordan. The soil is a very fine smectic, thermic Typic Chromoxerert, with a pH of 7.6 and 5.9% calcium carbonate [2]. The measured and the APSIM soil parameters for the Maru experiment are given in Fig. 1b and the corresponding PAW of Maru soil is 95 mm. A difference of 25 mm exists between DUL and LL of JR and Maru soils, with the higher values in the latter.

Wheat cultivars Horani 27 and Achtar (a bread type) were used in the Jordan and Moroccan studies, respectively. As the phenology of the cultivars was not given, the early Australian cv. Amery, which has similar growing characteristics, was used in this simulation (Table I).

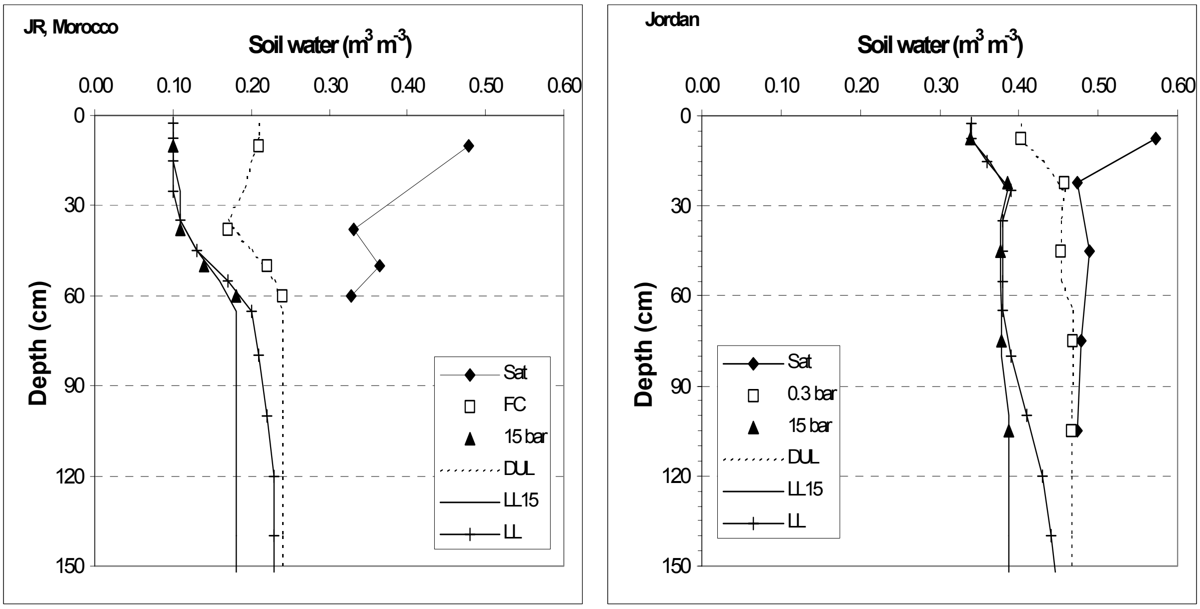

FIG. 1. The hydraulic properties and APSIM parameters for (a) JR, Morocco and (b) Maru, Jordan.

Table I. Wheat genotype coefficients

Parameter	Amery	Spear
plv[a]	1.6	1.5
pld[b]	1.8	3.5
p5[c]	680	740
Grno[d]	22	24
Fillrate[e]	2.9	2.1
stwt[f]	3.00	3.00
phint[g]	100	110

[a] Sensitivity to vernalization (1–5).

[b] Sensitivity to photoperiod (1–5).

[c] Thermal time (base 0°C) from beginning of grain filling to maturity (°C d).

[d] Coefficient of kernel number per stem weight at the beginning of grain filling [kernel (g stem)$^{-1}$].

[e] Maximum kernel growth rate (mg kernel^{-1} d^{-1}).

[f] Potential final dry weight of a single stem, excluding grain (g stem^{-1}).

[g] Phyllochron interval [°C d (leaf appearance)$^{-1}$].

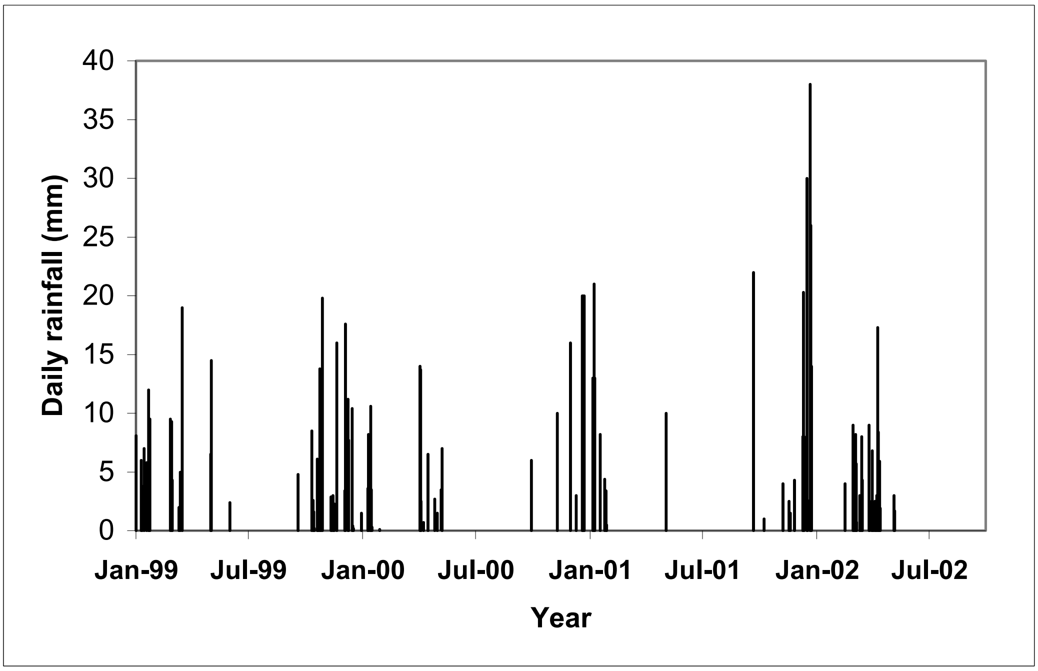

FIG. 2. Daily rainfall for JR, Morocco, during the experimental period.

The simulation was run over the whole experimental period from 1999 to 2002 for Morocco and for the 1998 to 1999 season for Jordan due to incomplete weather data in other years. The model was initialized with measured initial soil moisture and N level when available, otherwise they were estimated.

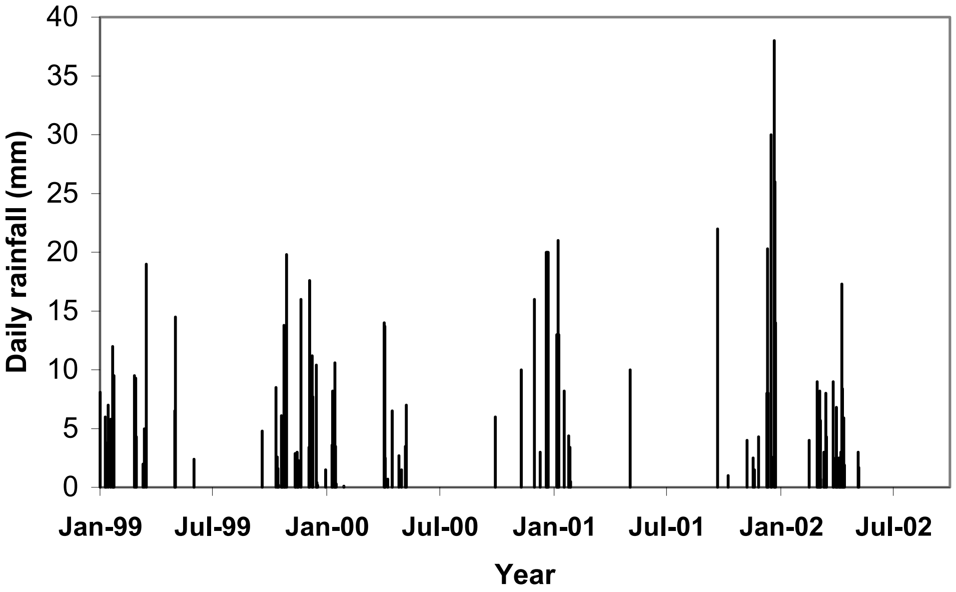

FIG. 3. Daily rainfall for Maru experimental station, Jordan.

3. RESULTS AND DISCUSSION

3.1. Rainfall

Daily rainfall patterns for the experimental period at JR, Morocco, and Maru, Jordan are given in Figs. 2 and 3. Cumulative growing-season rainfall, i.e. between October and April, is given in Fig. 4. The first two years (1999–2001) were dry in Morocco; the amounts and distribution of received rainfall during these years are an indication of the variation in climatic conditions that prevail in semiarid regions of Morocco. In the 1999–2000 season, although there were 236 mm of rainfall, around 70 mm were received in October (before planting), and 67 mm fell in April when crop growth had ceased pending harvest. During the 2000–2001 cropping season, fewer than 10 mm of rainfall were received after the end of January, resulting in low yields again. The highest rainfall during the above study was received during the 2001–2002 cropping season, which was 270 mm. The rainfall distribution in Jordan for the 1998–1999 growing season was (mm): Oct. 1.3, Nov. 0.4, Dec. 14.1, Jan. 96.7, Feb. 42.2, Mar. 49.2 and Apr. 8.4. The late rain in October to December resulted in delayed emergence and poor wheat growth.

3.2. Yields

The measured and simulated grain yields for Morocco and Jordan, plotted against the seasonal cumulative rainfall from October to April are shown in Fig. 5. The measured grain yields were extremely low in both countries, with most values less than 1.5 Mg ha^{-1}. The results also showed that most of the yields fell below the French and Schultz [6] 20 kg ha^{-1}mm^{-1} potential line, which is commonly used by farmers in Australia to set a target for potential yield using growing-season rainfall after accounting for 110 mm of soil evaporation. This indicates that in the WANA region, often the distribution rather than the total seasonal amount of rainfall determines potential grain yields.

Figure 5 also shows that the model simulated the yield reasonably well in most seasons except for the 2000–2001 cropping season in Morocco, which had 270 mm of rain. In that year, the model predicted yields of approximately 3 Mg ha^{-1} whereas the measured yields were only about 0.5 Mg ha^{-1}. The reason for the discrepancy is unknown. However, a parallel experiment carried out in another location, Jemaa

Shaim (JS) Agricultural National Research Institute (INRA) experimental station, located in the Safi-Abda region, with similar rainfall, produced grain yields close to that of the model prediction for the JR site (Fig. 5).

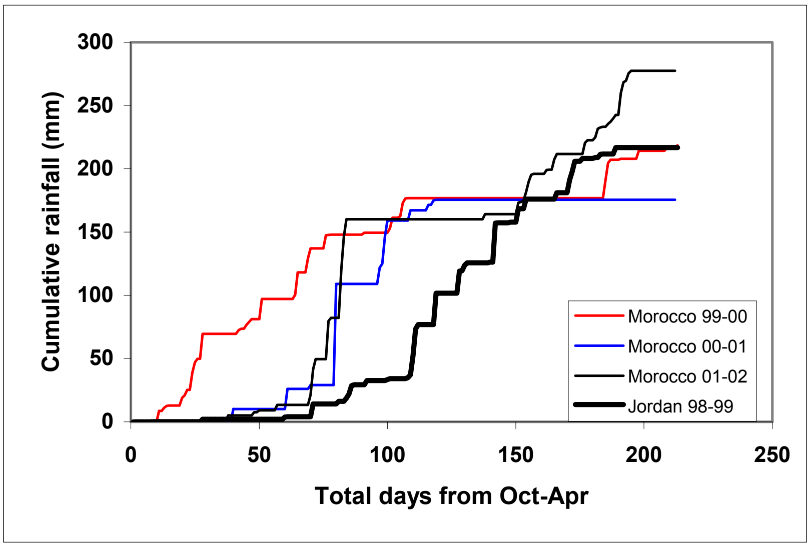

FIG. 4. Cumulative rainfall during the growing season, between October and April, for JR, Morocco, and Maru, Jordan.

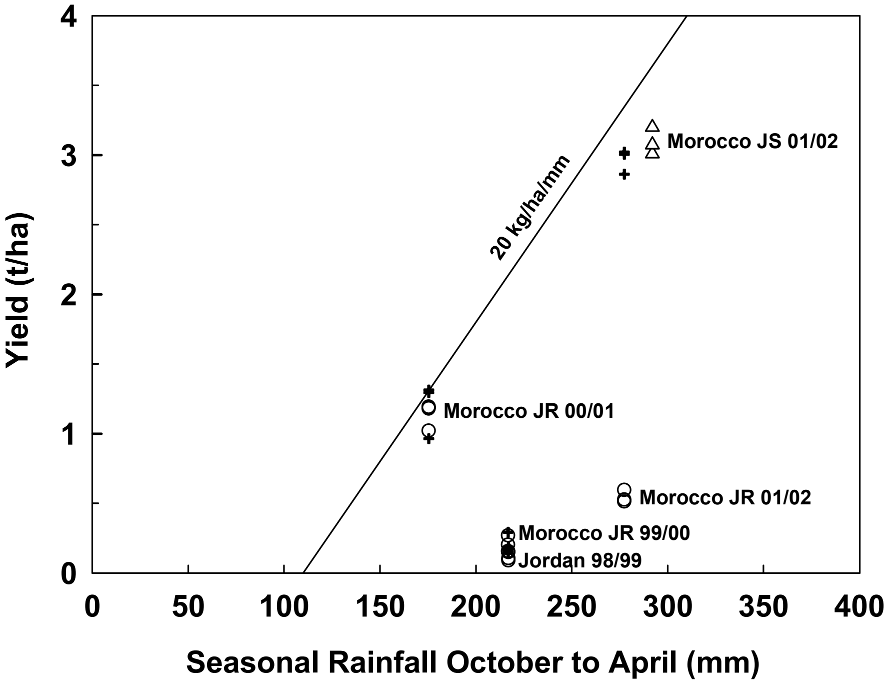

FIG. 5. Measured (open symbols) and simulated (+) wheat grain yields for Moroccan and Jordan versus cumulative seasonal October to April rainfall. Also shown is the French and Schultz [6] potential yield line of 20 kg ha^{-1}mm^{-1}.

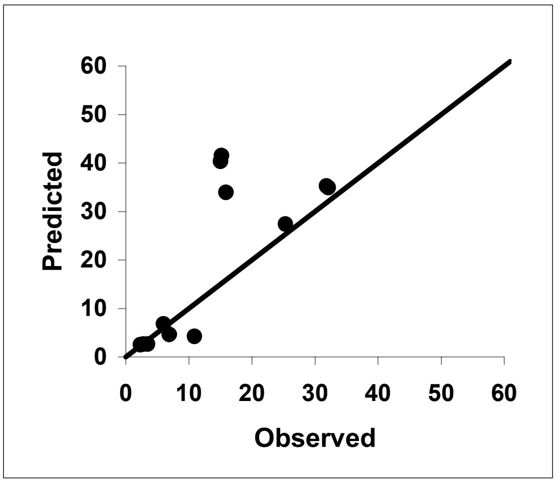

FIG. 6. Measured and predicted grain N (kg N ha^{-1}) for combined Morocco and Jordan.

The measured grain N was also reasonably well simulated, except for the 2001–2003 cropping season (Fig. 6).

3.3. Long-term simulation

In order to better understand the cropping-system and management options for the region, the model was run with a twenty-year historical weather record from Morocco, to assess effects of soil type, initial soil-water and inorganic N profile, cultivar, and sowing date, on grain-yield potential.

3.3.1. Initialization

A range of N-fertilizer combinations were used (thirty-two combinations in total) with different rates (N at 0, 30, 60 and 90 kg N ha^{-1}) and timing of application (at sowing and 4 and 7 weeks later) on the above two soil types. Initial soil water was set to either the lower limit (LL) at the beginning of each season or as having 30 mm moisture stored below 30 cm depth initially, to simulate the various management practices that could possibly increase stored soil moisture. The simulation was also compared between a fixed (Nov. 5 of each year, as used in the study) versus the optimum sowing date. Optimum sowing was assumed to be within a sowing window of November to mid-January of each year, whenever moisture in the first two layers of the soil profile reaches its field capacity value. Finally, two cultivars were compared; the early cultivar Amery was compared with the later Spear (phenologies are given in Table I).

To run the simulation, solar radiation or sunshine hour data are needed to calculate evapotranspiration; this was missing from the historical data which provides only daily rainfall and temperature. Where neither solar radiation nor sunshine hour data are available for at least a nearby site, FAO Irrigation and Drainage 56 Guidelines [7] recommend the use of Hargreave's radiation equation to estimate solar radiation:

$$R_s = k\sqrt{(T_{\max} - T_{\min})}R_a \tag{1}$$

where

R_s is solar radiation (MJ m^{-2} d^{-1}),
k is the adjustment coefficient ($^{o}C^{-0.5}$),
T_{max} and T_{min} are maximum and minimum air temperatures,
R_a is the extraterrestrial radiation (MJ m^{-2} d^{-1}).

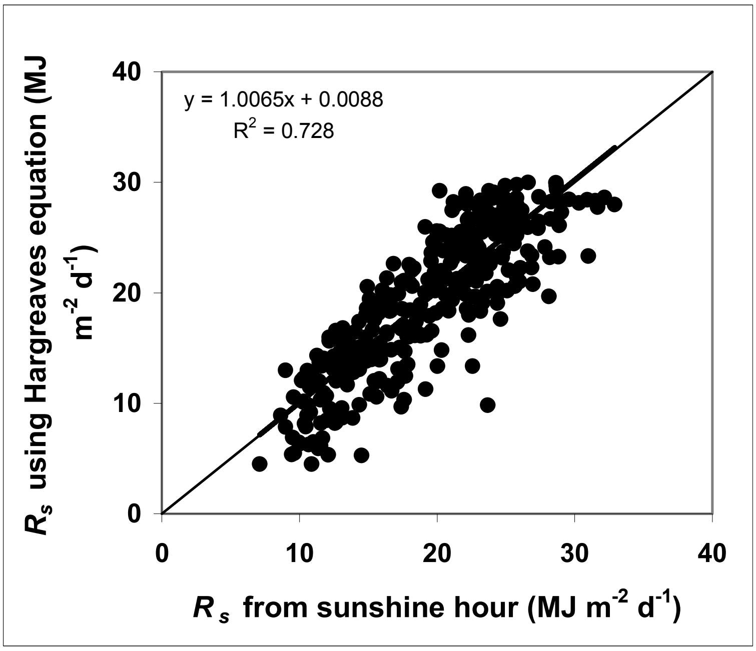

FIG. 7. Solar radiation (R_s) obtained from sunshine hour and using Hargreave's equation.

The value of *k* was derived from the 1999–2001 weather data, which included sunshine-hour information. A value of 0.12 was obtained by fitting R_s calculated from sunshine and that predicted from Eq. (1) (Fig. 7) — lower than the values (0.16 and 0.19) reported in the literature for most interior and coastal regions [8].

3.3.2. Simulated results

The twenty-year growing season (October to April) monthly rainfall pattern for JR, Morocco, is given in Fig. 8. It varies markedly between and within seasons, from 124 mm in 1994–1995 to 439 mm in 1987–1988 seasons.

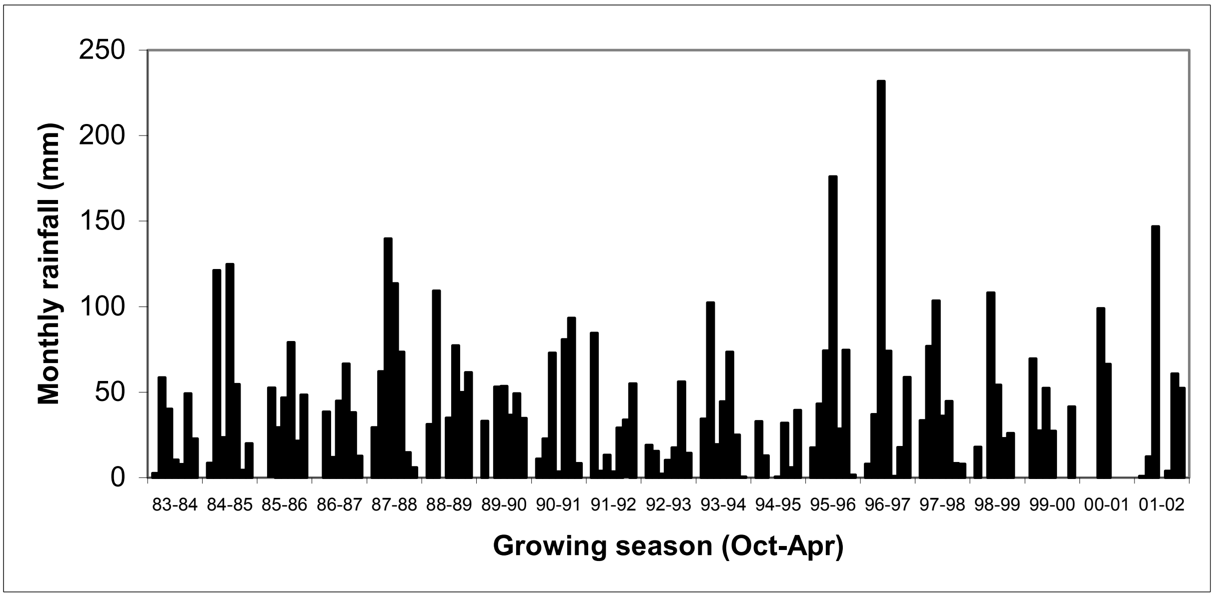

FIG. 8. The growing season (October-April) monthly rainfall, JR, Morocco, 1983–2002.

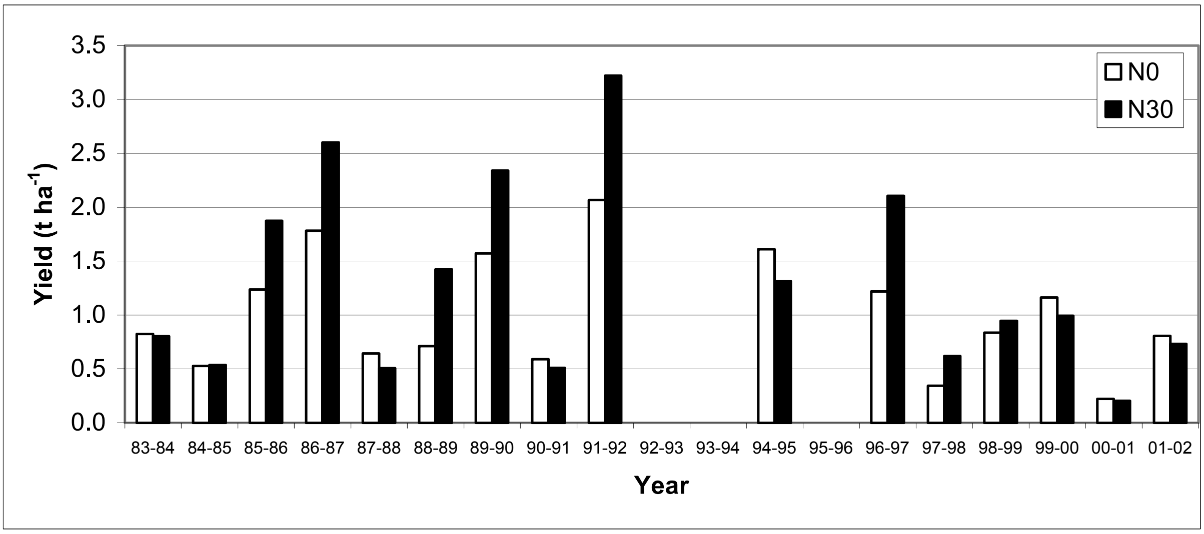

FIG. 9. Simulated wheat grain yield, for zero and 30 kg N ha^{-1} applied at sowing, JR, Morocco, 1983–2002.

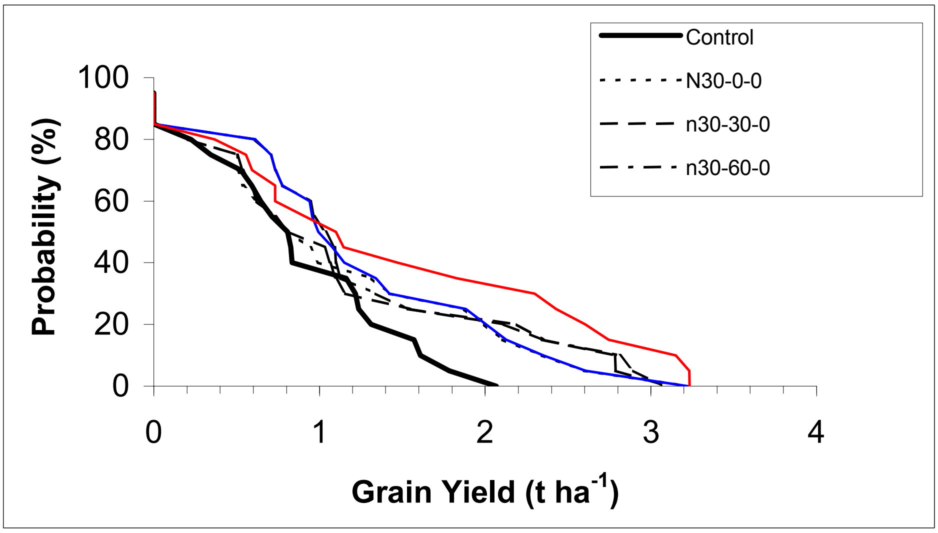

FIG. 10. Effect of N treatments and soil type on wheat grain yield, Morocco.

The highest simulated yield in the control, no-fertilizer treatment was close to 2.1 Mg ha^{-1} in 1990–1991 (Fig. 9), however, the application of 30 kg N ha^{-1} at sowing increased yield significantly to 3.2 Mg ha^{-1} for the same year, hence N fertilizer was needed to maximize yield. This was, however, not always simulated, and in fact in some years applying fertilizer gave negative yield responses. In all these simulations, no yield was predicted in the three dry years (1991–1992, 1992–1993 and 1994–1995) indicating that water was the limiting factor.

Figure 10 shows that further applications of N did not significantly affect yield, although splitting it between sowing and tillering improved yields in many simulated seasons. Having initial stored soil moisture was beneficial in the dryer years, but the effect was minimal in wet years. Nevertheless, management practices that enhance stored soil water should be practiced. Similarly, having a better soil with a higher water-holding capacity increases the probability of obtaining higher yield, especially when there is stored soil moisture at the time of sowing. The benefit of having a better water-holding capacity outweighs that of having 30 mm of initial stored moisture; it increases the probability of higher yield. Having a late maturing cultivar often gave a negative yield response (data not shown); the late wheat variety was not suitable for this environment because drought is often encountered at the end of the season.

4. CONCLUSIONS

Grain yield in arid and semi-arid rainfed environments such as the WANA region is highly dependent on, and sensitive to, the amount and timing of rainfall during the growing season. Yield also varies markedly depending on the water-holding capacity of the soil, and management of N and its interaction with stored soil moisture. All these parameters interact in a very complex manner; to fully understand the processes involved by field experimentation alone would be a costly and time-consuming task. Using a simulation model such as APSIM can help to integrate these factors and identify better nutrient- and water-management practices to increase crop production in rainfed arid and semi-arid areas, especially when it is combined with long-term climate data and soil information.

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THE EFFECT OF SOIL FERTILITY, CROP MANAGEMENT ON CARBON-ISOTOPE DISCRIMINATION AND THEIR RELATIONSHIPS WITH YIELD AND WATER-USE EFFICIENCY OF CROPS IN SEMI-ARID AND ARID ENVIRONMENTS

L.K. HENG[1], G. CAI[2], M.V. RAMANA[3], M.S. SACHDEV[4],
M.M. RUSAN[5], I.V. SIJALI[6], K. EL MEJAHED[7], W. MOHAMMAD[8],
M. SENE[9], D. PRIETO[10], M. ISSAKA[11], P. MOUTONNET[12]

[1] Soil Science Unit, FAO/IAEA Agriculture and Biotechnology Laboratory, Seibersdorf, Austria
[2] Institute of Soil Science, Chinese Academy of Sciences, Nanjing, China
[3] Acharya N.G. Ranga Agricultural University, Palem, Andhra Pradesh, India
[4] Nuclear Research Laboratory, Indian Agricultural Research Institute, New Delhi, India
[5] Jordan University of Science and Technology Faculty of Agriculture, Irbid, Jordan
[6] Kenya Agricultural Research Institute, Nairobi, Kenya
[7] Institut National de la Recherche Agronomique, Settat, Morocco
[8] Nuclear Institute for Food and Agriculture, Peshawar, Pakistan
[9] Centre National de Recherches Agricoles de Bambey, Institut Sénégalais de Recherches Agricoles, Dakar, Sénégal
[10] Estacion Experimental Agropecuaria Santiago del Estero, Santiago del Estero, Argentina
[11] Institut National de la Recherche Agronomique du Niger, Niamey, Niger
[12] International Atomic Energy Agency, Vienna

Abstract

A synthesis of data on carbon-isotope discrimination (Δ), yield and water-use efficiency (WUE) of various plant organs was carried out to determine if relationships exist among these traits for a range of C_3 and C_4 crops, and if Δ is a suitable selection tool for yield and WUE under different levels of applied nitrogen (N) and diverse cropping systems. The samples were from the co-ordinated research project on "Management of Nutrients and Water in Rainfed Arid and Semi-Arid Areas for Increasing Crop Production," with Members States covering a wide range of arid and semi-arid regions. The results showed that genotypic variation in carbon-isotope discrimination exists within plant organs in all crops, with Δ values lowest in the grain component. Genotypic variation in Δ also exists in different environments; in the case of wheat, the lowest Δ was found in the driest regions (Jordan compared with China, the latter having a higher growing-season rainfall). There were strong correlations between wheat grain Δ and grain yield in all studies; however, the correlations were negative in two (China and India) and positive in the other three countries (Jordan, Morocco and Pakistan). While various factors may influence Δ, these contrasting results showed that it is difficult to predict outcome in a particular environment and hence in using Δ as a tool for selecting yield; however, breeders could argue that yield in these two environments could be chosen based on lower Δ in relatively wet years in the negative cases, and high Δ in wet years in the positive cases. Correlation between Δ and WUE was less strong, and cropping system had little effect on the variation of Δ values within plant organs for most crops. The level of N applied affected Δ value in wheat, except in China. In all cases, Δ decreased with increasing leaf-N content. Nitrogen deficiency reduces photosynthetic capacity, and hence an inverse relationship between %N and Δ should exist. This relationship was more pronounced in the grain component than in straw. The association between yield and the carbon-isotope discrimination value in different organs of wheat showed that better correlations were achieved for grain Δ than for other organs, indicating that grain is the more suitable organ for Δ analysis. Weak correlations were observed for most C_4 crop traits with respect to Δ values. It appears that the use of Δ as a selection criterion for C_4 crops is even less obvious, but more studies are needed before concrete conclusions can be drawn, as the examination of the utility of Δ was not the main objective of the CRP.

1. INTRODUCTION

Poor soil fertility and low and erratic rainfall are the major constraints to sustainable agricultural productivity in many parts of the world. In addition to applying appropriate water-conservation practices, one strategy for coping with such stress in these tough environments is to exploit genotypic differences to select/identify plants that have superior resource-use efficiency for drought tolerance.

The carbon-isotope discrimination (Δ) technique has been shown to be a potentially valuable screening tool in breeding programs for improving water-use efficiency (WUE) and yield. Carbon-isotope discrimination is attractive because it provides a time- and spatially-integrated measure of the balance among the important traits influencing carbon gain and water use by plants. It has been used to evaluate drought stress and water-use efficiency in several C_3 crops, such as wheat [1], barley [2,3], peanuts [4,5], cowpea [6], cotton [7,8], and in some C_4 plant such as pearl millet [9] and sorghum [10].

However, Δ is influenced by stomatal conductance and by the photosynthetic capacity of mesophyll cells, therefore morphological, physiological as well as environmental variables—such as salinity, soil moisture supply and nitrogen (N) level—can affect its values. Studies have shown that plant attributes that increase water-use efficiency (WUE) can have opposite effects on Δ, as WUE can be improved by increasing the root depth or early stomatal closure [11,12]. Increasing the rooting depth should increase available water and Δ in C_3 plants, while early stomatal closure reduces Δ. As a result, highly variable relationships between yield and/or WUE and Δ have been reported, ranging from strongly positive to strongly negative, making it difficult sometimes to separate external from intrinsic effects in the use of Δ as a water-stress assessment tool [13]. In order to use Δ as a diagnostic tool, the influence of the various attributes on Δ, yield, and drought tolerance must be better understood.

Data on Δ, yield and WUE of various crops and plant organs, and their variation under different levels of applied N and under different cropping systems from the CRP on "Management of Nutrients and Water in Rainfed Arid and Semi-Arid Areas for Increasing Crop Production," which covers a wide range of arid and semi-arid regions in the world, were used in this synthesis paper. The objective was to determine if relationships exist between the above traits for a range of C_3 and C_4 crops, and if Δ is a suitable selection criterion for yield and WUE.

2. MATERIALS AND METHODS

The Δ data presented in this chapter comprise plant samples from the field experiments of the countries that participated in this CRP: Argentina, China, India (two), Jordan, Kenya, Morocco, Niger, Pakistan, Senegal and Zimbabwe. The samples were obtained at harvest, and they were separated into plant organs (e.g. straw and grain) before being finely ground and analyzed for $\delta^{13}C$ and total N in a mass spectrometer (IRMS Optima Micromass system, Micromass UK, Wythenshaw), linked to a Carlo Erba Strumentazione 1500 Nitrogen-Carbon Analyser, at IAEA's laboratory in Seibersdorf, Austria.

The initial results of carbon-isotope ratio were expressed in the delta notation as $\delta^{13}C$ (‰), which is not the absolute isotope ratio but relative to a standard:

$$\delta^{13}C_{sample}(‰) = (\frac{R_{sample}}{R_{s\tan dard}} - 1) \times 1000$$

where

$\delta^{13}C_{sample}$ is the isotope ratio in parts per mil (‰),
R_{sample} and $R_{standard}$ are the $^{13}C/^{12}C$ molar abundance ratios of the plant material and the Pee Dee Belemnite (PDB) standard, respectively.

They were re-expressed as carbon-isotope discrimination (Δ) [1], the preferred notation, using the following equation.

$$\Delta(‰) = \frac{\delta^{13}C_{air} - \delta^{13}C_{sample}}{1 + \delta^{13}C_{sample}}$$

where

$\delta^{13}C_{air}$ is assumed to be –8‰ relative to PDB, a value widely used for free atmospheric CO_2 [14].

The crops studied included C_3 and C_4 species (wheat, maize, barley, millet, chickpea, sorghum, pigeon pea, castor, mustard, cotton, and lentil). Details of the experimental protocols are given in the respective reports [15–22]. The physical and chemical properties of the soils and growing-season rainfall values are shown in Tables I and II, respectively. Most of the experimental sites were characterized by low rainfall during the growing season (<300 mm) with frequent dry spells.

Table I. Physical and chemical properties of topsoils at the experimental sites

Country	Sand	Silt	Clay	OC[a]	BD[b] (Mg m^{-3})	pH$_{water}$
	(%)					
Argentina	24	64	12	1.4	1.45	7.4
China	4.4	69	27	0.50	1.30	8.4
India 1–Andhra Pradesh	63	7.1	30	0.43	1.50	4.9
India 2–New Delhi	50	36	14	0.47	1.40	8.1
Jordan–Maru	1.1	49	50	0.58	1.00	7.6
Jordan–JUST	14	44	43	0.35	1.14	7.9
Kenya	50	8.0	42	0.80	1.31	6.7
Morocco–JS	18	22	60	1.20	1.15	7.7
Morocco–JR	60	10	30	1.20	1.25	6.7
Niger–Tarna	97	2.8	0.50	0.22	NA[c]	6.0
Niger–Bengou	81	12	6.9	0.37	NA	5.1
Pakistan–NIFA	20	46	34	0.31	1.62	8.0
Pakistan–Farmer1	40	46	14	0.20	1.53	7.8
Pakistan–Farmer2	40	46	14	0.20	1.53	7.9
Senegal	90	4.0	5.9	0.20	NA	5.0
Zimbabwe	96	4.0	3.0	0.30	NA	4.5

[a] Organic carbon. [b] Bulk density. [c]Not available.

Table II. Growing-season rainfall at the experimental sites

Country	1998–1999	1999–2000	2000–2001	2001–2002
	(mm)			
Argentina	NA	613	669	NA[a]
China	241	247	299	350
India 1–Andhra Pradesh	NA	427	450	644
India 2–New Delhi	140	44.5	37.8	36.3
Jordan–Maru	184	194	NA	NA
Jordan–JUST	NA	NA	159[b]	271
Kenya	239	144	222	172
Morocco–JS	177	199	171	292
Morocco–JR	194	236	200	270
Niger–Tarna[c]	547	585	465	NA
Niger–Bengou[c]	NA	NA	761	NA
Pakistan–NIFA	268+60	158	85+120	142
Pakistan–Farmer1	268	158	85	142
Pakistan–Farmer2	268	158	85	142
Senegal[d]	682	979	978	814
Zimbabwe	NA	NA	NA	NA

[a] Not available. [b]Supplemental irrigation of 65 mm was applied between January and April 2001.

[c] Growing season May to October.

[d] 1998–1999 refers to the 1998 season (June–October).

3. RESULTS AND DISCUSSION

The results are grouped according to species; wheat and maize were the two most-studied crops in this project.

3.1. Wheat

Wheat was studied in China, India (New Delhi), Jordan, Morocco and Pakistan. Brief descriptions of the experimental setups are given for each country before results are discussed.

3.1.1. China

The Chinese study which was carried out at Changwu experimental station, in Changwu County, Shaanxi Province (35° 12'N, 107° 40'E, elevation 1200 m), in the southern part of the loess plateau in northwest China, was to investigate the effects of N and mulching management on N and water productivity on rainfed wheat and maize. It is a Heilu soil derived from loess with a deep and even profile. The wheat variety was Changwu-134. The experiment compared four N treatments (0, 100, 150 kg N ha^{-1}, and 100 kg N ha^{-1} urea + 50 kg N ha^{-1} organic manure in 1998–1999, and 0, 60, 100, and 60 + 40 kg N ha^{-1} as organic matter (OM) in 1999–2000). A wheat-wheat-maize cropping sequence was adopted, with wheat traditionally planted (with a row spacing of 20 cm), and maize mulched and ridge planted [15].

Table III shows grain yields and WUE and Δ values of the various wheat components under the different cropping management systems for 1998–1999 and 1999–2000 growing seasons. Water-use efficiency is defined as the amount of wheat grain produced per mm of total crop water use (ET), which includes both crop transpiration and soil evaporation.

Table III. Wheat yield (kg ha^{-1}), water-use efficiency (kg ha^{-1} mm^{-1}) and Δ values (‰), 1999 and 2000, China

Year	Plant part	Control			N1[a]			N2[b]			N10[c]		
		Δ	Yield	WUE	Δ	Yield	WUE	Δ	Yield	WUE	Δ	Yield	WUE
1999	Grain	17.4	2,770	7.6	16.5	4,000	10.2	16.8	3,730	9.7	16.7	4,300	10.5
	Root	17.7			16.5			16.6			16.2		
	Straw	18.7			18.2			18.4			18.3		
2000	Grain	16.6	1,450	8.8	16.2	2,470	13.9	16.0	2,620	12.6	16.1	2,230	14.1
	Root	16.8			16.8			16.7			15.9		
	Straw	17.4			16.6			16.1			16.4		

Year	Plant part	W[d]			WM1[e]		
		Δ	Yield	WUE	Δ	Yield	WUE
2000	Grain	15.8	2,600	11.8	16.3	2,800	14.0
	Root	15.9			16.5		
	Straw	15.9			16.4		

[a] 100 kg N ha^{-1} in 1999 and 60 kg N ha^{-1} in 2000.

[b] 150 kg N ha^{-1} in 1999 and 100 kg N ha^{-1} in 2000.

[c] 100 kg N ha^{-1} urea + 50 kg N ha^{-1} OM in 1999 and 60 kg N ha^{-1} + 40 kg N ha^{-1} OM in 2000.

[d] Traditional planting, i.e. with a row spacing of 20 cm.

[e] Mulching and ridge planting: ridge 30 cm wide and covered with plastic film, with four rows of wheat seeds sowed between two ridges at a spacing of 15 cm.

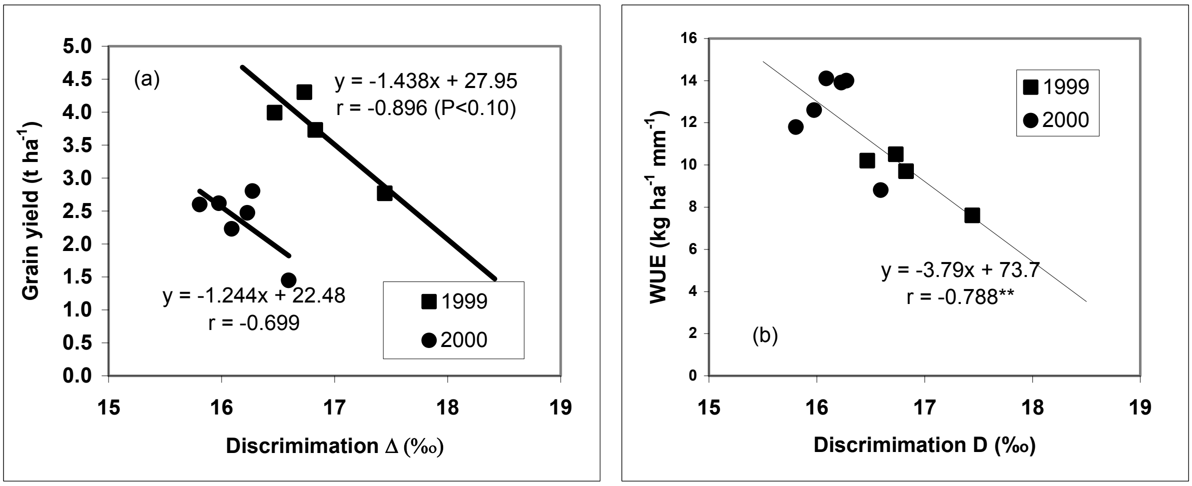

*FIG. 1. The relationship between Δ and grain yield and WUE of wheat in China (**P<0.01).*

The grain, straw and root Δ values were similar within and between cropping systems over the two years, with values ranging from 15.8 to 18.7‰ (Table III), slightly lower than a well watered, non-stressed wheat plant Δ value of approximately 20 ± 2‰. Although previous studies showed that Δ values in wheat were influenced by N level, as N deficiency reduces photosynthetic capacity [23,24], different levels of N fertilization seemed to have little effect on Δ in the Chinese study, and the correlation between Δ and %N in grain was not significant (data not shown). Condon et al. [25] also observed that N nutrition had little effect on Δ values in wheat. Water and N stress should have opposite effects on Δ [23,24]. In C_3 plants, N limitation should increase Δ whereas water stress decreases it. Nevertheless, there was a negative correlation between Δ of grain and grain-yield values (Fig. 1a), and between Δ and WUE (Fig. 1b), although only the WUE correlation was significant. Variation in Δ can result from variation in stomatal conductance or photosynthetic capacity. A negative correlation between Δ and grain yield suggests that the trait is dependent more on internal photosynthetic capacity.

3.1.2. New Delhi, India

The experiment carried out at the Indian Agricultural Research Institute farm consisted of mustard (*Brassica juncea*, variety T-59) and wheat (*Triticum aestivum*, variety WH-147), grown during the winter season under rainfed conditions, and cowpea during the monsoon season. The soil is an alluvial loam of the Mehrauli series and was classified as coarse loamy non-acid hypothermic typic Ustochrept. The experiments were laid out in a randomized block design with four replications with three levels of N and P (mustard: 0, 30 and 60 kg N ha^{-1} and 0, 15 and 30 kg P_2O_5 ha^{-1}; wheat: 0, 40 and 80 kg N ha^{-1}, 0, 20 and 40 kg P_2O_5 ha^{-1}). Nitrogen was given in two splits to both mustard and wheat, and P and K were applied in a single application as a basal broadcast and incorporated. In the case of the mustard crop, half of the N was broadcast at sowing and incorporated and the remaining half was top-dressed at the flowering stage, while for wheat one-third N was broadcast at sowing and incorporated and the remainder was top-dressed at the maximum tillering stage.

The results of the wheat study are given in Table IV. Contrary to the report of Sachdev [17], the correlations between Δ of grain and straw with grain or straw yield, WUE and %N were significant (Figs. 2, 3 and 4), and negatively correlated. The correlation between Δ of grain and N uptake in grain was significant in 1998–1999 (r = 0.768**, n=9) but not in 1999–2000 (r = 0.54, n=9) (data not shown). Although little difference between the Δ values of the different plant organs (grain and straw) wasreported in the Chinese study, the difference in the Δ values was significant in the Indian study (Table IV), with a higher Δ value in straw than in grain. Variations in Δ in different plant organs have also been reported previously [26–28]; they could be due to variation in carbon allocation to these organs or to differences in water availability during their formation.

Table IV. Water use efficiency (kg ha^{-1} mm^{-1}), grain and straw yields and Δ values of wheat, India

1998–99	WUE	Grain Δ	Straw Δ	%N Grain	Grain yield	Straw yield	1999–00	WUE	Grain Δ	Straw Δ	Grain yield	Straw yield
		(‰)			(kg ha^{-1})				(‰)		(kg ha^{-1})	
N0P0[a]	2.39	17.1	20.2	1.64	545	900	N0P0	2.57	17.0	20.2	533	717
N0P20	3.21	17.2	20.2	1.72	732	1,227	N0P20	2.79	17.2	20.0	581	836
N0P40	3.59	16.6	19.7	1.75	819	1,427	N0P40	2.82	16.9	19.6	586	957
N40P0	4.70	16.4	19.3	1.82	1,071	1,793	N40P0		16.1	19.2		1,280
N40P20	5.23	16.7	19.6	1.83	1,193	1,992	N40P20	3.53	16.7	19.5	733	1,308
N40P40	6.00	16.8	19.8	1.88	1,368	2,274	N40P40	4.94	16.4	19.7	1,027	1,456
N80P0	6.33	16.6	19.6	1.93	1,444	2,321	N80P0	5.16	16.5	19.6	1,073	1,453
N80P20	7.08	16.2	19.6	1.99	1,614	2,687	N80P20	5.53	16.6	19.7	1,149	1,484
N80P40	7.79	16.3	19.4	2.01	1,775	2,975	N80P40	5.82	16.5	19.6	1,210	1,632

[a] Nitrogen at 0, 40 and 80 kg N ha^{-1} and P_2O_5 at 0, 20 and 40 kg ha^{-1}.

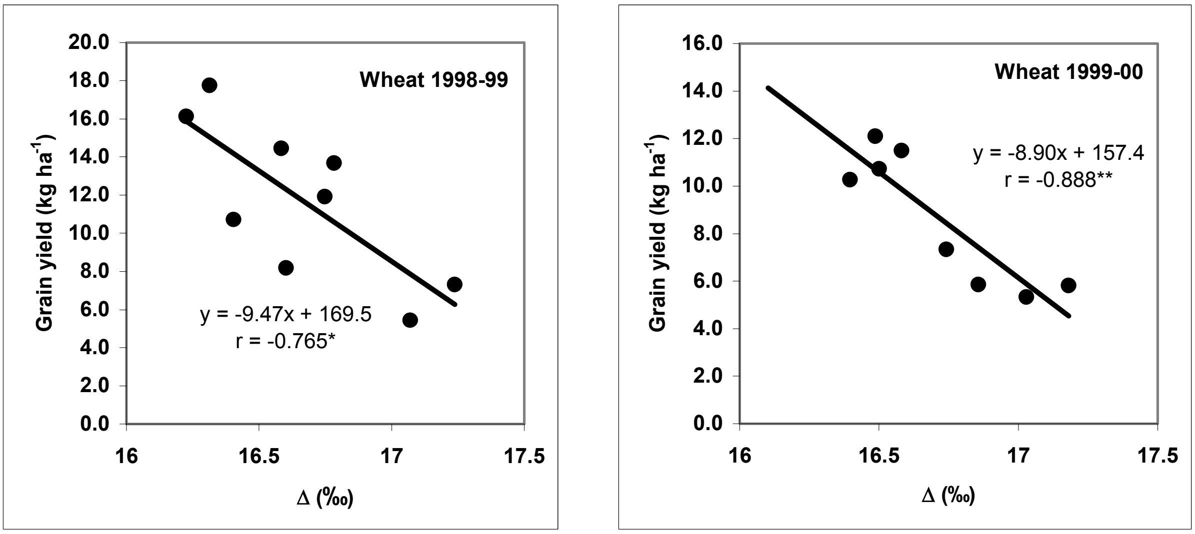

*FIG. 2. The relationship between Δ of grain and grain yield for 1998–1999 and 1999–1900, India. (*P<0.05, **P<0.01)*

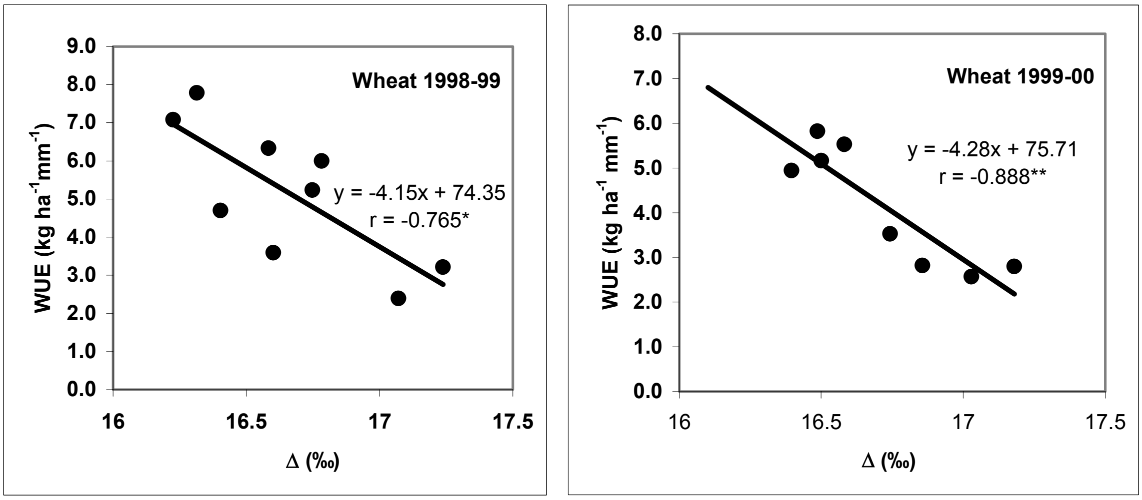

*FIG. 3. The relationship between Δ and WUE for 1998–1999 and 1999–2000, India. (*P<0.05, **P<0.01).*

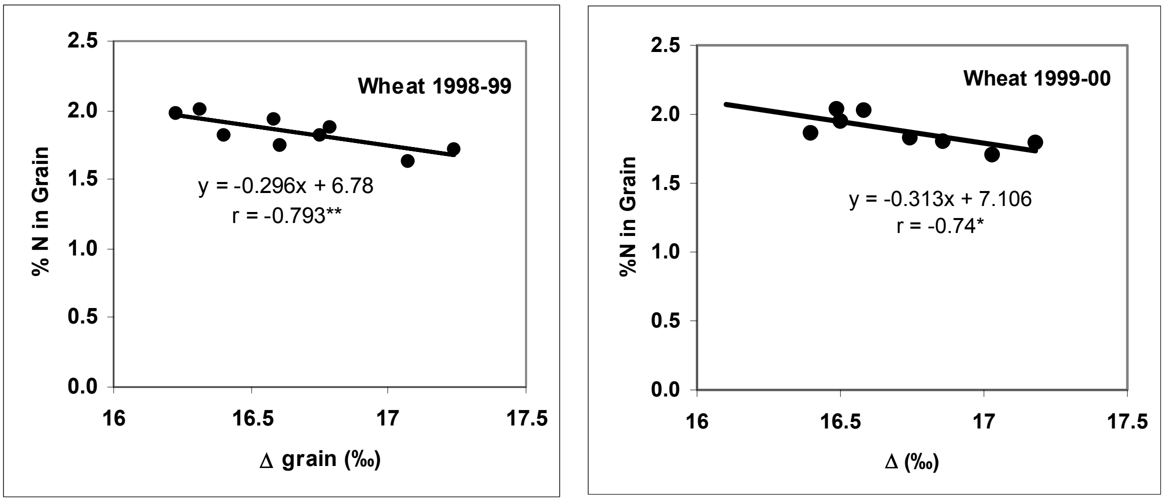

FIG. 4. The relationship between Δ and %N in grain for 1998–1999 and 1999–2000, India.

3.1.3. Jordan

Two field experiments on wheat (variety Horani 27) were carried out in Jordan, at Maru Agricultural Research Station, 100 km north of Amman. The experiment had a split-split plot design in four replications to investigate the role of wheat-crop residues and level of N fertilizer on the subsequent wheat crop in three crop rotations. The experiment included the following treatments: three crop rotations: wheat–fallow, wheat–lentil and wheat–wheat; two crop-residue practices (0 and 100% of the residue incorporated into the soil), and three N levels (0, 40 and 80 kg N ha^{-1} for wheat, and 20 kg N ha^{-1} for lentil). The soil is a fine smectic, thermic Typic Chromoxerert. It has a relatively high pH (~7.6) with 5.9% calcium carbonate.

Wheat-grain and straw yields, %N and the respective Δ values are presented in Table V. As in the Indian study, the straw Δ values were much higher than the corresponding grain Δ values. However, both the grain and straw Δ values were much lower than those reported in the previous two studies (China and India), indicating the severity of water stress in Jordan.

Table V. Wheat straw and grain yields, %N and Δ values,1998–1999, Jordan

Treatment	Plant part	Yield (kg ha^{-1})	%N	Δ (‰)
R0[a]N0[b]	Grain	156	3.82	13.43
R0N1	Grain	203	3.4	13.87
R0N2	Grain	268	4.06	13.37
R1[c]N0	Grain	293	3.47	13.84
R1N1	Grain	333	3.54	13.84
R1N2	Grain	259	3.47	13.79
R0N0	Straw	1,170	1.6	15.91
R0N1	Straw	2,045	1.31	17.16
R0N2	Straw	2,478	1.63	15.73
R1N0	Straw	2,008	1.31	16.74
R1N1	Straw	2,063	1.35	16.87
R1N2	Straw	2,610	1.43	16.76

[a] Zero residues incorporated into the soil.
[b] 0, 40 and 80 kg N ha^{-1}, respectively.
[c] 100% residues incorporated into the soil.

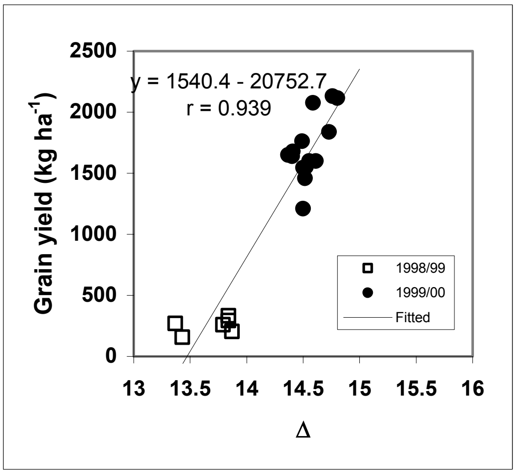

FIG. 5. The relationship between Δ and the respective grain and straw yield, Jordan.

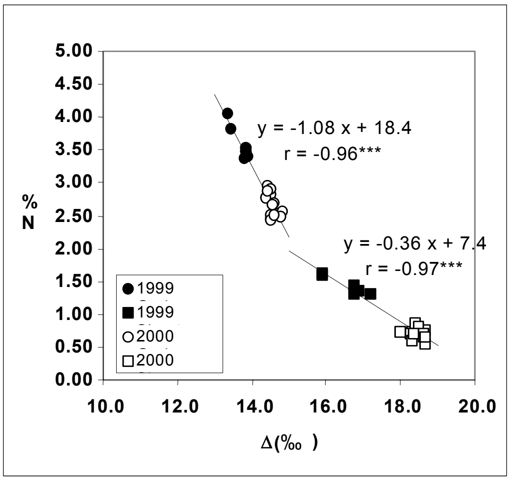

FIG. 6. The relationship between Δ and %N, Jordan.

A strong but positive relationship was observed between Δ of grain with the corresponding grain yield when data from both years were combined (Fig. 5), instead of the negative correlations in the China and India studies. Positive correlations have been widely reported [29, 30], especially under Mediterranean or similar environments, where there is a strong reliance on within-season rainfall [31–33], suggesting that stomatal conductance is the main factor accounting for variation in Δ. Linear relationships were again observed between the Δ values for wheat grain and straw and the corresponding %N (Fig. 6), as in the Indian study. WUE analyses were not carried out.

3.1.4. Morocco

Two field experiments with wheat were conducted between 1997 and 2002 at the Jemaa Riah (JR) and Jemaa Shaim (JS) experimental stations of the Agricultural National Research Institute (INRA), located in the Settat-Chaouia and Safi-Abda regions, respectively. The objective was to assess the substitution of fallow with green manure and its impact on soil properties, wheat yield and its response to N fertilizer, as well as the profitability of wheat–fallow, wheat–incorporated vetch and wheat–mowed vetch as forage. The soil at JR was classified as a fine montmorillonitic, thermic Palexerollic chromoxerert. At JS, the soil is a fine montmorillonitic, thermic Palexerollic chromoxerert. The experiment had a split-plot design arranged in a randomized complete block with four replicates. Rotations, wheat (cv. Achtar)–fallow (W/F), wheat–vetch mowed (W/VM), wheat–vetch incorporates (W/VI), fallow–wheat and vetch–wheat were assigned to main plots. The subplots consisted of N splits with 0 or 40 kg N/ha at planting (P), 46 kg N/ha at tillering (T) and N at planting and tillering (P+T). Therefore, the N treatments were 0, 46, 0–40 and 40–46.

In the rotation experiment at JR, the Δ value of grain in the W/F cropping system was significantly higher than those of W/VM and W/VI for the 1998–1999 growing season (Table VI). However, there was either no difference in the Δ values among cropping systems or no relationship between WUE and straw Δ or both, for the other cropping seasons [20]. Δ values within the grain and straw components at the Jemaa Riah site were similar for the different cropping systems (Table VI). For the JS site, the Δ of grain and straw for 1998–1999 and 2001–2002 growing seasons showed higher values for W/F which was significantly different from that of W/VM and W/VI (Table VII) [20]. When the dataset from the 2001–2002 growing season at JR were excluded, a single significant relationship existed between Δ and grain yield combining the datasets from both sites, as in the N-combination experiment (Fig. 7).

Except for the %N of the straw component at JR, there was a strong correlation between the %N of straw at JS with Δ of straw, and a good correlation was also obtained with %N in the grain in both sites (Fig. 8, Table VIII).

Table VI. Effect of rotation on wheat yield, water use efficiency and Δ values, Jemaa Riah, Morocco, 1998–2002

Parameter	1998–1999			1999–1900			2000–2001			2001–2002		
	W/F	W/VM	W/VI	W/F	W/VM	W/VI	W/F	W/VM	W/VI	W/F	W/VM	W/VI
Grain (kg ha^{-1})	2,746a	1,347b	1,154b	259a	30b	36b	1,210	1,123	1,143	689a	587a	338b
Straw (kg ha^{-1})	3,700	2,512	2,482	1,916	715	702	2,291	2,045	2,209	1,656a	1,226b	1,213b
Δ grain (‰)	14.6b	14.2ab	13.9a	12.8	NA	NA	14.2	14.6	14.5	15.5	15.7	15.5
Δ straw (‰)	17.4b	16.9a	16.9a	15.5	15.9	15.7	16.9	17.1	17.0	15.9	16.1	16.2
WUE grain (kg ha^{-1} mm^{-1})	14.2	6.94	5.96	1.10	0.13	0.15	5.78	5.37	5.46	2.24	1.90	1.10
WUE total (kg ha^{-1} mm^{-1})	30.9	19.9	20.5	8.12	3.03	2.97	16.7	15.1	16.0	7.61	5.88	5.03

[a] Numbers in a row within a year followed by different letters are significantly different ($P \leq 0.05$).

Table VII. Effect of rotation on wheat yield, water use efficiency and Δ values, Jemaa Shaim, Morocco, 1998–2002

Parameter	1998–1999			1999–2000			2000–2001			2001–2002		
	W/F	W/VM	W/VI	W/F	W/VM	W/VI	W/F	W/VM	W/VI	W/F	W/VM	W/VI
Grain (kg ha^{-1})	687	748	707	482a	277b	231b	553	354	420	3,860a	2,433b	3,003a
Straw (kg ha^{-1})	3,185	3,012	3,048	1,778a	1,493b	1,477b	2,214	1,796	1812	5,193a	3,711b	4,556ab
Δ grain (‰)	14.0b	13.2a	13.0a	13.3	NA	NA	12.6	12.4	12.2	17.1b	16.1a	16.5a
Δ straw (‰)	16.9b	16.3a	16.2a	16.3	15.6	15.7	15.1	14.7	14.6	18.8b	17.5a	18.1a
WUE grain (kg ha^{-1} mm^{-1})	3.88	4.23	4.00	2.42	1.39	1.16	2.05	2.44	2.84	12.7	7.99	9.86
WUE total (kg ha^{-1} mm^{-1})	21.9	21.2	21.2	11.4	8.81	8.65	12.2	12.9	14.36	29.7	20.2	24.8

[a] Numbers in a row within a year followed by different letters are significantly different ($P \leq 0.05$).

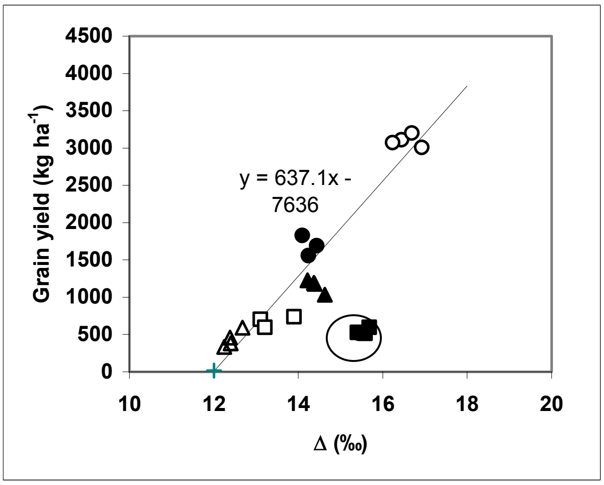

FIG. 7. The relationship between Δ and grain yield at Jemaa Riah and Jemaa Shaim, Morocco, for nitrogen-combination experiments; data from 2001–2002 at JS (circled) were excluded.

Table VIII. Effect of N combination on wheat yield, water-use efficiency and Δ values at Jemaa Riah and Jemaa Shaim, Morocco, 1998–2002

Season	Parameter	Jemaa Riah				Jemaa Shaim			
		0–40	40–0	40–46	0–0	0–40	40–0	40–46	0–0
1998–1999	Grain (kg ha^{-1})	1,556	1,689	1,827	1,923	704	737	597	819
	Straw (kg ha^{-1})	2,976	2,913	2,548	2,563	2,984	3,246	3,008	3,087
	WUE grain (kg ha^{-1} mm^{-1})	8.02	8.71	9.42	9.91	3.97	4.16	3.37	4.63
	WUE tot (kg ha^{-1} mm^{-1})	23.4	23.7	22.6	23.1	20.8	22.5	20.4	22.1
	Δ grain (‰)	14.2	14.4	14.1	NA	13.1	13.9	13.2	NA
	Δ straw (‰)	17.1	17.1	17.0	NA	16.2	16.8	16.3	NA
1999–2000	Grain (kg ha^{-1})	86	149	106	91	365	265	284	402
	Straw (kg ha^{-1})	1,008	1,165	942	897	1,414	1,811	1,694	1,410
	WUE grain (kg ha^{-1} mm^{-1})	0.36	0.63	0.45	0.39	1.83	1.33	1.43	2.02
	WUE tot (kg ha^{-1} mm^{-1})	4.63	5.57	4.44	4.19	8.94	10.4	9.94	9.10
	Δ grain (‰)	NA	NA	NA	NA	NA	NA	NA	NA
	Δ straw (‰)	15.6	15.7	15.6	15.7	15.8	15.9	15.6	16.3
2000–2001	Grain (kg ha^{-1})	1,229	1,181	1,192	1,034	457	383	336	593
	Straw (kg ha^{-1})	2,183	2,233	2,261	2,050	1,962	1970	2,001	1,831
	WUE grain (kg ha^{-1} mm^{-1})	5.87	5.64	5.69	4.94	2.69	2.11	1.93	3.03
	WUE tot (kg ha^{-1} mm^{-1})	16.3	16.3	16.5	14.7	13.7	13.1	11.7	14.2
	Δ grain (‰)	14.2	14.4	14.4	14.6	12.4	12.4	12.2	12.7
	Δ straw (‰)	17.0	17.0	16.9	17.2	14.8	14.6	14.8	15.0
2001–2002	Grain (kg ha^{-1})	517	513	526	597	3,112	3,199	3,073	3,008
	Straw (kg ha^{-1})	1,298	1,408	1,347	1,406	4,700	4,313	4,429	4,504
	WUE grain (kg ha^{-1} mm^{-1})	1.68	1.66	1.71	1.94	10.2	10.5	10.1	9.88
	WUE tot (kg ha^{-1} mm^{-1})	5.89	6.24	6.08	6.50	25.7	24.7	24.6	24.7
	Δ grain (‰)	15.5	15.6	15.4	15.7	16.4	16.7	16.2	–24.5
	Δ straw (‰)	16.1	16.2	15.9	16.1	17.9	18.3	18.0	18.3

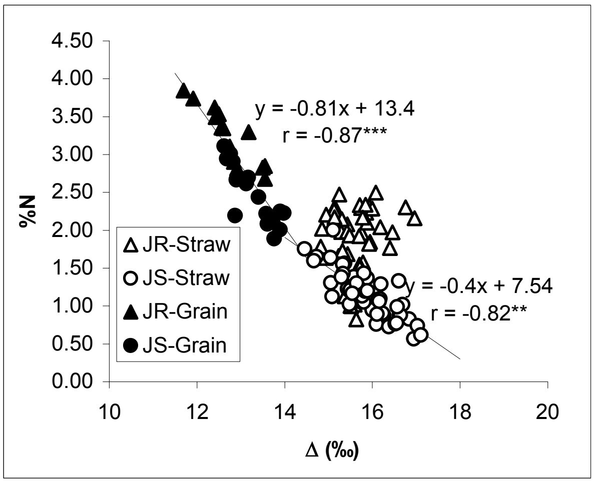

FIG. 8. Relationship between Δ of grain and straw and their respective %N values, Jemaa Riah and Jemaa Shaim, Morocco.

Table IX. Grain yield, water use efficiency and carbon-isotope discrimination in straw and grain of wheat at harvest, as influenced by tillage and nutrient treatments, at NIFA Research Station and two farmers' fields, 1998–1999

Location	Tillage	Parameter	Straw		Grain	
			P_1[a]	P_2[b]	P_1	P_2
NIFA Research Station	T_1[c]	Yield (kg ha^{-1})			4,666ab	4,883a
	T_0[d]	Yield (kg ha^{-1})			4,000c	4,100bc
	T_1	WUE (kg ha^{-1} mm^{-1})	29.4		12.3	
	T_0	WUE (kg ha^{-1} mm^{-1})	26.3		9.91	
	T_1	Δ (‰)	21.2	21.2	20.8	20.5
	T_0	Δ (‰)	21.1	21.3	20.6	20.6
Farmer-1 (Urmar)	T_1	Yield (kg ha^{-1})			1,917	2,067
	T_0	Yield (kg ha^{-1})			1,683	1,850
	T_1	WUE (kg ha^{-1} mm^{-1})	11.1		4.69	
	T_0	WUE (kg ha^{-1} mm^{-1})	11.2		4.16	
	T_1	Δ (‰)	21.1	21.1	18.4	18.7
	T_0	Δ (‰)	20.4	20.5	18.7	18.8
Farmer-2 (Jalozai)	T_1	Yield (kg ha^{-1})			2,667	2,767
	T_0	Yield (kg ha^{-1})			2,867	3,033
	T_1	WUE (kg ha^{-1} mm^{-1})	22.0		10.1	
	T_0	WUE (kg ha^{-1} mm^{-1})	26.3		11.0	
	T_1	Δ (‰)	20.8	20.4	19.4	18.9
	T_0	Δ (‰)	20.7	21.0	19.1	19.5

[a] $N_{60} + P_{30}$.

[b] $N_{60} + P_{60}$.

[c] Conventional tillage.

[d] No tillage.

Table X. Yield and carbon-isotope discrimination in straw and grain of wheat, as influenced by tillage and nutrient treatments, 2000–2001

Location	Tillage	Parameter	Straw		Grain	
			P_1[a]	P_2[b]	P_1	P_2
NIFA Research Station	T_1[c]	Yield (kg ha^{-1})			2,067	2,100
	T_0[d]	Yield (kg ha^{-1})			1,200	1,333
	T_1	Δ (‰)	20.9	20.9	18.9ab	19.0a
	T_0	Δ (‰)	20.5	21.0	19.0a	18.9b
Farmer (Urmar)	T_1	Yield (kg ha^{-1})			443b	433b
	T_0	Yield (kg ha^{-1})			500b	800a
	T_1	Δ (‰)	18.3	18.3	17.7	17.7
	T_0	Δ (‰)	18.3	17.2	17.7	17.6

[a] $N_{60} + P_{30}$.
[b] $N_{60} + P_{60}$.
[c] Conventional tillage.
[d] No tillage.

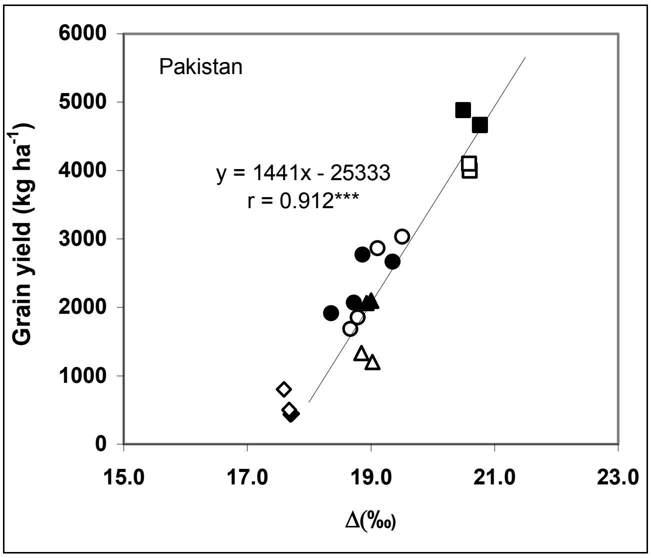

FIG. 9a. The relationship between Δ and grain yield conducted at NIFA, Pakistan, and on farmers' fields for 1998–1999 and 2000–2001, under conventional and no-till systems, respectively (NIFA conventional 1998–1999 ■, 2000–2001▲; NIFA no-till 1998–1999 □, 2000–2001 Δ; Farmers' conventional tillage 1998–1999 •, 2000–2001 o; Farmers' conventional tillage 1998–1999 ♦ 2000–2001 ◊).

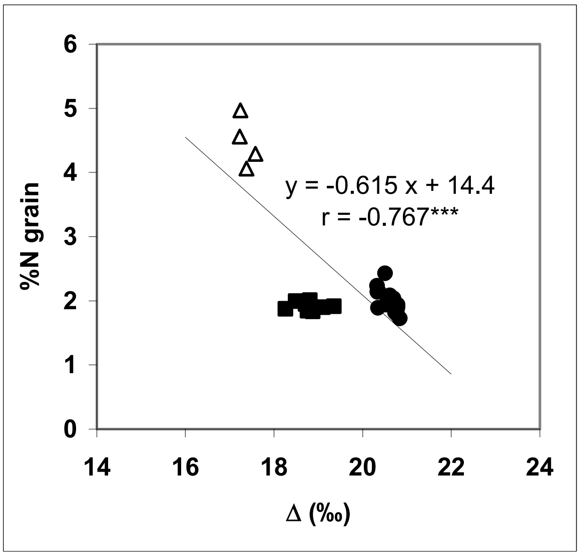

FIG. 9b. The relationship between Δ and %N of grain, NIFA, Pakistan (symbols as in 9a).

3.1.5. Pakistan

Field experiments were conducted from 1998 to 2002, at the Nuclear Institute for Food and Agriculture (NIFA) and in farmers' fields in rainfed areas around Peshawar (34°4' N, 72°25' W). The response of three cropping sequences [wheat (cv. Tatara)–wheat, lentil–wheat, chickpea–wheat] to two tillage (conventional T1, and no-till T0) and nutrient [30, 60 kg N ha^{-1} N (urea) and P] regimens was tested with a view to improving and developing sustainable water- and fertilizer-management practices under rainfed conditions. The soils of the experimental site at the institute are silt clay, alkaline, moderately calcareous, deficient in N (0.05%), P (7.0 μg g^{-1}) and OM (0.62%) and free from salinity. The non-saline soils at the farmer's fields were loam, alkaline, calcareous and very low in N (0.02–0.03%), P (3–4 μg g^{-1}) and OM (0.4–0.5%).

There were no significant differences in the Δ values of either plant component at NIFA under the two tillage systems; there was also no significant tillage × P interaction for any plant part at NIFA (Tables IX and X). On the other hand, a lower Δ value and lower yield were obtained in the 2000–2001 season as compared to those of 1998–1999, probably due to adverse effects of a prolonged dry spell [21].

The Δ values for grain from the farmers' fields were significantly lower than those at the NIFA Research Station, whereas the straw Δ values were relatively similar. However, the lower grain Δ values were not influenced by tillage, nutrient level or their interaction (Tables IX and X). The overall differences in Δ were not significant and showed no relationship to grain yield. However, when data from both years from the research station and farmers' fields were combined, a good relationship existed between the Δ value and grain yield (Fig. 9a). Although the correlation between grain and straw Δ with the corresponding WUE was non-significant (data not shown), a strong correlation existed between grain Δ and its %N value (Fig. 9b).

3.2. Maize

The next most commonly studied crop was maize, a C_4 species. Results are reported from Argentina, Kenya and Senegal.

3.2.1. Argentina

The experiments were carried out on the "La María" experimental field at the Santiago del Estero Research Station of the National Institute for Agriculture Technology (INTA-EEASE). The objective was to evaluate the effects of crop rotation, to optimize crop yield from the low-input production systems of the small-farm holders of the province of Santiago del Estero, Argentina. The specific objective was to test soil-management technologies for increasing soil moisture through improving rainfall infiltration into the root zone and/or reduction of soil-water losses. The La María soil is well drained. Maize (cv. H40, a double hybrid), and cotton (cv. Guazuncho II INTA) were grown in rotation (planting dates: cotton January 3, 1999; maize November 5, 1099) under conventional tillage and no-tillage (direct seeding) with N fertilizer applied at 0 or 50 kg N ha^{-1} to cotton and 0 or 60 kg N ha^{-1} to maize. The treatments were designated as follows: cotton with conventional tillage cotton but without fertilizer (C1), cotton with conventional tillage and fertilizer (C2), cotton without tillage and without fertilizer (C3), cotton without tillage but with fertilizer (C4), maize with conventional tillage but without fertilizer (M1), maize with conventional tillage and fertilizer (M2), maize without tillage and without fertilizer (M3), and maize without tillage and with fertilised (M4).

Yield, %N and Δ values for the different plant parts in the 1999–2000 season are presented in Table XI. There were significant differences in Δ values between the various plant organs, with grain Δ being the smallest with an average of 3.3‰ compared to 5‰ for the leaves. However, there was no effect of tillage or fertilization on the Δ values. Prieto (personal communication) attributed the lack of difference to the high seasonal rainfall, as soil moisture was reported to be above the threshold value associated with water stress (17% volumetric water) throughout the season. On the other hand, the correlation was significant between Δ of all plant parts with yield and between Δ of the grain and its %N value (Table XII). A significant positive correlation was obtained between the Δ values and the corresponding WUEs across the crop-management practices (Fig. 10).

Table XI. Effects of crop-management practice and nitrogen fertilization on yield, %N and Δ values of plant parts of maize, Argentina

Plant part	M1[a]			M2[b]			M3[c]			M4[d]		
	Yield (kg ha^{-1})	%N	Δ (‰)	Yield (kg ha^{-1})	%N	Δ (‰)	Yield (kg ha^{-1})	%N	Δ (‰)	Yield (kg ha^{-1})	%N	Δ (‰)
Stem	4,118	1.48	4.4	4,757	1.25	4.4	2,305	1.13	4.1	3,232	0.85	4.2
Leaves	2,349	1.49	4.9	2,571	1.58	5.1	1,359	1.36	4.9	1,795	1.62	4.9
Grain	3,826	1.88	3.4	5,600	1.92	3.4	2,537	1.57	3.0	3,849	1.61	3.2
Cob	1,398	1.00	3.8	1,615	0.97	3.7	788	0.99	3.4	1,356	0.93	3.5
Husk	1,232	0.99	4.3	1,317	0.84	4.3	644	1.20	4.2	1,276	0.99	4.3
Pod	1,426	1.23	4.9	1,541	1.15	4.9	905	1.14	4.8	1,232	1.16	4.7

[a] Conventional tillage zero fertilization.

[b] Conventional tillage fertilized.

[c] No tillage zero fertilization.

[d] No tillage fertilized.

Table XII. Correlation coefficients between carbon-isotope discrimination values (Δ) measured of maize plant parts and their respective yields (kg ha^{-1}), Argentina

Plant part	Δ vs yield (r)	Δ vs %N (r)
Stem	0.96*[a]	0.73ns[b]
Leaves	0.83ns	0.27ns
Grain	0.76ns	1.00**
Cob	0.80ns	0.33ns
Husk	0.89ns	0.87ns
Pod	0.70ns	0.59ns

[a]* $P \leq 0.05$, **$P \leq 0.01$.

[b] Not significant.

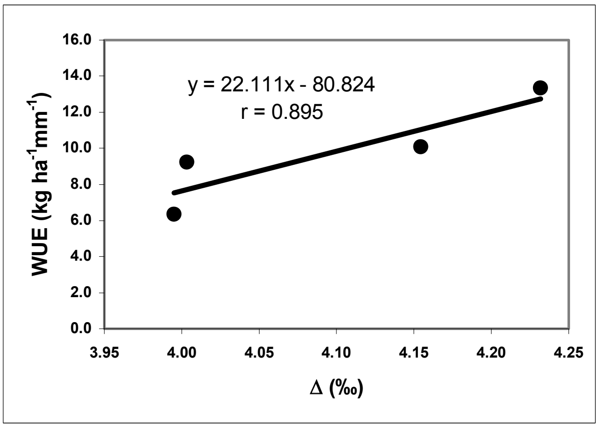

FIG. 10. Relationship of carbon-isotope discrimination (Δ) and water use efficiency (WUE) in maize, over the different crop management practices, Argentina.

3.2.2. Kenya

The experiments were conducted in Machakos District, a semi-arid area characterized by erratic rainfall, especially from March to June. Two soil- and water-management treatments were examined with ridging (SWM_1) and flat cultivation (SWM_2), three N treatments (0, 25, 50 kg N ha^{-1} as calcium ammonium nitrate or farmyard manure), and two modes and times of application of N fertilizer. The mode of application included basal application or equal splits at emergence (T_1) and knee high (T_2). The soils were well drained, with texture ranging from friable clay to sandy clay loam, and classified as chromic luvisols, developed on quartzo-feldsphatic gneisses.

Tables XIII to XV show yield (grain and total dry matter), Δ and the corresponding WUE values for the whole experimental period. There were no differences in the Δ values among the various N sources and management practices within years (Table XIV); however, Δ values were significantly higher in 1999 compared to 2001, due probably to higher seasonal rainfall. The mean Δ values were also higher under ridging compared to flat cultivation, both in 1999 and 2000 (Tables XVI and XVII). Correlation between Δ and dry-matter production was non-significant for both years (Fig. 11a), while the relationship between Δ and grain yield was positive in 1999 and negative in 2001 (Fig. 11b). Correlations of Δ and dry matter WUE varied from a strong correlation in 2000 (r = 0.93) to weak in 1999 (r =0.14) and 2001 (r = 0.48).

Table XIII. Grain yield and total dry matter for maize for 1999–2001, Kenya

Treatment	Grain yield			TDM		
	1999	2000	2001	1999	2000	2001
	(kg ha^{-1})					
Nil	736	–[a]	859	4,595	851	3,720
50 kg N ha^{-1} at T1	784	–	702	4,307	1,151	3,291
I[b] +50 kg N ha^{-1} at T1	NA[c]	–	2,306	NA	NA	5,374
FYM[d] + 50 kg N ha^{-1} at T1	NV[e]	–	NV	NV	734	NV
50 kg N ha^{-1} at T2	861	–	684	4,168	NA	3,049
25 kg N ha^{-1} split at T1 and T2	936	–	995	4,244	561	4,143

[a] Crop died before maturity.
[b] Irrigation.
[c] Not assessed
[d] Farmyard manure.
[e] Not available.

Table XIV. Carbon-isotope discrimination, maize, Kenya

Treatment	1999	2000	2001
	(‰)		
Nil	4.50	NA[a]	3.89
50 kg N ha^{-1} at T1	4.62	4.27	3.94
I[b] +50 kg N ha^{-1} at T1	NA	NA	3.65
FYM[c] + 50 kg N ha^{-1} at T1	NA	4.34	NA
50 kg N ha^{-1} at T2	4.46	NA	3.72
25 kg N ha^{-1} at T1 and T2	4.29	4.45	3.89

[a] Not Available.
[b] Irrigation.
[c] Farmyard manure.

Table XV. Water-use efficiency, maize, Kenya

Treatment	Grain			Total biomass		
	1999	2000	2001	1999	2000	2001
	(kg ha^{-1} mm^{-1})					
Nil	3.8	–[a]	6.3	23.7	10.2	27.1
50 kg N ha^{-1} at T1	3.3	–	5.1	22.2	9.9	24.1
I[b] +50 kg N ha^{-1} at T1	NA[c]	–	7.9	NA	NA	18.3
FYM[d] + 50 kg N ha^{-1} at T1	NA	–	NA	NA	7.0	NA
50 kg N ha^{-1} at T2	4.5	–	5.1	21.6	NA	22.6
25 kg N ha^{-1} at T1 and T2	4.8	–	7.3	22.2	5.0	30.3

[a] Crop died before maturity.

[b] Irrigation.

[c] Not assessed.

[d] Farmyard manure.

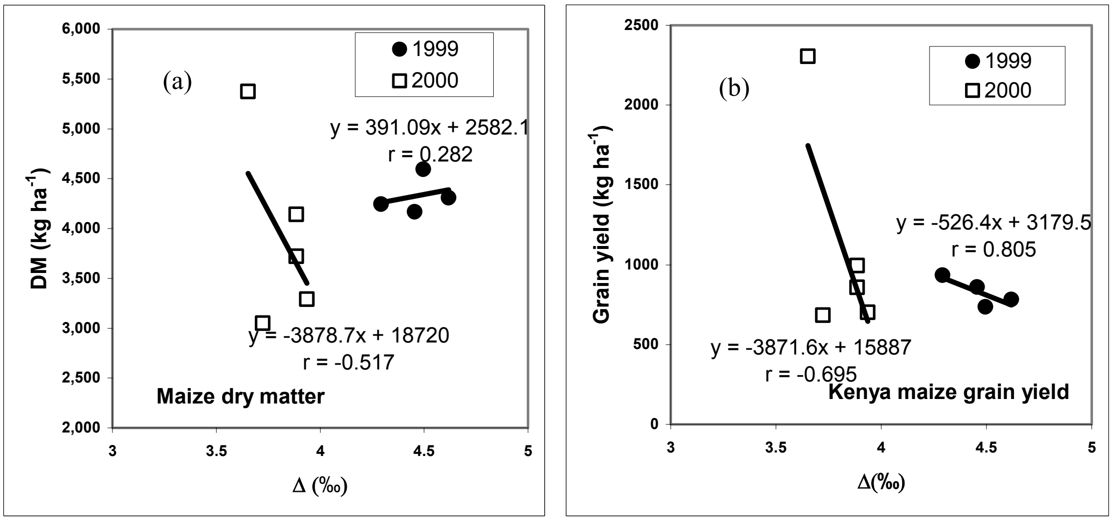

FIG. 11. Relationships between dry matter and grain yield versus carbon-isotope discrimination in maize, Kenya.

Table XVI. Maize grain and total biomass yields and water-use efficiency for soil- and water-management options, Kenya

Soil & water management	Grain yield[a]		WUE		Total DM Yield			WUE		
	1999	2001	1999	2001	1999	2000	2001	1999	2000	2001
	(kg ha^{-1})		(kg $\text{ha}^{-1}\text{mm}^{-1}$)		(kg ha^{-1})			(kg $\text{ha}^{-1}\text{mm}^{-1}$)		
Ridging	901	1,184	4.5	7.0	4,548	691	3,927	23.4	6.6	24.5
Flat cultivation	682	1,035	3.7	5.6	4,109	958	3,904	21.4	9.5	24.5

[a] No yield in 2000; the crop died before reaching maturity.

Table XVII. Carbon-isotope composition for water management, maize, Kenya

Soil & water management	Δ of dry matter		
	1999	2000	2001
		(‰)	
Ridging	4.52	4.40	3.89
Flat cultivation	4.41	4.30	3.75

3.2.3. Senegal

The experiments in Senegal were to study crop water and N-use efficiency as influenced by soil amendments. During the 2000 and 2001 rainy seasons, on-farm tests were conducted on the use of a phosphocalcic soil amendment, alone or in combination with manure. These tests were aimed at the sustainable improvement of the three main crops: peanut, millet and maize. Millet cv. Souna III, and maize cvv. synthetic C (1997) and Pool Across 86 were used in 1999 and 2001, respectively.

The treatments were: plowing (P) + fertilizer N and K applied at the recommended rates (P + NK), P + NK + 50 % phospho-gypsum (PG) and 50% Taïba phosphate rock (PR) mixed at 1,000 kg ha^{-1}: (P + NK + PG-PR), P + NK + manure at 5 t ha^{-1} added once every two years, in 1997 and in 1999 (P + NK + M), and P + NK + PG-PR + M. For an on-farm trial at Diamaguene, started in 1998, a fifth treatment was added consisting of plowing and NPK fertilizer application at the recommended rate .

There were significant differences within and between the grain and dry matter Δ values between the 1999 and 2001 seasons, with a higher Δ recorded in 1999 from the Nioro Agricultural Research Station (Table XVIII). However, there was little soil-amendment effect on the maize Δ both on the research station and on the farmer's field (Tables XVIII and XIX). On the other hand, there were negative correlations between grain yield and Δ and between WUE and Δ (Fig. 12). On the whole, total biomass Δ values were not affected by soil P- and Ca-source amendments (Tables XX and XXI), with a mean value of 3.0‰.

Table XVIII. Grain yield, water-use efficiency and Δ for grain and total above-ground biomass of maize in 1999 and 2001 as affected by soil amendments at Nioro Agricultural Research Station, Senegal

	Component	Parameter	Control	PG-PR	Manure (M)	PG-PR + M
1999	Grain	Yield (kg ha^{-1})	806	1,042	1,698	1,829
		Δ (‰)	2.70	2.80	2.51	2.50
		WUE (kg ha^{-1} mm^{-1})	2.03	3.09	4.50	4.20
	Total DM	Yield (kg ha^{-1})	1,663	2,028	3,286	3,494
		Δ (‰)	3.14	3.22	3.00	2.99
2001	Grain	Yield (kg ha^{-1})	442	591	1,591	1,610
		Δ (‰)	2.32	2.12	2.13	2.14
		WUE (kg ha^{-1} mm^{-1})	1.06	1.56	3.63	3.74
	Total DM	Yield (kg ha^{-1})	819	1,227	2,557	2,812
		Δ (‰)	2.38	2.43	2.46	2.40

Table XIX. Soil-amendment effects on grain, straw and Δ for maize in 2001, on a farm at Diamaguene, Senegal

Treatment	Grain	Straw	Total biomass Δ
	(kg ha^{-1})		(‰)
NK (no P)	2,916	1,594	2.67
NPK	2,623	1,673	2.81
PG-PR	2,882	1,504	2.59
Manure (M)	2,697	1,622	2.75
PG-PR +M	3,187	1,672	2.72

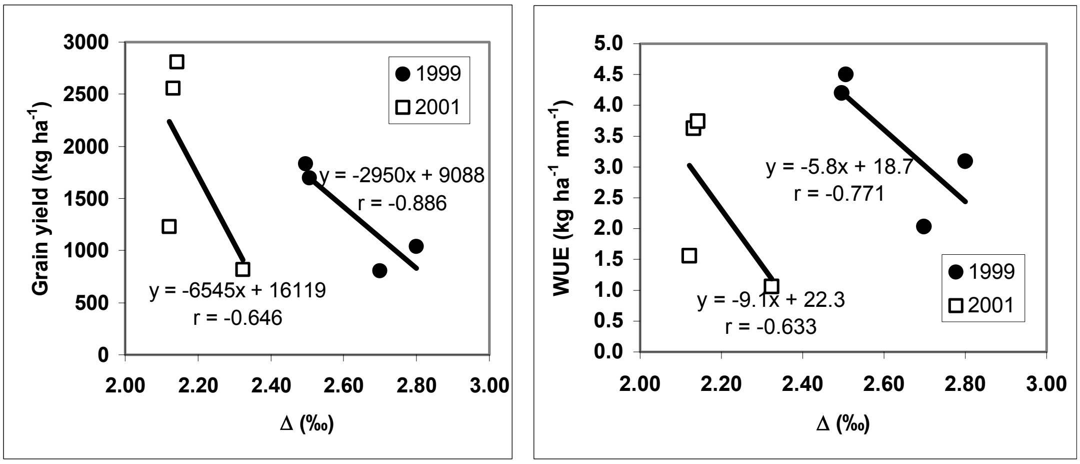

FIG. 12. The relationship between maize grain yield and water-use efficiency and Δ, Nioro Research Station, Senegal.

Table XX. Soil amendment effects on maize yield and total biomass Δ in 1999 and 2001, Nioro Research Station, Senegal

Treatment	1999		2001		1999	2001
	Grain	Straw	Grain	Straw	Total biomass Δ	
	(kg ha^{-1})				(‰)	
T0[a]	1,640	1,501	802	765	3.11	2.93
T1	1,390	1,600	817	763	NA	2.96
T2	1,820	1,850	665	472	3.08	2.97
T3	1,560	1,590	994	830	NA	2.93
T4	1,500	1,670	530	470	3.11	2.85
T5	1,680	1,740	783	774	NA	2.84
T6	1,540	1,580	800	878	NA	2.96
T7	1,370	1,330	662	667	2.98	2.77

[a] T0=no RP and no PG; T1= no PR and no PG + 30 kg ha^{-1} P_2O_5 as TSP; T2 =0%PR + 100%PG; T3=25%PR +75%PG; T4=50%PR+50%PR; T5=75% PR+ 25%PG; T6= 100%PR +0% PG; T7 =100% PR.

Table XXI. On-farm yields (grain + straw) and total biomass Δ for maize on farms at Darou Pakathiar and Dieri Kao in 2000

Treatment	Darou Pakathiar[a]			Dieri Kao[b]	
	Grain (kg ha^{-1})	Straw (kg ha^{-1})	Δ (‰)	Grain (kg ha^{-1})	Δ (‰)
T1	699	717	3.27	714	3.00
T2	896	806	3.28	765	3.07
T3	926	725	3.24	621	2.89

[a]T1, T2 and T3 are 5 t ha^{-1}manure, 1 t ha^{-1} PG-PR, and 5 t ha^{-1} manure + 1 T ha^{-1} PG-PR applications, respectively. [b]T1, T2 and T3 correspond to applications of 150 kg ha^{-1} NPK, 150 kg ha^{-1} NPK + 500 kg ha^{-1} of lime, and 150 kg ha^{-1} NPK + 1,000 kg ha^{-1} PG-PR.

3.3. **Castor and sorghum**

3.3.1. Southern Telangana, Andhra Pradesh, India

A sorghum and castor-based cropping system was examined in the southern Telangana region of Andhra Pradesh in India, with the objective of developing a set of options for improving the N nutrition of these dry-land cropping systems with inputs of biologically fixed N, fertilizer and organic matter at the regional agricultural research station (RARS), Palem, Mahabubnagar District. The main experiment, on an Alfisol, consisted of traditional (sorghum–castor) and improved (sorghum/pigeon pea–castor) cropping systems on a two-year rotation cycle arranged in a split-plot design with four N-management options (0N, 1.5 t FYM ha^{-1}, 60 kg N ha^{-1} as urea, and 45 kg N ha^{-1} as urea + 1.5 t FYM ha^{-1}).

The Δ values of the plant organs were different for the three crops: sorghum, pigeonpea and castor, with lowest Δ values in the grain (Table XXII). The Δ values of castor and sorghum were not affected by cropping system or N source and were stable between seasons; however, there were significant differences in the Δ values of the various plant components (Table XXIII). There was also no correlation between Δ and grain yield or between Δ and WUE for sorghum or castor; neither was a relationship found between Δ and %N in the different plant parts for the three crops (results not presented). The above analyses indicate that Δ is not a good predictor for sorghum, castor or pigeon pea in terms of grain or WUE. More data are needed to confirm this.

Table XXII. Δ and %N values of various crop components of sorghum, pigeon pea and castor, India

Cropping system	Crop	Plant part	Δ (‰)	%N
C–s[a]	Sorghum	Stalk	3.9	0.54
		Chaff	3.5	0.67
		Grain	3.1	1.20
C–s/pp[b]	Pigeon pea	Stalk	18.9	0.75
		Chaff	15.6	0.67
		Grain	15.0	3.55
S–c[c]	Castor	Stalk	19.8	0.76
		Chaff	20.6	1.20
		Grain	20.2	2.71

[a] Castor–sorghum cropping system.
[b] Castor–sorghum intercropped with pigeon pea.
[c] Sorghum–castor.

Table XXIII. Effect of N source on Δ values of castor and sorghum grain for 1999 and 2000, India

Crop	Cropping system	N source	1999 Δ (‰)	1999 Grain yield (kg ha^{-1})	2000 Δ (‰)	2000 Grain yield (kg ha^{-1})
Castor	S–c[a]	FYM[b]	20.4	1,280	20.1	1,007
		60N[c]	19.8	1,623	19.8	1,482
		45N[d]+FYM	19.9	1,452	19.6	1,282
	S/pp–c	FYM	20.8	1,399	20.2	1,171
		60N	20.8	1,622	20.5	1,442
		45N+FYM	19.9	1,550	20.0	1,478
Sorghum	C–s	FYM	3.0	854	3.0	1,454
		60N	3.1	2,259	3.0	2,666
		45N+FYM	3.1	2,326	3.2	2,814
	C–s/pp	FYM	2.9	906	3.1	1,196
		60N	3.0	1,847	3.1	2,056
		45N+FYM	3.1	1,748	2.9	2,210

[a] Sorghum–castor; sorghum intercropped with pigeon pea–castor; castor–sorghum; castor–sorghum intercropped with pigeon pea.

[b] Farmyard manure at 1.5 t ha^{-1}.

[c] 60 kg N ha^{-1} as urea.

[d] 45 kg N ha^{-1} as urea.

3.4. Mustard

3.4.1. New Delhi, India

The Δ values of mustard grain, straw and pod-husk were relatively uniform and were not affected by the various N and P treatments over two years (Table XXIV). However, there were differences between the plant-organ Δ values. Correlation coefficients of Δ values of grain with grain yield, WUE and %N in grain showed no significant relationships. With the current limited data set, it is difficult to determine if Δ is a good indicator for grain yield or WUE.

Table XXIV. Water-use efficiency, grain yield and associated Δ values of mustard, India

Treat.	Year	Δ Grain (‰)	Δ Straw (‰)	Δ Pod-husk (‰)	WUE (kg ha^{-1} mm^{-1})	Grain yield (kg ha^{-1})	Year	Δ Grain (‰)	Δ Straw (‰)	Δ Pod-husk (‰)	WUE (kg ha^{-1} mm^{-1})	Grain yield (kg ha^{-1})
N0P0	1998–1999	20.5	21.2	19.7	2.01	1,549	1999–2000	20.4	21.4	19.9	2.83	386
N0P15		20.4	21.5	19.7	2.22	1,633		20.2	21.6	19.6	3.00	408
N0P30		20.5	21.2	19.6	2.21	1,566		20.3	21.2	19.6	3.08	420
N30P0		20.2	21.1	19.7	3.70	2,037		20.6	21.7	19.9	4.66	636
N30P15		20.9	21.5	19.7	5.83	2,414		20.7	22.0	19.9	7.25	988
N30P30		20.8	21.4	19.8	6.39	2,571		20.8	22.0	19.9	8.03	1,095
N60P0		20.4	21.1	19.6	5.24	3,042		20.7	21.8	19.8	6.66	907
N60P15		20.2	21.2	19.5	6.95	3,175		20.4	21.9	19.7	8.27	1,128
N60P30		20.5	21.7	19.7	6.79	3,053		20.5	21.8	19.7	8.17	1,114

3.5. Lentil

3.5.1. Jordan and Pakistan

The Δ data for lentil from studies in Jordan and Pakistan are presented in Tables XXV and XXVI; smaller values were obtained with straw in the Jordanian study. Slightly smaller values were obtained in the presence of residues (Table XXV). In Pakistan, the differences in Δ values for lentil were not significantly influenced by tillage or nutrient treatments in straw, grain and roots. There was a positive but non-significant correlation between Δ and grain and straw yields (Fig. 13). In view of the limited data available, it is not possible to conclude if Δ is an appropriate tool for selection for grain yield.

Table XXV. Straw yield, Δ value and %N of lentil for 1998–1999, Jordan

Treatment	Yield (kg ha^{-1})	Δ (‰)	%N
R0N0	76	17.5	2.52
R0N1	324	18.5	2.57
R0N2	404	18.2	2.50
R1N1	230	18.8	2.32
R1N2	166	18.7	2.13

Table XXVI. Effects of tillage and nutrient treatments on grain yield, Δ in straw, grain and roots of lentil on two farmers' fields, 1998–1999, Pakistan

Location	Tillage	Parameter	Straw		Grain	
			P_1[a]	P_2[b]	P_1	P_2
			(kg ha^{-1})			
Farmer-1 (Urmar)	T_1[c]	Yield (kg ha^{-1})			1,016	1,050
	T_0[d]	Yield (kg ha^{-1})			783	783
	T_1	WUE (kg ha^{-1} mm^{-1})	3.89		2.58	
	T_0	WUE (kg ha^{-1} mm^{-1})	3.21		2.01	
	T_1	Δ (‰)	20.3	20.3	17.2	17.3
	T_0	Δ (‰)	20.4	20.2	17.8	17.5
Farmer-2 (Jalozai)	T_1	Yield (kg ha^{-1})			1,100	1,267
	T_0	Yield (kg ha^{-1})			1,267	1,133
	T_1	WUE (kg ha^{-1} mm^{-1})	8.40		4.48	
	T_0	WUE (kg ha^{-1} mm^{-1})	8.15		4.42	
	T_1	Δ (‰)	19.8	20.5	17.3	18.6
	T_0	Δ (‰)	20.4	19.9	18.3	17.8

[a] $N_{60} + P_{30}$.
[b] $N_{60} + P_{60}$.
[c] Conventional tillage.
[d] No tillage.

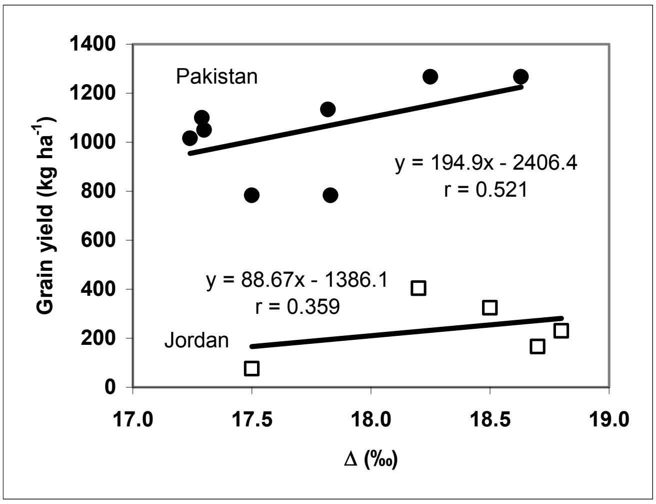

FIG. 13. The relationship between lentil grain (Pakistan) and its Δ values and lentil straw (Jordan) and the corresponding Δ values. The correlations were non-significant.

3.6. Barley

3.6.1. Jordan

Barley was studied for one year at the University of Science and Technology as the second part of the Jordanian experiments. Just like the non-significance within the dry matter, grain and straw yield reported [18], the grain and straw Δ values were also not affected by the crop rotation or N rate (Table XXVII). Correlations between Δ values of grain and straw with the corresponding grain and straw yields were also not significant (Fig. 14). In rainfed conditions in southern Spain, Garcia del Moral et al. [34] found that the most important determinant of barley yield was number of spikes per m^2, followed by number of grains per spike.

Table XXVII. Carbon-isotope discrimination and yield of barley, 2001–2002, Jordan

Treatment	Grain Δ	Shoot Δ	Dry matter	Grain	Straw
	(‰)		(kg ha^{-1})		
BB[a]N0[b]	16.0	18.4	6,150	1,814	4,336
BBN1	15.2	18.0	7,700	2,041	5,659
BBN2	15.1	18.2	7,500	1,978	5,356
BVN0	15.2	18.5	7,520	2,116	5,405
BVN1	15.0	18.6	9,730	2,505	7,225
BVN2	15.1	18.8	10,230	2,613	7,618
BFN0	14.3	18.4	7,220	1,935	5,285
BFN1	14.8	18.2	9,100	2,508	6,592
BFN2	15.3	18.8	9,870	2,652	7,218

[a] Barley after barley, barley after vetch, barley after fallow, respectively.
[b] 0, 40, 80 kg N ha^{-1}, respectively.

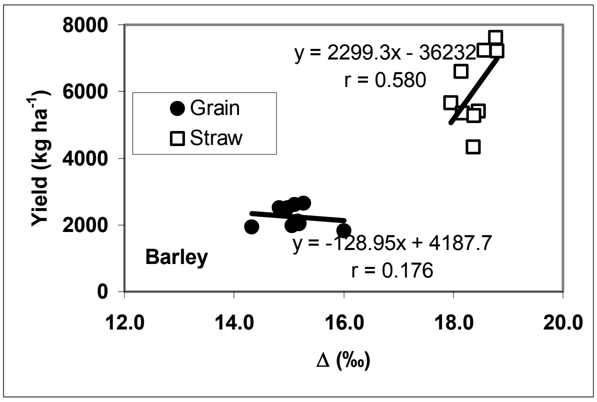

FIG. 14. The relationship between grain and straw yields of barley and their Δ values.

3.7. Millet

3.7.1. Niger and Senegal

The study in Niger was on sandy soils at two locations, Tarna (or Maradi) and Tara (Gaya or Bengou) Research Stations, to determine the influence of combinations of organic and inorganic fertilizers and cropping systems on crop production. The cropping systems consisted of continuous millet, rotation of millet and cowpea and a millet-cowpea intercrop. Three levels of N and P (0, 30 kg N ha^{-1}+ 20 P_2O_5 ha^{-1} and 60 kg N ha^{-1} + 40 kg P_2O_5 ha^{-1}) combined with three levels of organic fertilizer (0, 0.9 and 2.7 t ha^{-1}) were factorially arranged to give nine treatments in a split-plot design with four replicates. The annual rainfall amounts at Tarna and Tara are 500 and 800 mm, respectively. Tarna soils are sandier than those at Tara. The variety of millet used was CT6.

In Senegal, a long-term experiment was conducted at Nioro du Rip Research Station within the maize-peanut cropping system in the Senegal Peanut Basin. The aim was to optimize water and nutrient use by maize, peanut and millet in rotations based on organic and phosphate rock (Taïba PR) soil amendments. The soil at the experimental site is classified as an Alfisol with pH values less than 5.4 in the top 30 cm. The millet-peanut rotation experiments were carried out on-farm at the villages of D. Pakathiar and K. Madieng, the purpose being to correct either soil acidity or P deficiency. There were four treatments: T0, farmers practice (control); T1, manure application once every two years at the rate of 5,000 kg ha^{-1}; T2, PG-PR application once every four years at the rate of 1,000 kg ha^{-1}; T3, combination of T1 and T2. The variety of millet used was Souna III.

While the Niger millet grain yield and straw increased with increasing organic manure input (0 to 2.7 t ha^{-1}), the Δ values of grain decreased with increasing grain yield (Fig. 15 and Table XXVIII). Unpublished data showed that Δ values of straw are significantly higher than those of grain (3.35 ± 0.03 cf 2.35 ± 0.01 ‰) but there was no correlation between the grain and straw Δ. The grain Δ data at Maradi were slightly higher than those at Tara: the values ranged from 2.18 to 2.56‰ with a mean of 2.368 ± 0.018 ‰ compared to 2.25 to 2.32 with a mean of 2.282 ± 0.001.

Millet grain and straw yields were low in Senegal compared to those in Niger (Table XXIX). The various soil amendments did not have any effect on the Δ of the biomass. There was no correlation between Δ of biomass and biomass (Fig. 15).

The results from Niger and Senegal were insufficient to conclude whether Δ can be utilized as a selection tool for yield.

Table XXVIII. Millet grain and straw yields and grain Δ values, 1999, Niger

Treatment	Grain	Straw	Grain Δ
	(kg ha^{-1})		(‰)
E2[a]F0[b]	1080	2210	2.89
E2F1	1380	2205	2.87
E2F2	1510	2400	2.84

[a] 60 kg N ha^{-1} inorganic fertilizer.

[b] 0, 0.9 and 2.7 t ha^{-1} of organic manure, respectively.

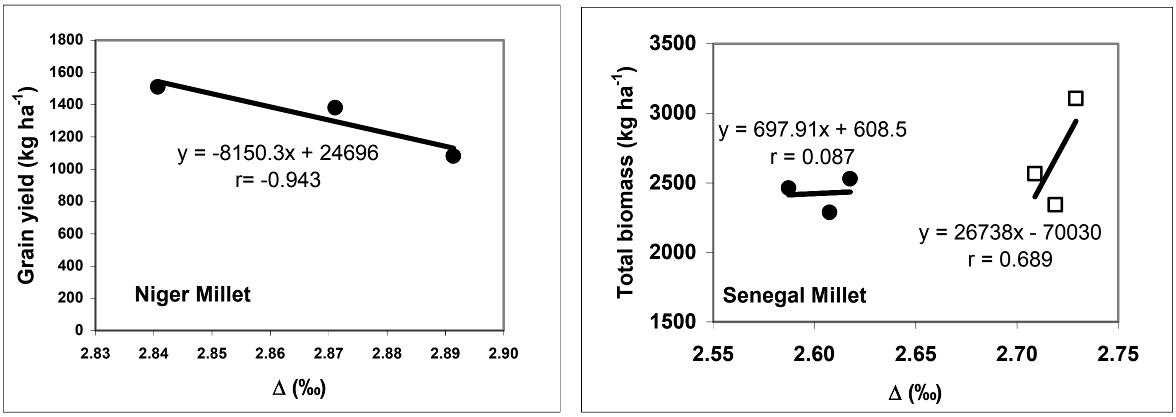

FIG. 15. Correlation between Δ of grain (Niger) and of total biomass and grain (•) and biomass (□) (Senegal)

Table XXIX. On-farm yields of grain and straw and total biomass (grain + straw) Δ for millet, at Keru Madien in 2000 and Darou Pakathiar in 2001, Senegal

Location	Treatment	Grain	Straw	Biomass Δ
		(kg ha^{-1})		(‰)
Keur Madien	T11[a]	808	1,721	2.62
	T12	853	1,435	2.61
	T13	905	1,556	2.59
Darou Pakathiar	T21[b]	677	1,665	2.72
	T22	722	1,843	2.71
	T22	864	2,243	2.73

[a] 5 t ha^{-1}manure; 1 t ha^{-1} PG-PR; 5 t ha^{-1} manure + 1 t ha^{-1} PG-PR, respectively.

[b] 150 kg ha^{-1} NPK; 150 kg ha^{-1} NPK + 500 kg ha^{-1} lime; 150 kg ha^{-1} NPK + 1,000 kg ha^{-1} PG-PR, respectively.

3.8. Cotton

3.8.1. Argentina

The yields and %N values of the various cotton components, and the corresponding carbon-isotope discrimination values are shown in Table XXX. The Δ values for leaves were high compared to those in another study [8] in which a mean Δ value of 18.4‰ was obtained from twenty-seven cotton cultivars studied. The lower Δ values were probably due to the drier environment in that study.

Table XXX also shows that Δ values differed between plant parts. Statistically significant differences in the Δ values were observed for leaves of plants grown without tillage, but there were no significant differences in Δ values between fertilized and unfertilized treatments. The Δ values tended to be lowest in fruits and highest in carpels.

No relationship was found between the Δ value of fruit and carpel of cotton and their respective yields. A positive correlation between the Δ of cotton seed and its yield and a negative correlation between Δ of cotton leaves and their yield were obtained. Correlations between Δ of various plant parts with the respective %N value were strong except for leaves (Fig. 16). Gerik et al. [33](1996) also observed a positive correlation between Δ and seed yield over a range of environments and years.

4. CONCLUSIONS

The above analyses show that there is genotypic variation in the carbon-isotope discrimination of wheat, with Δ values lowest in the driest regions. Wheat crops in extremely dry environments such as in Jordan tend to have low Δ and high WUE values, and low productivity. There were good correlations between grain Δ and grain yield in all of the studies. However, the correlation was negative in China and India and positive in Jordan, Morocco and Pakistan. These contrasting results show that various factors influence Δ, making it difficult to utilize this parameter as a diagnostic tool; however, one can argue that breeding for yield in these two should involve selecting for lower Δ in relatively wet years in the negative cases, and selecting for high Δ in wet years in the positive cases.

Table XXX. Effects of crop-management and N fertilization on yield, %N and Δ values for parts of cotton.

Plant part	CCTNF[a]			CCTF[b]			CNTNF[c]			CNTF[d]		
	Yield (kg ha^{-1})	%N	Δ (‰)	Yield (kg ha^{-1})	%N	Δ (‰)	Yield (kg ha^{-1})	%N	Δ (‰)	Yield (kg ha^{-1})	%N	Δ (‰)
Seed	669	5.7	21.2	754	5.7	21.0	410	5.84	20.8	465	5.99	20.8
Fruits	1,748	3.6	19.3	1,602	3.45	19.5	2,822	3.31	19.7	1,822	3.28	20.0
Carpel	1,470	2.4	21.8	1,630	2.65	21.5	1,901	2.81	21.5	1,377	2.86	21.5
Stem	6,584	1.32	20.4	7,002	1.06	20.1	8,080	1.31	20.4	4,981	1.24	20.4
Leaves	2,028	4.26	20.7	1,832	3.97	20.7	2,154	4.17	20.8	1,486	3.98	20.8

[a] Cotton, conventional tillage, zero fertilization. [b]Fertilized cotton, conventional tillage. [c]Cotton, no tillage, zero fertilization. [d]Fertilized cotton, no tillage

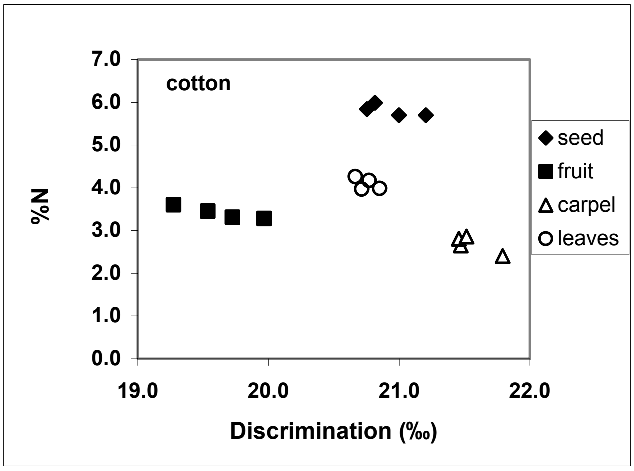

FIG. 16. Relationship between carbon-isotope discrimination (Δ) and %N of various parts of cotton, Argentina.

Positive correlations have been observed in field trials of wheat especially in Mediterranean and similar environments [31–33], where there is strong reliance on within-season rainfall. The correlation between Δ and WUE was less strong in general. In order to use Δ as a diagnostic tool, properly designed studies are needed to understand the influence of the various factors on Δ, yield and drought tolerance.

In general, cropping system had little effect on Δ values within plant organs. However, level of N applied affected Δ in wheat, except in China. In all cases, Δ decreased with increasing leaf-N content, as reported from previous studies [23, 24, 35]. Nitrogen deficiency reduces photosynthetic capacity, hence an inverse relationship between %N and Δ should exist; this relationship was more pronounced in grain than in straw.

Genotypic variation existed in Δ values of various plant organs in all crops, with grain Δ being the lowest. The association between yield and carbon-isotope discrimination in different organs of wheat in all of these studies showed that better correlations were achieved for grain Δ than for other organs, indicating grain is the more suitable plant organ for Δ analysis. This observation was also made in a study of durum wheat under Mediterranean conditions [36].

Although there was genetic variation within each C_4 crop (maize, sorghum and millet), correlations between grain Δ and other traits (grain yield, %N and WUE) were non-significant in most cases, indicating that Δ is not suitable as a selection tool. According to Farquhar [37], Δ in C_4 plants is also affected by the initial fixation of CO_2 by phosphoenolpyruvate carboxylase (PEPC), and the "leakiness" of CO_2 from bundle-shealth chloroplast cells, in addition to:

— fractionation due to CO_2 diffusion,
— changes in stomatal resistance or assimilation rate, and
— fractionation by ribulose-1,5-bisphosphate carboxylase-oxygenase (rubisco).

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A SIMULATION ANALYSIS OF WATER-USE EFFICIENCY OF RAINFED WHEAT

S. ASSENG, N.C. TURNER
CSIRO Plant Industry,
Wembley, Australia

Abstract

The APSIM-Nwheat model was used to analyze the water-use efficiency [WUE (kg grain yield ha^{-1} mm^{-1} ET)] of rainfed wheat crops in the Western Australian wheat-belt, where soils vary between locations and rainfall varies between seasons and rainfall zones. Management options such as improved N supply and breeding options such as early vigour and increased transpiration efficiency were investigated. Studies were carried out to analyze the impact of these options on WUE across major soil types, rainfall zones and with over eighty years of historical weather records. Results indicated a large potential for improving the WUE of wheat, in particular when tailoring management and breeding to specific soil types and rainfall locations.

1. INTRODUCTION

In many environments, water supply is a major source of variability in crop yields [1]. Total water use or total evapotranspiration (ET) by a crop can vary substantially due to limited water storage in the soil or due to limited rainfall. It can also vary with crop transpiration changes resulting from management, such as nutrient supply [2] and sowing time [3], or from use of different species [4] or cultivars [5]. The seasonal water use of a crop consists of both crop transpiration and soil evaporation [6], with the latter varying between 14% [7] and 75% [8] of total water use. The ratio between grain yield and evapotranspiration, the generally accepted definition of water-use efficiency [WUE (kg grain yield ha^{-1} mm^{-1} ET)] for grain production, can be an important parameter defining the productivity of crops in water-limited environments [9,10].

In water-limited environments, WUE has been quantified in only a limited number of experiments aimed at comparing cropping systems and management practices [e.g. 2, 4, 7, 11–15]. However, interpreting these direct measurements and assessing the value of the management strategies imposed is made difficult by season-to-season variability in both the total amount and seasonal distribution of rainfall. Extrapolation of such field measurements to other sites and seasons is further complicated by diversity of soils and crops, and lack of information on interactions among crop, soil and climate on water use and water loss.

Differences in production in dryland cropping have been explained with simple models including those based on rainfall between ear-emergence and maturity [16], soil-water supply after ear-emergence estimated from a soil-water model [17], total ET from sowing to maturity [18], total water use less an amount for soil evaporation [6] or total water use and the proportion of water used after anthesis [19, 20]. Fischer [21] argued that to understand yield variability, important physiological information regarding crop-climate interactions — such as pre-anthesis conditions and grain number — evaporation and air saturation vapour deficit need to be considered in relation to biomass production and total water use. Hence, for a simulation model to be comprehensive, it must take into account the dynamics of crop-soil-weather interactions and capture the principles inherent in all the above simple models. Such a model would then be able to fully explore cropping systems across a range of seasons, soil types and rainfall zones. Indeed, some crop-soil models consider the dynamics of crop-soil-weather interactions and capture the physiological and bio-physical principles of such systems, and can be effective tools in extrapolating research findings over time, soil types and climatic regions (e.g. [22–27].

The Agricultural Production Systems Simulator (APSIM) [28] for wheat has been rigorously tested against field measurements and used in various studies under a large range of growing conditions [22, 29–31] and in particular in the Mediterranean climatic region of Western Australia [22, 32, 33]. This paper demonstrates how a crop-soil simulation model was used in evaluating WUE of rainfed wheat in a Mediterranean-type climate.

2. THE SIMULATION MODEL

2.1. APSIM

APSIM [28] was configured with the Nwheat crop module (www.apsim-help.tag.csiro.au), SOILN2, SOILWAT2 and RESIDUE2 soil and residue modules [34]. This model configuration simulates carbon (C), water and nitrogen (N) dynamics and their interactions within a wheat crop/soil system that is driven by daily weather information (rainfall, maximum and minimum temperatures and solar radiation). It calculates the potential yield, that is, the yield not limited by pests and diseases, but limited only by temperature, solar radiation, water and N supply. The model has been successfully tested against data from field experiments in Western Australia and elsewhere [22, 32, 33].

Potential evapotranspiration in the APSIM model is calculated with a modified [35] approach as in the CERES models [36] and is a function of solar radiation, soil and crop albedo, and air temperature. Likewise, soil evaporation is calculated according to the CERES model [36] in two consecutive stages. Stage I applies to a wet soil surface after a rain event and is energy-limited, based on potential evapotranspiration and the soil cover by the crop. However, stage II is limited by hydraulic conductivity of the soil supplying water to the surface. Unlike the CERES model, water uptake in Nwheat is linked to biomass production via transpiration efficiency and vapour pressure deficit [37]. Simulated water uptake is a function of uptake demand, the distribution of root length density and available soil water in the different soil layers. Documented model source code in hypertext format is available (www.apsim-help.tag.csiro.au) or can be obtained by writing to Dr. B.A. Keating (Brian.Keating@csiro.au).

2.2. Simulation experiments

A number of simulation experiments have been conducted, described in detail by Asseng et al. [33, 38]. Briefly, two major soil types, a sand (55 mm plant-available soil water in the rooting zone) and a clay soil (109 mm), from the central agricultural zone of south-western Australia were chosen to study the effect of available water-holding capacity of the soil in interaction with rainfall zone, seasonal rainfall and crop management on wheat (*Triticum aestivum* L.) yields and WUE. The two soils were considered non-waterlogging. Their characteristics were derived from field measurements. The plant-available lower limit (LL) was derived from measured soil-water contents at maturity of wheat crops in years of little or no rainfall during grain filling. The drained upper limit (DUL) was derived from measured soil-water contents after sufficient rainfall had wet the profile and several days were allowed for drainage. The difference between DUL and LL within the root zone was defined as extractable water-holding capacity of the soil. Root hospitality factors (RHF), which affect the downward elongation of a root system, were derived from measured changes in root length densities (> 0.1 cm cm^{-3}) and measured soil water change due to crop uptake. Soil characteristics for the sand were based on data from Anderson et al. [39] and for the clay soil on data from Rickert et al. [40].

Table I. Rainfall at locations in the central agricultural zone of Western Australia

Location	Latitude & longitude	Rainfall zone	Mean annual	Growing-season (April–October)		
				Mean	s.d.	Range
			(mm)			
Merredin	31.3° S, 118.2° E	Low	310	235	57	102–418
Wongan Hills	31.0° S, 116.7° E	Medium	391	322	78	112–535
Moora	30.6° S, 116.0° E	High	458	392	87	165–648

Simulations were carried out with long-term daily weather records from three locations, namely Merredin (low rainfall zone), Wongan Hills (medium) and Moora (high) (Table I). Each simulation run commenced on 1 January (DOY 1) and was re-set each year with soil water at LL on 1 January. Sowing time was controlled by a sowing rule in the model. Sowing was set between 5 May (DOY 125) and 31 July (DOY 212), but before 5 June (DOY 156) it did not occur unless at least 25 mm of rainfall had accumulated within the previous 10 days or after 5 June it did not occur until at least 10 mm of rainfall had accumulated. The variety Spear (late maturing) was simulated as being sown before 5 June, otherwise the variety Amery (early maturing) was simulated. All planting rules represented current "best farmer practices."

Seasonal rainfall (or effective growing-season rainfall) was defined as rainfall between April and October. WUE was defined as the ratio of grain yield (in kg ha^{-1}) to evapotranspiration (in mm) during the main growing season between May and October. When comparing WUE with the French and Schultz [41] approach, Water use efficiency was defined as the ratio of grain yield (in kg ha^{-1}) to seasonal rainfall (in mm) between April and October.

2.3. Role of fertilizer input in improving water use efficiency

Rainfall is very variable in the central agricultural zone of Western Australia, with between two thirds and three quarters of the total annual amount falling in the cropping season. Growing season rainfall increases from Merredin (235 mm average, April–October) to Wongan Hills (322 mm) to Moora (392 mm) (Table I). The sowing date for wheat varies from early May to July depending on when the first significant rainfall occurs after the dry summer. Sowing before May is often not possible due to too little rainfall, low water-holding-capacity soils, high temperature, disease and cultivar limitations. The restricted sowing opportunity and a period of 2 to 3 months of low biomass accumulation in wheat after sowing in this environment restricts substantial biomass growth prior to August. Depending on sowing date and phenology, wheat crops flower between September and October, and grain filling is often affected by high temperatures and terminal drought before maturity in November and December [42].

High N had a major effect on simulated biomass growth (average increase from 3.7 to 6.3 t ha^{-1}) in the medium rainfall location, but had only minor effects on ET (Fig. 1).

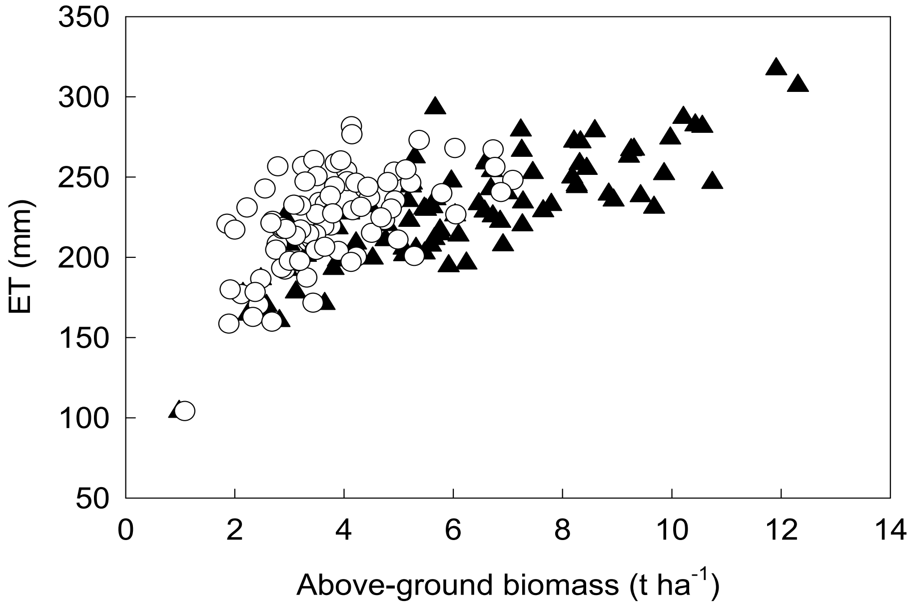

FIG. 1. Simulated evapotranspiration between May and October versus above-ground biomass with low N (○) and high N (▲) on a deep sandy soil at a medium rainfall location in Western Australia.

Table II. Simulated long-term average grain yields and evapotranspiration (ET) (May–October) for a sand and a clay soil at three sites differing in growing-season (April–October) rainfall, Merredin (235 mm), Wongan Hills (322 mm) and Moora (392 mm) given two levels of N

Growing-season rainfall (mm)	Grain yield				ET			
	Sand		Clay		Sand		Clay	
	30[a]	210	30	210	30	210	30	210
	(t ha^{-1})				(mm)			
235	1.2	1.4	1.1	1.0	192	193	224	226
322	1.5	2.1	2.2	2.3	224	230	277	288
392	1.4	2.5	2.4	2.9	246	259	304	327

[a] N applied at 30 and 210 kg ha^{-1}.

Large increases in biomass growth rate (BGR) between July and October occurred in conjunction with large increases in crop transpiration (E_c) during these months (Fig. 1). However, the increased BGR with high N application also induced more rapid leaf-area development and reduced soil evaporation. Despite higher E_c in conjunction with increased N because of the reduction in soil evaporation, the increase in total ET was relatively small (on average from 222 to 230 mm). In addition, the simulated increases in BGR in July and August from additional N occurred at the time of lowest vapour-pressure deficit, resulting in a simulated increase of transpiration efficiency (TE) [33].

Water-use efficiency increased from 17 kg biomass ha^{-1} mm^{-1} ET in the low-N treatment to 27 kg biomass ha^{-1} mm^{-1} ET in the high-N treatment on average over the cropping season, approximately a doubling in efficiency. The effect of higher N input on water use later in the season only marginally reduced the water content of the sandy soil after harvest.

One conclusion from the simulation is that biomass production and grain yield (Table II) can be increased by fertilizer use in many seasons with little impact on ET, particularly on sandy soils. Hence, the largest impact on WUE on sandy soils in such an environment will be by increasing grain yields. Substantially increased biomass production and grain yields (41%) have also been observed by Zhang et al. [15] in wheat crops with high N input, while ET was increased by only 21 mm (8%). In this case, crop transpiration was increased by 40 mm, but soil evaporation was reduced by 19 mm, which is in good agreement with the simulation results. Gregory et al. [4] reported that a range of crop treatments, including low and high N fertilizer, that varied by as much as 50% in biomass, ultimately used the same amount of water (250–255 mm), and the corresponding fallow treatment used only 15 mm less water (237 mm), which agrees well with our simulations. This also agrees with findings in the Mediterranean climate of northern Syria by Shepherd et al. [2], who showed that biomass production and grain yield were increased with increased levels of fertiliser use at different sites and seasons. In most cases the increase in biomass and grain yield resulted from shifting E_s to E_c without increasing total ET.

In addition, Anderson [43] has shown in Western Australia that changing from low- to high-input agronomic practices had little effect on seasonal water use, with only five out of twelve sites responding to additional N fertilizer by increasing water use by an average of 14 mm. This value is very similar to the long-term simulated average for the medium rainfall zone. These observations together with the simulation results suggest that in a Mediterranean climate increased biomass can be achieved without an increase in water use (in terms of total ET), because there is a trade-off between E_c and E_s

French and Schultz [41] predicted that where growing-season rainfall did not exceed 500 mm, the maximum WUE was 20 kg grain ha^{-1} mm^{-1} ET in the growing season after accounting for 110 mm of E_s. This has proved to be a simple and easy-to-use approach to estimate potential yields and has been widely adopted by farmers and farm consultants, employing growing-season (April–October) rainfall as a surrogate for water use [41]. However, simulation studies have shown [33] that the potential yield estimated by French and Schultz [41] based on growing-season rainfall is rarely achieved on sandy soils due to losses of water by deep drainage below the root zone and losses of N leached with the draining water, and on texture-contrast soils from runoff and overland flow [4, 44]. Further, the amount of rainfall alone does not determine grain yield. Rather it is the distribution of rainfall, particularly on soils with low water-holding capacity [22], that affects the availability of water after anthesis [13, 45]; it is of greater significance than the amount of rainfall in determining WUE. On soils of greater water-holding capacity, the effects on after-anthesis water use can be larger and will increase grain yields, but also overall WUE. Poor agronomy uses less water after anthesis and, therefore, can leave additional water behind on better water-holding soils at harvest [33] resulting in low WUE. Water left behind at harvest and carried over to the next season will often have little impact on the following-year crop in terms of water supply, but rather adds to deep drainage in the subsequent year in the high rainfall region [33]. Therefore, improved crop agronomy can also play an important role in reducing deep drainage, the main cause of dryland salinity in Southern Australia [46].

Simulated grain yields were more closely correlated with the amount of water use after anthesis on clay than on sandy soils [33]. In most years on clay soil, N-fertilizer input reduced water use in the post-anthesis period due to increased pre-anthesis water use. However, on sandy soil, N input increased the water use after anthesis in 26% of the years (Fig. 2), and the majority of these years (87%) involved above-average rainfall in September and October, rainfall that could not be utilized when N input was low. On the clay soils with high-N input, only 10% of the years had increased water use after anthesis, with half of these being years with above-average rainfall in September and October [33]. With an increase in the actual amount of water used after anthesis, grain yields have been shown to generally increase [2,5,2,13]. But at any one value of water use, increased fertilizer input significantly increases yields and WUE [47], which agrees with the simulation results (Fig. 2).

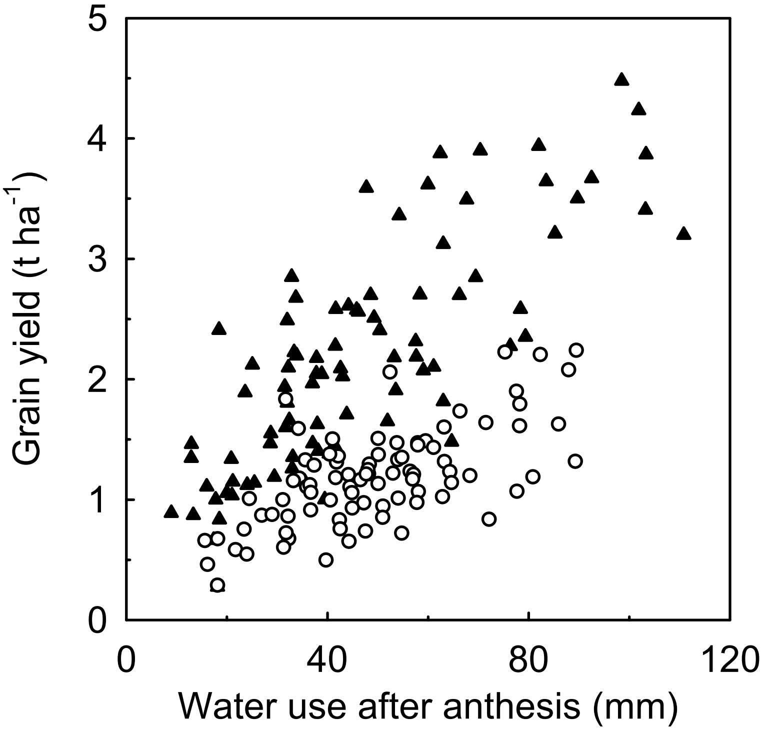

FIG. 2. Relationship between simulated grain yields and water use after anthesis by wheat for sandy soil with low N (○) and high N (▲) in a medium rainfall location of Western Australia (after Ref. [33]).

In addition, on the clay soils in the low-rainfall zone, early sowing and the presence of stored water in the profile both provided opportunities for increased yields and WUE, and should be taken into consideration when making N-management decisions [33].

2.4. Role of deeper roots on improving WUE

Compaction in the upper horizons is a widespread problem in sandy and loamy soils of the Western Australian wheat-belt [48]. Deep ripping to about 30 to 40 cm to mitigate compaction increased root growth and the maximum depth of water uptake by 60 cm [49]. Differences in root depth in annual crops have been reported by Hamblin and Hamblin [50] with roots of some legumes, such as narrow-leafed lupin (*Lupinus angustifolius* L.), reaching more than 70 cm deeper than wheat on a deep loamy sand.

Genetic differences in root-growth rates have been observed for wheat by O'Brien [51] and Bai et al. [52]. Simulation studies have shown that faster root growth can increase grain yields in the Mediterranean-type environment of Western Australia, particularly on sandy soils, by enabling the plant to keep pace with the downward movement of N in low fertilizer-N treatments [33]. However, the positive yield effect of faster root growth, induced either by deep ripping the soil or by genetic means, can largely be overridden by increased fertilizer-N supply according to crop demand [38, 49]. Faster root growth, therefore, represents mainly a N effect on grain yield, rather a water-supply effect. Nevertheless, it improves WUE. Furthermore, enhanced root growth is less of an advantage on clay soils, due to less nitrate leaching and can even have a negative effect on yields in low-rainfall years with a shallow soil-wetting front inducing severe water stress when roots reach the dry subsoil before grain filling is completed. This confirms findings by Jarvis [48] and Delroy and Bowden [49] with deep ripping that showed positive, no, or negative effects on grain yield in a number of field experiments depending on soil type and season

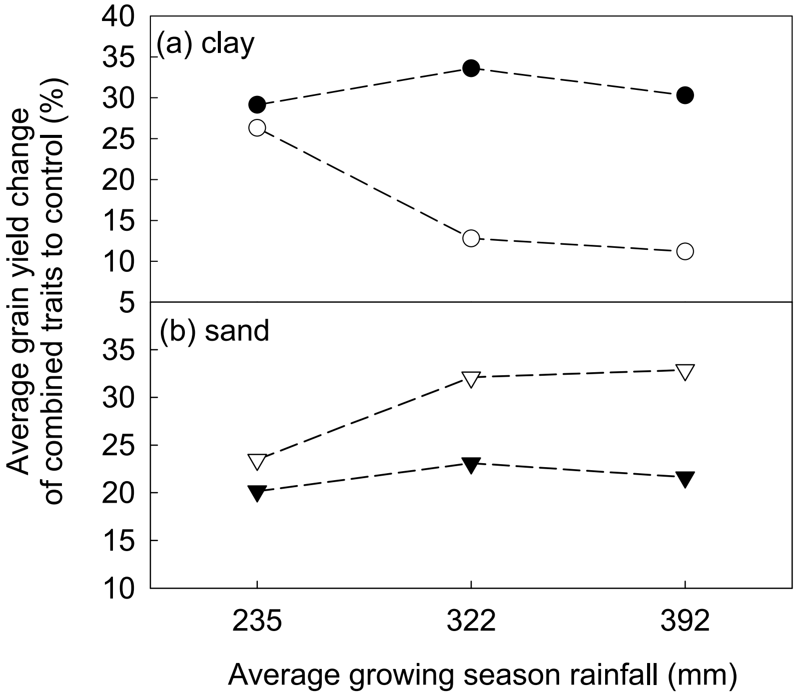

FIG. 3. Simulated relative average yield increase for wheat with the full complement of traits associated with early vigour and high TE in low to high rainfall locations in Western Australia with low N (open symbols) and high N (filled symbols) on (a) clay soil and (b) deep sand (after Ref. [38]).

2.5. Genetic options for improving WUE

A combination of traits has been associated with selection for early vigour (R. Richards, pers. comm. 2002). These are increased specific leaf area (SLA), faster early root growth, earliness and reduced radiation use efficiency. In addition, early vigour has been combined with increased transpiration efficiency (TE) (R. Richards, pers. comm. 2002). In a simulation experiment, the combination of all these traits in a wheat crop (Asseng et al. 2003) grown on clay soil in the low rainfall region showed a 30% yield increase on average, regardless of N supply (Fig. 3a). The average yield advantage remained at 30% in the higher rainfall regions with high N input, but with low N input the average yield advantage was reduced to 10%. In contrast, on the deep sand the average yield increase with early vigour and high TE was 20 to 30% with low N input and about 20% with high N input across all rainfall regions (Fig. 3b).

The reason for the different yield response on the sandy soil compared to the clay soil was due to the single traits associated with early vigour and high TE acting differently in response to N on the two soil types (Fig. 4). On the sandy soil, doubling SLA increased yield by 15%, but only when sufficient N was supplied. On the clay soil, doubling SLA reduced yield under low N, but was marginally beneficial under high N. One of the traits associated with early vigour, faster early root growth, increased grain yields by more than 15% on the sandy soil with low N input, but this trait became less important with high N input on the sand and gave little benefit on average on the clay [38]. Water use efficiency in these increased in parallel to increased grain yields.

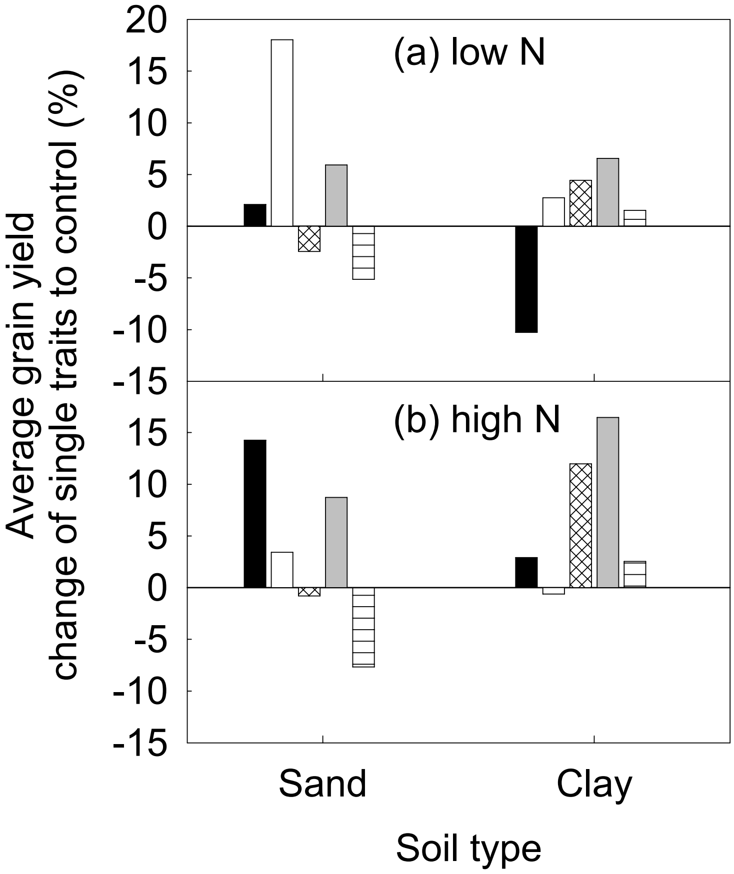

FIG. 4. Simulated effect of individual traits comprising early vigour and high transpiration efficiency (TE) on wheat yields compared to control (yields given in Table II) in a deep sand and a clay soil with (a) low N and (b) high N, for a medium rainfall location in Western Australia (322 mm growing-season average). Increased specific leaf area (SLA) (dark filled bar), faster root growth (open bar), earliness (cross-hatched bar), +10% TE (grey bar) and –10% radiation-use efficiency (horizontal lines in bar).

3. CONCLUSIONS

This analysis has indicated that yield and WUE of wheat crops in the Mediterranean climatic region of Western Australia vary markedly depending on soil water-holding capacity, N management and rainfall amount. The degree of variation in yield and WUE from the simulations is difficult to quantify from field experimentation alone. Thus, simulation modelling provides a powerful tool for integrating all of these factors and when combined with long-term climatic data and regional soil information is able to markedly extend the interpretation possible from limited experimental studies.

The results suggest that there is large potential for increasing yield and WUE, in particular in the high- and medium-rainfall zones of Western Australia on soils with high water-holding capacity. The analysis also highlights that in low-rainfall years and in the low-rainfall zone the yields were higher and the responses to N fertilizer were greater on sandy than on clay soils. Breeding for early vigour and increased TE will further allow increased yields and WUE in the Mediterranean climatic region of Western Australia. The different traits associated with early vigour and increased TE have been shown to have different impacts on yield, depending on soil type, management and rainfall season.

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INCREASING LAND SUSTAINABILITY AND PRODUCTIVITY THROUGH SOIL-FERTILITY MANAGEMENT IN THE WEST AFRICAN SUDANO-SAHELIAN ZONE

A. BATIONO, B. VANLAUWE, J. KIMETU, J. KIHARA
Tropical Soil Biology and Fertility Institute,
Nairobi, Kenya

M.S. ABDOULAYE, A. ADAMOU, R. TABO, S. KOALA
International Centre for Research in the Semi-Arid Tropics,
Niamey, Niger

Abstract

Food production has lagged behind population growth in most parts of the West African semi-arid tropics (WASAT). One of the reasons for low food production is decline in soil fertility as a consequence of continuous cropping without fertilization. As a result, there is a negative nutrient balance in most land-use systems in WASAT. The amount of nutrients leaving the soil, through crop uptake, leaching and erosion exceeds that returned through natural processes such as atmospheric deposition and biological nitrogen fixation or through additions of inorganic and organic fertilizers. Use of mineral fertilizers by many smallholder farmers remains low because of socio-economic constraints. Lack of adequate foreign exchange to import fertilizers, poor infrastructure and poor distribution mechanisms have hampered the use of inorganic fertilizers. Organic inputs such as manure, compost and crop residues are often proposed as alternatives to mineral fertilizers, however, it is important to recognize that in most cases the use of organic inputs is part of an internal flow of nutrients within the farm and does not add nutrient from outside the farm; also, quantities available are inadequate to meet nutrient needs over large areas because of limited availability, low nutrient content of the material, and high labour demands for processing and application. The beneficial effects of combined manure and inorganic nutrients on soil fertility have been repeatedly shown, yet there is need for more research on the establishment of the fertilizer equivalency of manures, in determining the optimum combination of these two plant nutrients and in taking into account the high variability in their quality. Such information is useful in formulating decision-support systems and in establishing simple guidelines for management and utilization of the resources. This paper highlights current research results on the management of nitrogen, phosphorus and organic matter and summarizes our findings on farmers' evaluation of soil-fertility restoration technologies. We also discuss new research opportunities in the WASAT.

1. INTRODUCTION

The Sudano-Sahelian zone of West Africa (SSZWA) is home to the world poorest people, 90% of whom live in villages and depend on subsistence agriculture. Per-capita food production has declined significantly over the past three decades. According to FAO, total food production in Sahelian countries grew by an impressive 70% from 1961 to 1996, but lagged behind the population which doubled, causing food production per capita to decline by approximately 30% over the same period [1].

The present farming systems in the Sahel are unsustainable, low in productivity and destructive to the environment. Plant nutrient balances are negative [2]. Increasing needs for cropland have prompted farmers to cultivate more and more marginal lands that are prone to erosion.

In this paper, after a brief description of the crop-production environment, we will present the state of the art of nitrogen (N), phosphorus (P) and organic matter management for sustainable land use in the Sudano-Sahelian zone. Before presenting new opportunities for future research for soil-fertility restoration in this zone, we will discuss the effect of various cropping systems on soil fertility and also the main research achievements of on-farm evaluations of soil-fertility restoration technologies.

Land degradation is one of the most serious threats to food production. Rates of soil loss through erosion are about ten times greater than the rate of natural soil formation while deforestation rate is thirty times greater than that of planned reforestation. Buerkert et al. [3] measured absolute soil loss as 190 t ha^{-1} in one year on bare plots, as opposed to soil deposition of 270 t ha^{-1} on plots with 2 t ha^{-1}

millet-stover mulch. Sterk et al. [4] reported a total loss of 45.9 t ha^{-1} of soil during four consecutive storms. Buerkert et al. [5] reported that in unprotected plots up to 7 kg of available P and 180 kg ha^{-1} of organic carbon (C) were lost from the soil profile within one year. Wind erosion, which also decreases the exchangeable base and increases soil acidification, constitutes one of the major causes of land degradation. Loss of the top-soil, which can contain ten times more nutrients than the sub-soil, is particularly worrying, since it potentially affects crop productivity in the long term by removing the soil that is inherently rich in organic matter.

The data in Table I show physical and chemical properties of soils in the SSZWA. Most of the soils are sandy. One striking feature is inherent poor fertility, expressed in low levels of organic C (generally <0.3%), low total and available P and N and low effective cation exchange capacity (ECEC). The ECEC is attributed to low clay content and the kaolinitic mineralogy of the soils. Bationo and Mokwunye [6] found that the ECEC is more related to the organic matter than to the clay content, indicating that a decrease in organic matter will decrease ECEC and, consequently, nutrient-holding capacity. De Ridder and Van Keulen [7] reported that a difference of 0.1% in organic C content results in a difference of 4.3 cmol kg^{-1} in ECEC.

Soil-nutrient depletion is a major bottleneck to increased land productivity in the region and is a major cause of poverty and food insecurity. Such depletion occurs when nutrient inflows are less than outflows. Nutrient balances are negative for many cropping systems, indicating that farmers are mining their soils. Table II shows aggregated nutrient budgets for some West African countries.

Table I. Physical and chemical properties of selected West African soils, 0–15 cm [3]

Parameter	Mean	SD
pH H_2O (2:1 water:soil)	6.17	0.66
pH KC1 (2:1 KC1:soil)	5.05	0.77
Clay (%)	3.9	2.67
Sand (%)	88	8.0
Organic matter (%)	1.4	1.1
Total N (mg kg^{-1})	446	455
Exchangeable bases (cmol kg^{-1})		
Ca	2.2	3.0
Mg	0.59	0.55
K	0.20	0.22
Na	0.04	0.01
Exchangeable acidity (cmol kg^{-1})	0.24	0.80
Effective cation exchange capacity (ECEC; cmol kg^{-1})	3.4	3.8
Base saturation (%)	88	17

Table II. Nutrient losses for some West African countries [2]

Country	Area (1,000 ha)	Nutrient loss		
		N	P_2O_5	K_2O
		(1,000 tons)		
Benin	2,972	41.4	10.4	32.5
Burkina Faso	6,691	95.4	27.8	78.8
Ghana	4,505	137	32.3	90.5
Mali	8,015	61.7	17.9	66.7
Niger	10,985	176	55.3	147
Nigeria	32,813	111	317	946

Brief but intense rainstorms, frequent in the region, pose special problems in terms of soil conservation [8]. Charreau [9] reported rainfall intensities between 27 to 62 mm h^{-1}. Runoff and soil loss depend on soil type and erodibility, land form and management system [10].

2. MANAGEMENT OF NITROGEN, PHOSPHORUS AND ORGANIC MATTER

2.1. Nitrogen

2.1.1. Introduction

For many years, scientists in the Sudano-Sahelian zones have attempted to

- assess the performance of the various sources of N fertilizers,
- to assess the efficiency of different methods of N placement,
- to calculate ^{15}N balances in order to determine N uptake and losses, and
- to determine efficiency of N under various management systems and the effect of soil and agro-climatic factors on the performance of N fertilizers [11–15].

2.1.2. Nitrogen-fertilizer efficiency as affected by source, method of placement and time of application

Christianson and Vlek [13] used data from long-term experiments in the SSZWA to develop response functions to N for pearl millet and sorghum, and found that the optimum rates are 50 kg N ha^{-1} for sorghum and 30 kg N ha^{-1} for pearl millet. At these rates the returns were 20 kg grain per kg N for sorghum and 9 kg grain per kg N for pearl millet. The use of ^{15}N to calculate N balances and to determine fertilizer-N uptake and loss provides an important tool for N management. The following conclusions may be drawn from early research results with ^{15}N [11]:

- Apparent uptake of fertilizer N exceeds measured uptake using ^{15}N.
- Uptake of ^{15}N-labelled fertilizer and apparent recovery of unlabelled N decreases with increasing rates of application.
- Loss of ^{15}N-labelled fertilizer to the atmosphere and recovery of ^{15}N in the soil increase with increasing rates of fertilizer application.
- Estimated losses of N are high regardless of N source.

Urea and calcium ammonium nitrate (CAN) are the most common sources of N in the region. Trials were undertaken to evaluate them with basal or split application, banded, broadcast or point-placed as urea supergranules (USG) or CAN point-placed. Nitrogen-15 was applied in microplots in order to construct N balances and to determine uptake and losses of N from the different sources, with different methods of application and different timings of application.

The following conclusions can be made from the data in Tables III, IV and V:

- Fertilizer N recovery by plants was very low, averaging 25 to 30% over all years.
- There was higher loss of N with point-placement of urea (USG) (>50%) and the mechanism of N loss is believed to have been ammonia volatilization.
- For all years, losses of N from CAN were less than from urea because half of the N in CAN is in the non-volatile nitrate form.
- Although CAN has a lower N content than urea, it is attractive as an N source because of its low potential for N loss via volatilization, and point-placement will improve its spatial availability.

The data in Fig. 1 clearly indicate that CAN point-placed outperformed urea point-placed or broadcast and similar trials indicate that ^{15}N uptake by plants was almost three times higher from CAN than from urea applied in the same manner (Table V).

Table III. Recovery of ^{15}N in millet plants and soil at harvest, Sadoré, Niger, 1982 [16]

Treatment	Grain yield[a] (kg ha^{-1})	N recovery: Grain (%)	Plant[b] (%)	Soil (%)	Loss (%)
Check	590	–	–	–	–
CAN[c] split band	970	21	37	38	25
Urea split band	1,070	19	31	37	32
Urea split broadcast	1,070	17	31	41	28
Urea basal broadcast	1,010	17	27	42	32
USG[d] basal	960	16	28	39	33
USG split	1,070	14	27	33	40
LSD (0.01)	167	4.6	6.0	6.0	9.8

[a] Averages for all N rates for each source.
[b] Sum of grain and stover ^{15}N.
[c] Calcium ammonium nitrate.
[d] Urea supergranules.

Table IV. Yield and recovery of ^{15}N in millet plants and soil at harvest (1983-85), Sadoré, Niger [16]

Year	Treatment	Grain yield[a] (kg ha^{-1})	Stover yield (kg ha^{-1})	^{15}N recovery: Grain (%)	Plant[b] (%)	Soil (%)	Loss (%)
1983	Check	660	–	–	–	–	–
	CAN[c] split band	940	–	13	29	34	37
	Urea split band	1,040	–	9.8	23	39	38
	USG[d] split	990	–	8.0	22	25	53
	LSD (0.01)	110	–	1.6	3.2	3.4	2.2
1984	Check	460	1,570	–	–	–	–
	CAN split band	480	1,850	9.9	37	37	26
	Urea split band	470	1,930	5.5	20	40	40
	USG split	490	1,780	8.1	22	25	54
	LSD (0.01)	30	220	1.6	3.8	4.2	4.4
1985	Check	900	2,315	–[e]	–	–	–
	CAN split band	1,320	2,910	–	–	–	–
	Urea split band	1,225	3,020	–	–	–	–
	USG split	1,350	3,000	–	–	–	–
	LSD (0.05)	175	386	–	–	–	–

[a] Averages for all N rates for each source.
[b] Sum of grain and stover ^{15}N.
[c] Calcium ammonium nitrate.
[d] Urea supergranules.
[e] Nitrogen-15 was not used in 1985.

2.1.3. Efficiency of N fertilizers as affected by soil and crop management and rainfall

Mughogho et al. [11] found significant relationships between crop yield and N recovery. Nitrogen losses averaged 20% with maize in the humid and sub-humid zones, significantly less than the average loss of 40% found over all treatments in the Sudano-Sahelian zone.

Table V. Recovery ^{15}N fertilizer by millet applied at Sadoré, Niger, 1985 [13]

N source	Application method	^{15}N recovery			
		Grain	Stover	Soil	Total
		(%)			
CAN[a]	Point incorporated	21	17	30	68
CAN	Broadcast incorporated	11	11	43	65
Urea	Point incorporated	5.0	6.5	22	34
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

[a] Calcium ammonium nitrate.

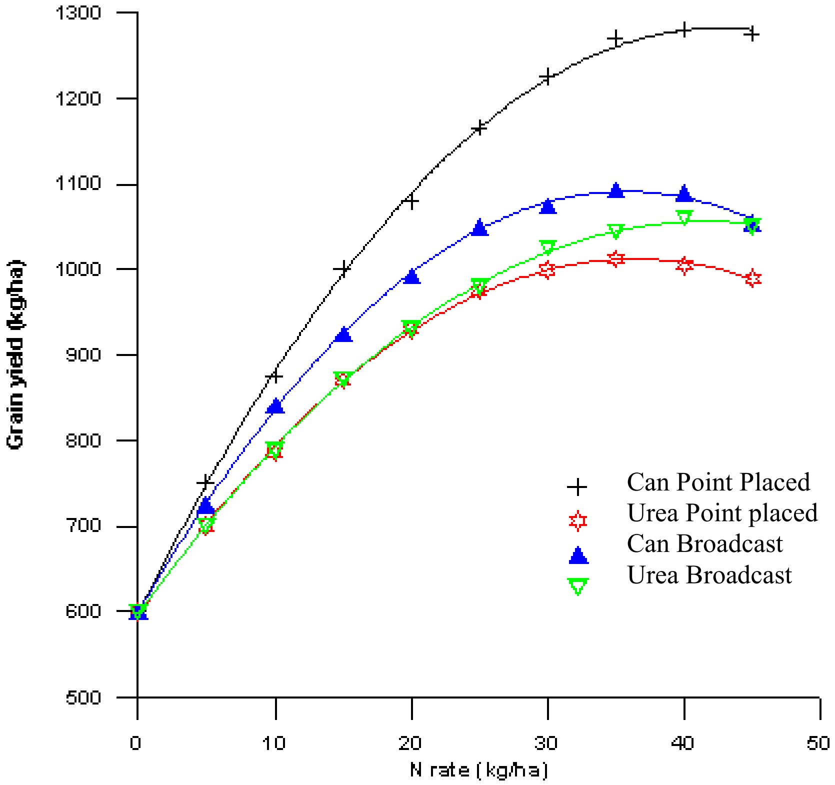

FIG 1. Effects of urea and calcium ammonium nitrate on grain yield, Gobery, Niger, 1985 [13].

In the Sahelian zone, an N-use efficiency value of 14% in plots without lime and P was reported [17], whereas it increased to 28% when lime and P were applied.

Rotation of cereals with legumes could be a way to increase N-use efficiency. Bationo and Vlek [17] reported a value of 20% in the continuous cultivation of pearl millet, whereas it increased to 28% when pearl millet was rotated with cowpea.

Bationo et al. [12] found a strong effect of planting density on response to N fertilizer. Christianson et al. [16] developed a model on the effect of rainfall on N for pearl millet production in the Sahel and found that the response to N was affected by rainfall over a 45-day yield-sensitive period, which coincides with the culm-elongation and anthesis growth stages for millet (Fig. 2).

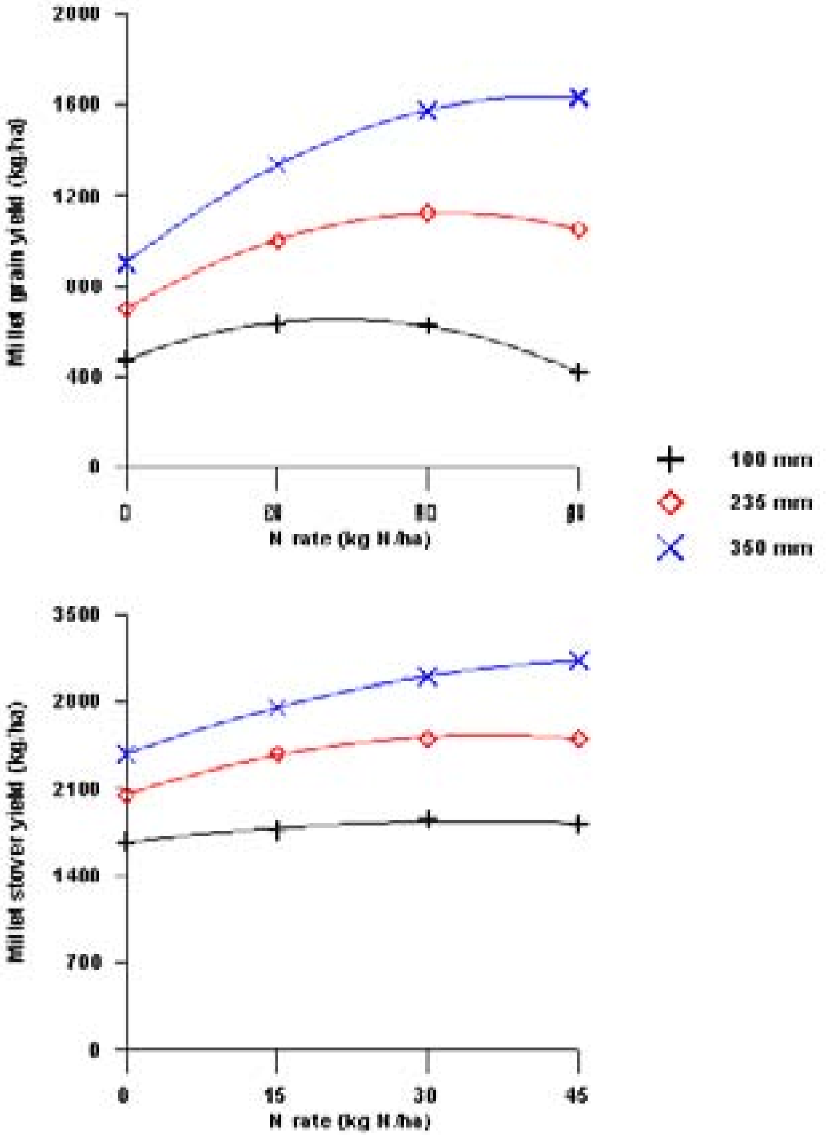

FIG. 2. Grain and stover yields of millet affected by N rate and mid-season rainfall, Sadoré, Niger, 1982–1985 [16].

2.2. Phosphorus sources and management

2.2.1. Introduction

Among soil-fertility factors, phosphorus deficiency is a major constraint to crop production in the Sudano-Sahelian zone. For many years, research has been undertaken to assess extent of soil-P deficiency, to estimate P requirement of major crops, and to evaluate the agronomic potential of various local deposits of phosphate rock (PR) [18–31].

About 80% of the soils in sub-Saharan Africa are deficient in this critical nutrient element and, without application of P, other inputs and technologies are ineffective. However, sub-Saharan Africa uses 1.6 kg P/ha^{-1} of cultivated land as compared to 7.9 and 14.9 kg P/ha^{-1}, respectively, for Latin America and Asia. It is now accepted that the replenishment of soil capital P is not only a crop-production issue but also an environmental issue, and P application is essential for the conservation of the natural resource base.

Availability and total-P levels of soil are very low in the SSZWA as compared to the other soils in West Africa [25,32–34]. For the sandy Sahelian soils, total values can be as low as 40 mg P kg^{-1} and available P can be less than 2 mg P kg^{-1}. A study of the fertility status of selected pearl millet-producing soils of West Africa [35] found that total P ranged from 25 to 340 mg kg^{-1} with a mean of 109 mg kg^{-1}. The low content of both total and available P parameters may be related to several factors including:

— parent materials, mainly composed of eolian sands, contain low mineral reserves and lack primary minerals necessary for nutrient recharge,

— a high proportion of total P in these soils is often in occluded form and is not available for crop uptake [9],

— low level of organic matter and the removal of crop residues from fields.

Organic matter has a favourable effect on P dynamics of the soil; in addition to P release by mineralization, competition with organic ligands for Fe- and Al-oxide surfaces can result in decreased fixation of applied and native P.

The P-sorption characteristics of various soil types have been investigated. Compared to the soils of more humid regions, the soils of the SSZWA have very low P-fixation capacity [25, 36–38]. For pearl millet-producing soils, sorption data were fitted to the Langmuir equation [35] and P-sorption maxima were determined using the method of Fox and Kamprath [39]. From these representative sites in the Sudano-Sahelian zone, the values of maximum P sorbed ranged from 27 mg kg^{-1} to 253 mg kg^{-1} with a mean of 94 mg kg^{-1}.

Phosphorus deficiency is a major constraint to crop production, and response to N is substantial only when neither moisture nor P are limiting. Field trials were established to determine the relative importance of N, P and K fertilizers. The data in Table VI indicate that from 1982 to 1986 the average control plot yielded 190 kg grain ha^{-1}. The sole addition of 30 kg P_2O_5 ha^{-1} without N fertilizer increased the average yield to 714 kg ha^{-1}. The addition of 60 kg N ha^{-1} alone did not increase yield significantly over the control at an average of 283 kg ha^{-1}.

Table VI. Effect of N, P, and K on pearl millet grain and total dry matter at Sadoré and Gobery, Niger

Treatment	1982		1983		1984		1985	1986	
	Sadoré		Sadoré	Gobery	Sadoré		Sadoré	Sadoré	
	Grain	TDM[a]	Grain	Grain	Grain	TDM	Grain	Grain	TDM
	(kg ha^{-1})								
N0P0K0[b]	217	1,595	146	264	173	1,280	180	180	1,300
N0P30K30	849	2,865	608	964	713	2,299	440	710	2,300
N30P30K30	1,119	3,597	906	1,211	892	3,071	720	930	3,000
N60P30K30	1,155	3,278	758	1,224	838	3,159	900	880	3,200
N90P30K30	1,244	3,731	980	1,323	859	3,423	1,320	900	3,400
N120P30K30	1,147	4,184	1,069	1,364	1,059	3,293	1,400	1,000	3,300
N60P0K30	274	2,372	262	366	279	1,434	290	230	1,500
N60P15K30	816	2,639	614	1,100	918	3,089	710	920	3,100
N60P45K30	1,135	3,719	1,073	1,568	991	3,481	1,200	980	3,500
N60P30K0	1,010	3,213	908	1,281	923	3,377	920	910	3,400
S.E.	107	349	120	232	140	320	162	250	400
CV(%)	24	22	26	30	24	22	28	32	25

[a] Total dry matter.

[b] Amounts applied as N, P_2O_5 and K_2O kg ha^{-1}.

These data clearly indicate that P is the most limiting factor in those sandy Sahelian soils and there is no significant response to N without correcting first for P deficiency. When P is applied, the response to N can be substantial and with the application of 120 kg N ha^{-1} a pearl millet grain yield of 1,173 kg ha^{-1} was obtained as compared to 714 kg ha^{-1} with P alone. Additions of K did not significantly increase yield of either grain or total dry matter of pearl millet.

2.2.2. The use of alternative locally available phosphate rock

Despite the fact that deficiency of P is acute in the soils of West Africa, very little P is applied by local farmers, partially because of the high cost of imported fertilizers. The use of locally available phosphate rock (PR) indigenous to the region offers a less-expensive alternative. The effectiveness of (PR) depends on its chemical and mineralogical composition [40–42]. The most important feature of the empirical formula of francolite is the ability of carbonate ions to substitute for phosphate in the apatite lattice. Smith and Lehr [43] concluded from their studies that the level of isomorphic substitution of carbonate for phosphate within the lattice of the apatite crystal influences the solubility of the apatite in the rock and, therefore, controls the amount of P that is released when PR is applied to soil. The most reactive PRs are those having a molar PO_4/CO_3 ratio of less than 5.

West African PRs are not very reactive. Chien [44] found that the solubility of PR in neutral ammonium citrate (NAC) was directly related to the level of carbonate substitution. Diamond [45] proposed a classification of PRs for direct application based on citrate solubility: >5.4% high; 3.2–4.5% medium and <2.7% low. Based on this classification, only Tilemsi PR has a medium reactivity.

For certain crops and soils, Bationo et al. [21] have shown that direct application of PR indigenous to the region may be an economical alternative to the use of more expensive imported water-soluble P fertilizers. While evaluating Parc-W and Tahoua PRs indigenous to Niger, Bationo et al. [21] found that PR was only 48% as effective as single superphosphate (SSP), whereas the effectiveness of the more reactive Tahoua rock was as high as 76% of SSP. Further studies [22] showed that Tahoua PR was suitable for direct application, but Parc-W had less potential for direct application.

The data from a long-term benchmark experiment showed that SSP outperformed other sources and its superiority to sulphur-free triple superphosphate (TSP) indicated that with continuous cultivation, sulphur deficiency would develop. For both pearl millet grain and total dry matter yields, relative agronomic effectiveness was similar for TSP and partially acidulated Parc-W phosphate, indicating that 50% acidification of Parc-W PR can significantly increase its effectiveness [1].

2.2.3. Phosphorus placement and replenishment with phosphate rock

The data in Table VII clearly shows that hill-placement of a small quantity of P fertilizer had a higher P-use efficiency (PUE) as compared to broadcasting 13 kg P ha^{-1} as recommended by the extension services.

Single superphosphate, Tahoua phosphate rock (TPR) and Kodjari phosphate rock (PRK) were broadcast (BC) and/or hill-placed (HP). For pearl millet, grain PUE for broadcasting SSP at 13 kg P ha^{-1} was 18 kg kg^{-1} P, but hill-placement of SSP at 4 kg P ha^{-1} gave a PUE of 83 kg kg^{-1} P. Whereas the PUE of TPR broadcast was 16 kg grain kg^{-1} P, the value increased to 34 kg kg^{-1} P when additional SSP was hill-placed at 4 kg P ha^{-1}. For cowpea fodder, PUE for broadcast SSP was 96 kg kg^{-1}P and the hill placement of 4 kg P ha^{-1} gave a PUE of 461 kg kg^{-1} P. These data clearly indicate that P placement can greatly increase PUE and the placement of small quantities of water-soluble P fertilizer can also improve the effectiveness of PR (Table VII).

Table VII. Effect of P source and placement on pearl millet and cowpea yield and P-use efficiency (PUE)

P source (placement)	2001				2002			
	Millet		Cowpea		Millet		Cowpea	
	Grain yield (kg ha^{-1})	PUE[a] (kg kg^{-1} P)	Fodder (kg ha^{-1})	PUE (kg kg^{-1} P)	Grain yield (kg ha^{-1})	PUE (kg kg^{-1} P)	Fodder (kg ha^{-1})	PUE (kg kg^{-1} P)
1 Control	468		1,406		634		1,688	
2 SSP[b] (BC)[c]	704	18	2,656	96	887	19	2,375	134
3 SSP (BC) + SSP (HP)[d]	979	30	4,468	180	1,898	74	3,125	147
4 SSP (HP)	798	83	3,250	461	1,026	98	2,969	584
5 15-15-15 (BC)	958	38	4,250	219	1,110	37	3,813	245
6 15-15-15 (BC) + 15-15-15 (HP)	1,559	64	6,500	300	2,781	126	5,156	266
7 15-15-15 (HP)	881	103	4,062	664	1,196	141	3,531	724
8 TPR[e] (BC)	680	16	2,531	86	744	8	2,094	112
9 TPR (BC) + SSP (HP)	1,048	34	3,781	140	1,039	24	3,375	161
10 TPR (BC) + 15-15-15 (HP)	1,065	35	4,281	169	1,242	36	3,844	189
11 PRK[f] (BC)	743	21	2,468	82	745	9	2,469	141
12 PRK (BC) + SSP (HP)	947	28	4,750	197	1,002	22	3,219	152
13 PRK (BC) + 15-15-15 (HP)	1,024	33	5,125	219	1,171	32	3,688	180
SE	46		120		60		222	
CV	18%		11%		10%		14%	

[a] P use efficiency, kg yield kg^{-1} P applied.

[b] Single superphosphate,15-15-15, N_2 P_2O_5 K_2O compound fertilizer.

[c] Broadcast at 13 kg P ha^{-1}.

[d] Hill-placed at 4 kg P ha^{-1}.

[e] Tilemsi phosphate rock.

[f] Kodjari phosphate rock.

In long-term soil-management trials, application of N, crop residue and ridging, and rotation of pearl millet with cowpea were evaluated to determine their effects on PUE. The results show that productivity of sandy soils can be dramatically increased with the adoption of improved crop- and soil-management technologies, whereas the absolute control recorded 33 kg ha^{-1} of pearl millet grains, 1,829 kg ha^{-1} were obtained when P, N and crop residues were applied to the ridged and fallowed leguminous cowpea in the the previous season. Results indicate for the grain yield that PUE increased from 46 with P alone to 133 when P was applied in combination with N, crop residue and the crop was ridge-planted in a rotation system (Table VIII).

2.3. Organic matter management

2.3.1. Introduction

Maintaining soil organic matter is a key to sustainable land-use management. Organic matter acts as source and sink for plant nutrients. Other important benefits resulting from the maintenance of organic matter include retention and storage of nutrients, increasing buffering capacity in low-activity clay soils, and increased water-holding capacity.

Table VIII. Effect of mineral fertilizers, crop residue and crop rotation on pearl millet yield and P-use efficiency, Sadoré, Niger, 1998 rainy season

Treatment	– CR[a] –N				– CR +N			
	TDM[b] yield	PUE[c]	Grain yield	PUE	TDM yield	PUE	Grain yield	PUE
Control	889		33		2,037		58	
13 kg P ha^{-1}	2,704	140	633	46	4,339	177	1,030	75
13 kg P ha^{-1} + ridge	2,675	137	448	32	4,057	155	946	68
13 kg P ha^{-1} + rotation	5,306	340	1,255	94	6,294	327	1,441	106
13 kg Pha^{-1} + ridge + rotation	5,223	333	1,391	104	5,818	291	1,581	117
SE	407		407		407		407	

Treatment	+ CR –N				+ CR +N			
	TDM yield	PUE	Grain yield	PUE	TDM yield	PUE	Grain yield	PUE
Control	995		61		1,471		98	
13 kg P ha^{-1}	4,404	185	726	51	4,594	240	1,212	86
13 kg P ha^{-1} + ridge	3,685	210	785	56	4,530	235	1,146	81
13 kg P ha^{-1} + rotation	5,392	338	1,475	109	6,124	358	1,675	121
13 kg P ha^{-1} + ridge + rotation	6,249	404	1,702	126	7,551	468	1,829	133
SE	407		407		407		407	

[a] Crop residue.

[b] Total dry matter (kg ha$^{-1)}$.

[c] P-use efficiency (kg grain kg^{-1} P).

In 1960, Nye and Greenland estimated that the annual increase in N under forest fallow was 30 kg ha^{-1} in the soil and 60 kg N ha^{-1} in the vegetation. For the savannah ecosystems, the annual increase was 10 kg N ha^{-1} in the soil and 25 kg N ha^{-1} in the vegetation.

Bationo et al. [49] reported that continuous cultivation in the Sahelian zone has led to drastic reductions in organic matter and subsequent soil acidification. Bationo and Mokwunye [6] reported that, in the Sudano-Sahelian zone, the ECEC is more related to organic matter than to clay, indicating that a decrease in organic matter will decrease the ECEC and. subsequently. the nutrient-holding capacity.

A study to quantify the effects of changes in organic C on cation exchange capacity (CEC) [7] found that a difference of 1 g kg^{-1} in organic C resulted in a difference of 4.3 mol kg^{-1}. In many cropping systems, few if any agricultural residues are returned to the soil. This leads to decline in organic matter, which frequently results in lower crop yields.

The concentration (mg kg^{-1}) of organic C in the topsoil is reported to average 12 for the forest zone, 7 for the Guinean zone, 4 in the Sudanian zone and 2 for the Sahelian zone. The soils of the Sudano-Sahelian zone are inherently low in organic C due to low root growth of crops and natural vegetation and rapid turnover of organic materials at high soil temperature by microfauna, particularly termites. A survey of millet-producing soils, [35] found an average soil organic C content of 7.6 g kg^{-1} with a range of 0.8 to 29.4 g kg^{-1}. The data also showed that organic C content was highly correlated with total N (R = 0.97), indicating that, in the predominant agro-pastoral systems without application of mineral-N fertilizers, N nutrition of crops largely depend on the maintenance of soil organic C.

2.3.2. Effect of soil management practices on organic C content

There is much evidence for rapid decline in soil organic C levels with continuous cultivation of crops in the SSZWA [49]. For these sandy soils, average annual losses in C often expressed by the K-value (calculated as the percentage of organic C loss per year), may be as higher as 4.7%, whereas for sandy loam soils, reported losses seem much lower, with an average of 2% (1989, Table IX).

The data in Table IX also clearly indicate that soil erosion can increase organic C losses from 2% to 6.3% and management practices such as crop rotation, following soil tillage, application of mineral fertilizers and mulching have significant effect on annual losses of C. The K-value in cotton-cereal rotations was 2.8%, lower than the 2.8%, lower than the 2.8% in continuous cotton system. At Nioro-du-Rip in Senegal, soil tillage increased annual losses of organic C from 3.8 to 5.2% and NPK application decreased losses from 5.2 to 3.9%.

Table IX. Annual loss rates of soil organic C measured at selected research stations in the SSWA

Country & location	Dominant cultural succession	Observations	Years[a]	Clay+silt (0–0.2 m) (%)	Annual loss rate (k) (%)
Burkina Faso		With tillage			
Saria, INERA-IRAT	Sorghum monoculture	No fertilizer	10	12	1.5
		Lo fertilizer	10	12	1.9
		Hi fertilizer	10	12	2.6
		Crop residue	10	12	2.2
CFJA, INERA-IRCT	Cotton–cereals	Eroded watershed	15	19	6.3
Senegal		With tillage			
Bambey, ISRA-IRAT	Millet–groundnut	No fertilizer	5	3	7.0
		With fertilizer	5	3	4.3
		Fertilizer + straw	5	3	6.0
Bambey, ISRA-IRAT	Millet monoculture	PK fertilizer + tillage	3	4	4.6
Nioro-du-Rip, IRAT-ISRA	Cereal–legume	F0T0[b]	17	11	3.8
		F0T2[c]	17	11	5.2
		F2T0[d]	17	11	3.2
		F2T2[e]	17	11	3.9
		F1T1[f]	17	11	4.7
Chad		With tillage			
Bebedjia, IRCT-IRA	Cotton monoculture	High-fertility soil	20	11	2.8
	Cotton–cereals		20		2.4
	+ 2 years fallow		20		1.2
	+ 4 years fallow		20		0.5

[a] Number of years of measurement.

[b] No fertilizer, no manual tillage.

[c] No fertilizer with heavy tillage.

[d] 400 kg ha^{-1} of NPK fertilizer + Taiba phosphate rock, no manual tillage.

[e] 400 kg ha^{-1} of NPK fertilizer + Taiba phosphate rock with heavy tillage.

[f] 200 kg ha^{-1} of NPK fertilizer with light tillage.

2.3.3. Effects of crop residues and manure on soil productivity

In long-term crop-residue and management trials in the Sahelian zone, a very significant interaction between crop residue and mineral fertilizer was observed [50]. In these experiments, which were started in 1984 [51], grain yield declined to 160 kg ha^{-1} in unmulched and unfertilized plots. However, grain yields were increased to 770 kg ha^{-1} with a crop-residue mulch of 2 t ha^{-1} and to 1,030 kg ha^{-1} with 13 kg P plus 30 kg N ha^{-1}. The combination of crop residue and mineral fertilizers resulted in a grain yield of 1,940 kg ha^{-1}. The application of 4 t of crop residue per hectare maintained topsoil organic C at the same level as that in an adjacent fallow field, whereas continuous cultivation without mulching resulted in drastic loss of C (Fig. 3). In the Sudanian zone, available reports show much smaller or even negative effects of crop residue used as soil amendment [49]. In the Sahelian zone, application of crop residue increased soil pH and exchangeable bases and decreased the capacity of the soil to fix P.

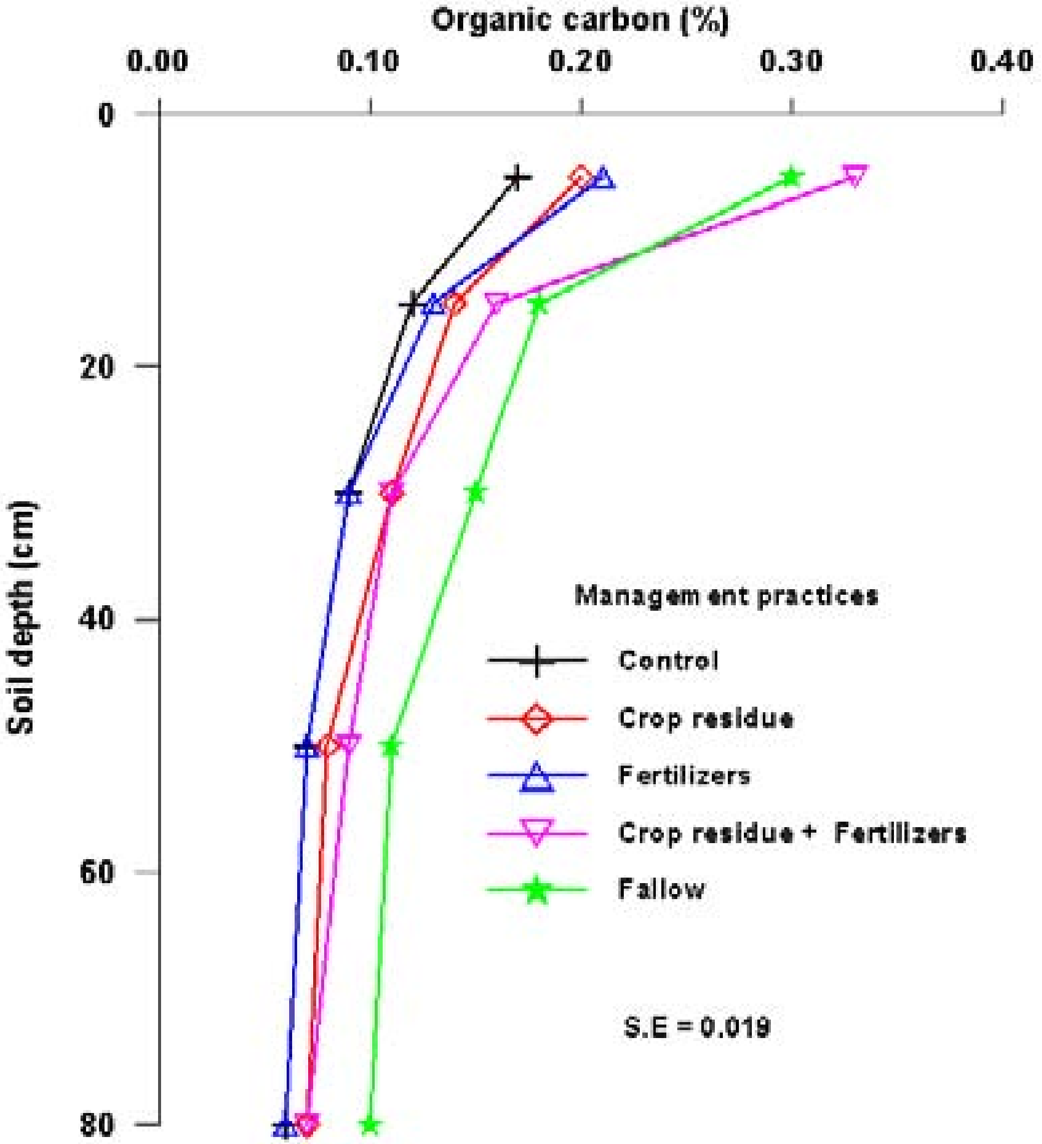

FIG 3. Effect of management practice on soil organic C content after fourteen years of cultivation, Sadoré, rainy season, 1997.

On nutrient-poor West African soils, manure can substantially enhance crop yields. In Niger, McIntire et al. (1992) reported grain yield increases of 15 to 86 kg for millet and between 14 and 27 kg for groundnut per ton of applied manure. Similar effects of manure application have been reported in other Sahelian countries. However, given the large variation in nutrient concentration according to manure source, comparisons of results of different experiments should be made with caution. Powell [52] found very significant effects of manure and urine application to pearl millet in the Sahelian zone.

At the farm level, the maintenance of organic C in the soils of the region will largely depend on increased fixation of C by plants. Given the strong limitation of plant growth by low availability of mineral nutrients, yield-effective applications of mineral fertilizers are crucial. It would not only allow large increases in crop production and amounts of by-products, but also would improve soil coverage by forage grass and weeds.

2.3.4. Placement of manure

The placement of manure affects the yield achieved. For instance, a complete factorial experiment was carried out in Niger, West Africa, with three levels of manure (0, 3, 6 t ha^{-1}) and three level of P (0, 6.5 and 13 kg P ha^{-1}) using two methods of application (broadcast and hill-placement). For pearl millet, hill-placement of manure performed better than broadcasting, and with no application of P fertilizer, broadcasting 3 t ha^{-1} of manure resulted in a pearl millet grain yield of 700 kg ha^{-1} whereas point-placement of the same quantity of manure gave about 1,000 kg ha^{-1} (Fig. 4). Similar effects were observed with cowpea.

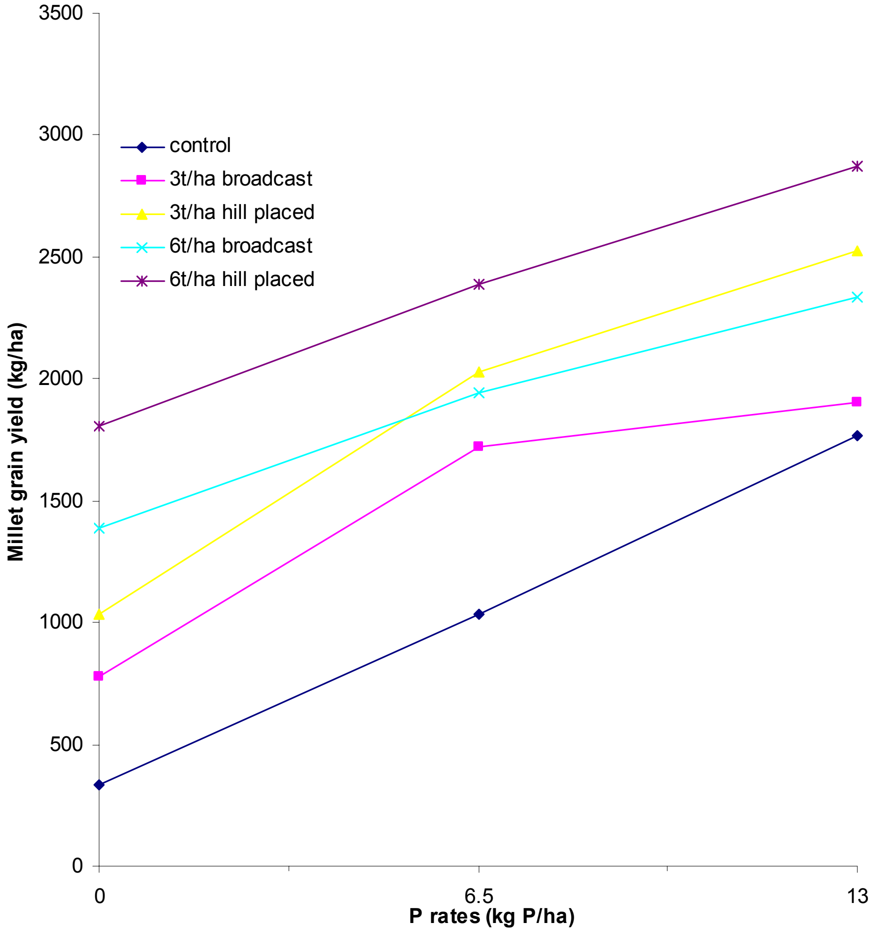

FIG. 4. Millet grain yield response to P and manure at different rates and methods, Karabedji, Niger, 2002 rainy season.

Table X. Optimum combination of plant nutrients for cowpea fodder yields in the Sahel

Treatment	2001	2002
	(kg ha^{-1})	
Absolute control	1,875	2,406
30 kg N ha^{-1}	2,531	2,625
12 kg P ha^{-1}	3,781	3,281
8 t manure + 30 kg N ha^{-1}	5,718	3,531
6 t manure + 3 kg P + 30 kg N	4,843	4,625
4 t manure + 6 kg P + 30 kg N	4,656	3,625
2 t manure + 8 kg P + 30 kg N	4,281	3,375
12 kg P + 30 kg N	5,000	3,156
SE	204	200
CV	14%	12%

2.4. Combining organic and inorganic plant nutrients

Combined application of organic resources and mineral inputs forms the technical backbone of the integrated soil fertility management approach. The data in Table X clearly indicate the comparative advantage of combining organic and inorganic plant nutrients for soils in the Sahel. Combination of both organic and inorganic P and N sources achieved more yield as compared to inorganic sources alone. Successive levels of manure from 2 to 8 t ha^{-1}, with reduction in inorganic P applied, resulted in yields of up to 5,700 kg ha^{-1}.

In Mali, low-quality manures derived from livestock fed predominantly with rice residues were used in combination with urea at 0, 30, 60, 90 and 120 kg ha^{-1}. The research showed that application of 90 to 120 kg N gave the highest paddy yield (approx 7.5 t ha^{-1}) double that of the control. Integration with manure did not significantly increase the rice yields at any N level; rather there was a slight additive effect of the low-quality material.

In Burkina Faso, low-quality manure (<1.0% N) applied at 1, 2, 3 and 4 t dm ha^{-1} was combined with urea at 0, 40, 80 and 120 kg N ha^{-1}. Applications of N alone doubled rice grain yield over the unfertilized control. There were additive effects of all levels of manure organic matter with inorganic-N, however the increases were not significant.

At Zaria, Nigeria, typical farm-produced low-quality manure was applied at 1, 2, 3 and 4 t dm ha^{-1} and combined with 0, 30, 60 and 90 kg N ha^{-1} in a split-plot arrangement with N as the main plots and manure as the sub-plots. Additive effects of manure and fertilizer combinations were not significant indicating that these manures contributed little to the N demand of maize. However, low-quality manures can contribute significantly to overcoming P deficiency in maize (Fig. 5).

2.4.1. Interactions of nitrogen, phosphorus and manure.

A factorial experiment of manure (0, 2 and 4 t ha^{-1}), N (0, 30 and 60 kg ha^{-1}) and P (0, 6.5 and 13 kg ha^{-1}) established in Banizoumbou to assess the fertilizer equivalency of manure for N and P showed very significant effects of N, P and manure on pearl millet yield (Table XI). Whereas P alone accounted for 60% of the total variation, N accounted for less than 5%, indicating that P was the more strongly limiting factor. Manure accounted for 8% of the total variation.

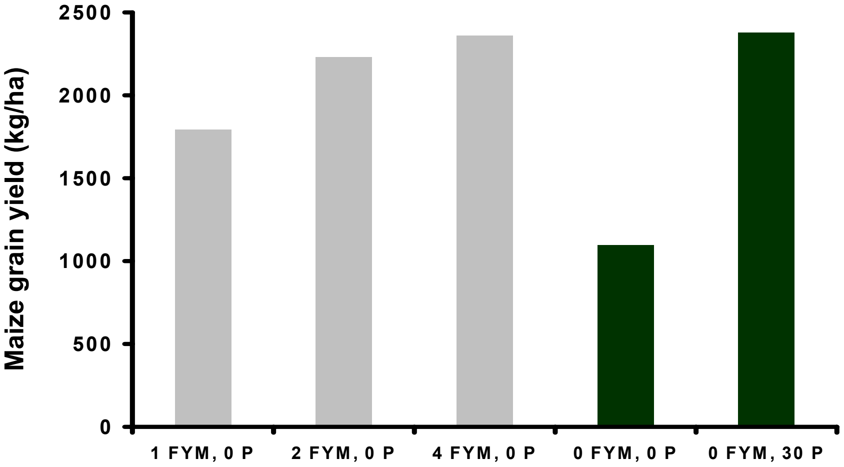

FIG. 5. Use of low-quality manure (<1% N) to alleviate P-deficiency in maize in Zaria, Nigeria, 2001.

Table XI. Fertilizer equivalency of manure at Banizoumbou, Niger, in 2001 and 2002

Parameter	2001		2002	
	Grain	TDM[a]	Grain	TDM
	(kg ha^{-1})			
Absolute control	290	1,275	338	1,238
Control for N	1,210	4,550	1,008	3,895
Control for P	635	2,280	916	3,545
% N in manure	0.71	0.71	1.6	1.6
% P in manure	0.18	0.18	0.32	0.32
Yield at 2t ha^{-1} of manure without N	1,530	5,450	1,167	4,746
Yield at 4t ha^{-1} of manure without N	1,695	4,855	1,609	5,640
Yield at 2t ha^{-1} of manure without P	810	2,910	1,229	4,659
Yield at 4t ha^{-1} of manure without P	1,070	3,625	1,411	5,294
Equivalent N for 2 t ha^{-1} of manure	42	39	8.0	13
Equivalent N for 4 t ha^{-1} of manure	—[a]	21	49	33
Equivalent P for 2 t ha^{-1} of manure	3.0	2.7	8.7	7.2
Equivalent P for 4 t ha^{-1} of manure	7.5	5.57	11.8	9.6
N fertilizer equivalency at 2 t ha^{-1} of manure	292	273	25	41
N fertilizer equivalency at 4 t ha^{-1} of manure	—	74	77	52
P fertilizer equivalency at 2 t ha^{-1} of manure	83	75	136	113
P fertilizer equivalency at 4 t ha^{-1} of manure	104	77	92	75

[a]Total dry matter. [b]Data missing.

Grain production with manure and no P was lower than with manure and no N (Table XI), indicating the importance of P at this site. Addition of both manure and N fertilizer increased the yields; however, using equivalent N for 2 t ha^{-1} of manure had an even greater effect.

Superior results following combinations of crop residues and inorganic fertilizer were reported from a long-term soil-fertility management experiment established at the Sahelian Center of the International Centre for Research in the Semi-Arid Tropics (ICRISAT) in 1986. The objective was to study the sustainability of pearl-millet-based cropping systems in relation to management of N, P, and crop residue, rotation with cowpea and soil tillage (Table XII). In this split-split-plot design, the sub-sub-plot consisted of crop residue application (half of the total residue produced left on the plot) or no residue application and the sub plot was with or without N application.

Table XII. Effect of fertilizer, crop residue, tillage and rotation on cowpea and millet yield, Sadoré, Niger 1998–2002

Treatment	– CR[a] –N				– CR +N			
	MG[b]	I.MT[c]	CG[d]	CF[e]	MG	II.MT	CG	CF
	(kg ha^{-1})							
Traditional practices	118	822	40	256	177	1,207	50	348
AT[f] +no rotation+intercropping + P	463	2,248	54	235	567	2,556	50	263
AT + rotation+intercropping + P	777	3,591	68	431	923	4,011	96	542
			94[g]	*490*			*99*	*539*
HC[h] +no rotation+intercropping + P	389	1,971	48	326	596	2,618	68	536
HC + rotation+intercropping + P	769	3,578	72	199	868	4,139	86	235
			132	*744*			*122*	*883*
AT +no rotation +pure millet + P	484	2,110			646	2,751		
AT + rotation + pure millet + P	802	3,427	90	352	957	4,108	66	440
HC +no rotation + pure millet + P	526	2,219			785	3,028		
HC + rotation + pure millet + P	818	3,524	156	1,044	1,030	4,139	138	1,269
SE	43	149	12	83	43	149	12	83
CV	27%	21%	69%	66%	27%	21%	69%	66%

Treatment	+CR–N				+CR+N			
	MG	III. MT	CG	CF	MG	IV. MT	CG	CF
	(kg ha^{-1})							
Traditional practices	197	1,141	51	416	295	1,467	43	427
AT +no rotation +Intercropping + P	596	2,766	52	247	736	3,410	59	278
AT + rotation + intercropping + P	939	4,117	106	602	1,107	4,788	111	713
			115	*720*			*120*	*871*
HC +no rotation +Intercropping + P	627	2,920	43	392	768	3,498	66	659
HC + rotation +intercropping + P	981	4,430	49	234	1,104	5,044	54	262
			150	*1,084*			*153*	*1,314*
AT +no rotation +pure millet + P	626	2,669			846	3,520		
AT + rotation + pure millet + P	1,033	4,348	84	420	1,141	5,155	87	673
HC +no rotation + pure millet + P	708	2,875			1,065	3,835		
HC + rotation + pure millet + P	1,135	4,305	120	1,001	1,301	4,929	126	1,216
SE	43	149	12	83	43	149	12	83
CV	27%	21%	69%	66%	27%	21%	69%	66%

[a] Crop residue. [b] Maize grain. [c] Maize stover. [d] Cowpea grain. [e] Cowpea fodder. [f] Animal traction. [g] Italics are sole cowpea yields in rotation. [h] Hand cultivation

2.5. Cropping systems and fertility management

2.5.1. Intercropping

Fussell and Serafini [53] reported yield advantages from 10 to 100% by intercropping millet with cowpea. Yield stability has been proposed as a major advantage of intercropping; farmers want management practices that increase yields, when possible, without jeopardizing stability of production in both good- and poor-rainfall years. Relative stability of intercropping and cropping using stability analysis have been compared [54,55]; with groundnut/cereal systems in northern Nigeria, intercropping systems were more stable. Ntare [56] reported yield advantages of 20 to 70%, depending on the combination of pearl millet and cowpea cultivars.

Although traditional intercropping covers over 75% of the cultivated area in the SSZWA, there is a scarcity of information on the efficiency of fertilizers under these systems. The number of days before planting the second crop will depend on the importance of the next rains after the first cereal crop has been planted. With a basal application of P fertilizer, the cereal growth is rapid and can suppress completely the second crop if its planting occurs more than 3 weeks later. In contrast, if the legume crop is planted early, it will compete more for light, water and nutrients and may significantly reduce the yield of the cereal.

2.5.2. Relay and sequential cropping

In the Sudanian zone with a longer growing season and higher rainfall, there is greater opportunity than in the Sahelian zone to manipulate systems with respect to genotype and management. Field trials to examine performance of cultivars under relay and sequential systems revealed their potential over traditional sole or mixed cropping [57, 58].

In Mali, by introducing short-season cultivars of sorghum in relay cropping with short-duration cowpea and groundnut cultivars, substantially increased yields of legume and cereal were obtained as compared to traditional systems [59].

In the Sahelian zone, analysis of data on the onset and ending of the rains and the length of the growing period indicated that early rains offer the probability of a longer growing period while delayed onset may result in a considerably shorter growing season. Even in the Sahel, relay cropping can increase soil productivity with early onset of the rains.

2.5.3. Crop rotation

Despite the recognized need for chemical fertilizers for high yields, their use in West Africa is limited by lack of capital, inefficient distribution infrastructure, poor enabling policies and other socio-economic factors. Cheaper means of improving soil fertility and productivity are necessary.

Nitrogen-15 has been used to quantify the amounts of N biologically fixed by cowpea and groundnut under various soil-fertility levels. The N derived from the air (NDFA) varies from 65 to 88% for cowpea and from 20 to 75% for groundnut. In a complete treatment, with all nutrients applied, cowpea stover fixed up to 89 kg N ha^{-1} whereas groundnut fixed only 40 kg N ha^{-1} in the Sahel. In order to determine N recovery from various cropping systems, ^{15}N-labelled fertilizers were applied to microplots of pearl millet grown continuously, in rotation with cowpea, in rotation with groundnut, intercropped with cowpea, and intercropped with groundnut. The data indicated that N-use efficiency increased from 20% in continuous pearl millet cultivation to 28% when pearl millet was rotated with cowpea [17]. The same authors reported that in the Sudanian zone, N derived from the soil increased from 39 kg N ha^{-1} in continuous pearl-millet cultivation to 62 kg N ha^{-1} when pearl millet was rotated with groundnut. These data indicate that although all the above-ground biomass of the legume will be used to feed livestock and not returned to the soil, rotation will increase not only the yield of a succeeding cereal crop but also its N-use efficiency.

Cropping system significantly affects soil organic C. The soil organic C level averaged 0.22% in continuous system whereas it increased to 0.27% in rotation systems. As a result of this, soil pH was higher in the rotation systems as compared to continuous monoculture.

An on-going experiment in the Sahel region involving a combination of rotation, inorganic and organic nutrient sources has clearly indicated the high potential to increase the staple pearl millet yields in very poor Sahelian soils (Table XIII)

Table XIII. Effects of fertilizers, soil tillage, crop residue and cropping system on pearl-millet grain yield; Sadoré 2001–2002

Treatment	2001								2002							
	–Rotation				+Rotation				–Rotation				+Rotation			
	– CR[a]		+CR		– CR		+CR		– CR		+CR		– CR		+CR	
	–N	+N	–N	+N	–N	+N	–N	+N	–N	+N	–N	+N	–N	+N	–N	+N
	(kg ha^{-1})															
Traditional	146	181	331	473					104	104	156	183				
P + HC[b]	873	1,145	1,247	1,649	703	1,067	1,649	1,866	244	337	438	594	583	667	724	807
P + AT[c]	708	816	935	1,114	904	1,225	1,381	1,529	280	355	456	574	586	788	781	903

[a] Crop residue.

[b] Hand cultivation, planting on flat.

[c] Animal traction, planting on ridges.

3. SOIL-FERTILITY RESTORATION TECHNOLOGIES

3.1. Farmer-managed trials

Research results have indicated a very attractive technology consisting of hill-placement of small quantities of P fertilizers. With diammonium phosphate (DAP), containing 46% P_2O_5 and a compound NPK fertilizer (15-15-15) containing only 15% P_2O_5, fields trials were carried out by farmers to compare the economic advantage of the two sources of P for millet production. As hill-placement can result in soil-P mining, a treatment was added consisting of application of PR at 13 kg P ha^{-1} plus hill-placement of 4 kg P ha^{-1} as NPK compound fertilizer.

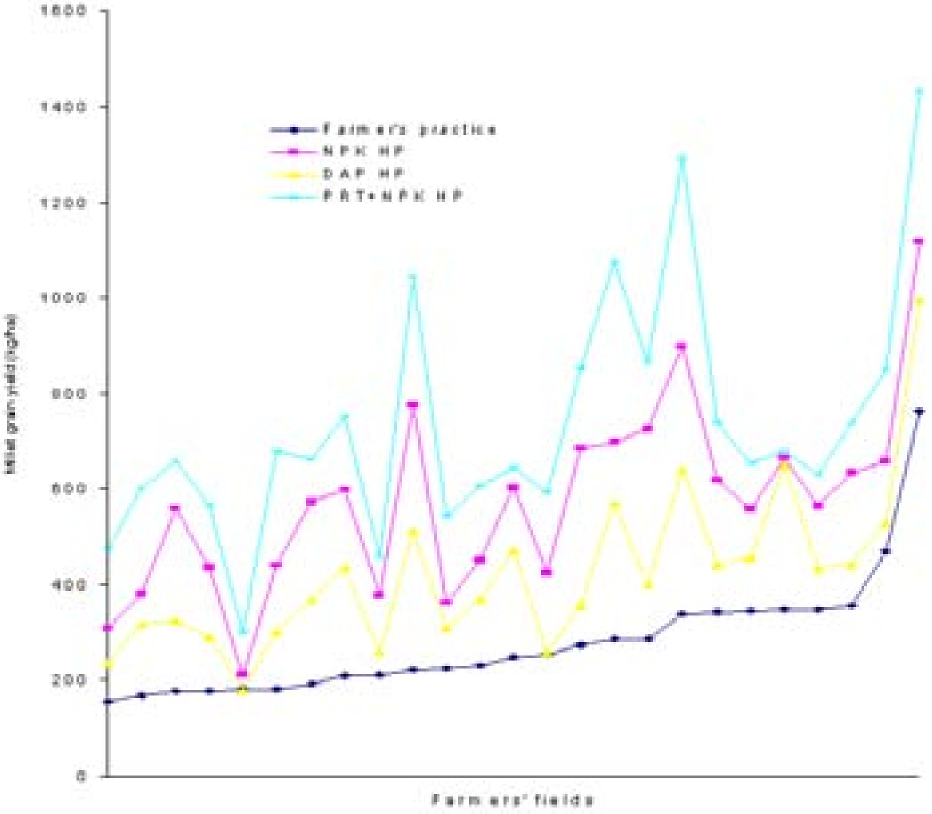

FIG. 6. Millet-grain response to four management practices, Gaya, Niger, 2002 rainy season.

There was no difference between hill placement of DAP and 15-15-15 indicating that with the low cost per unit of P associated with DAP, this source of fertilizer should be recommended to farmers. The basal application of Tahoua PR gave an additional 300 kg/ha of pearl millet grain (Fig. 6). The combination of hill-placement of water-soluble P fertilizer with PR seems a very attractive option for the resource-poor farmers in this region. Similar results were been found previously [60, 61]

4. NEW RESEARCH OPPORTUNITIES

4.1. Strategies for integrated nutrient management

In the past, integrated nutrient management concentrated mainly on judicious and efficient utilization of available organic and inorganic sources of plant nutrients. Integrated nutrient management is now perceived much more broadly as the judicious manipulation of all soil nutrient inputs and outputs and internal flows.

Future research needs to adopt this new holistic approach to integrated nutrient management. For a given cropping system or watershed, this will require the establishment of nutrient balances. Interventions to limit nutrient losses through erosion can, in some cases, be as important as research on increasing the efficiency of use of organic and inorganic plant nutrients for sustainable land use. This new approach will enhance more C sequestration and increase biomass production for on-farm use and more biomass will be available as livestock feed and mulch.

4.2. Integration of socio-economic and policy research

In the past, several technical solutions to the problem of land degradation in the SSZWA have been researched and tested, and have shown potential for addressing the problem in some places. Unfortunately a review of the state of the art indicated that very few of these technologies have been adopted by the resource-poor farmers. Therefore, future research should focus more on problems driven by socio-economic factors and on enabling policy environments in order to enhance farmers' capacity to invest in soil-fertility restoration. Adoption of the participatory approach will be essential. In this way, technologies generated have a better chance of adoption by land users.

4.3. Combining rain-water and nutrient-management strategies

In the SSZWA. high inter-annual variability and erratic rainfall distribution in space and time result in water-limiting conditions during the cropping season. In areas with inadequate rainfall or in runoff-susceptible land, water-conservation techniques and -harvesting techniques offer the potential to secure agricultural production and reduce the financial risks associated with the use of purchased fertilizers. With adequate water supply, the addition of organic and inorganic amendments is the single most effective means of increasing water-use efficiency. Future research needs to focus on enhancing rainwater- and nutrient-use efficiencies and on capitalizing on their synergies for increasing crop production and preventing soil degradation.

4.4. Increasing the legume component for better integration with livestock production

Rotations of cereals with legumes have led to increased cereal yields at many locations in the SSZWA. Factors such as mineral-N increase, enhancement of infection with vesicular-arbuscular mycorrhiza (VAM) for better P nutrition and decrease in parasitic nematodes have been identified as mechanisms of yield enhancement in cereals in rotation with legumes. Most of the research has focused on the quantification of above-ground N fixed by different legumes cultivars, but very little is known of the amounts of N fixed that remain below ground.

There is need to increase the legume component in mixed cropping systems for better integration of crops and livestock. The increase of the legume component in the present cropping system will not only improve the soil conditions for the succeeding cereal crop, but will provide good quality livestock feed, and the manure produced will be of better quality for soil amendment.

4.5. Exploiting genetic variation for nutrient-use efficiency

Phosphorus is the most limiting nutrient for crop production in the SSZWA and there is ample evidence that marked genotypic differences exist for P uptake. A better understanding of the factors affecting P uptake would help the process of selection for superior P-use efficiency, such as the ability of plants to:

- solubilize soil P through acidification of the rhizosphere and the release of chelating agents and phosphate-solubilizing enzymes,
- explore a large volume of soil,
- absorb P from low-P solutions.

Another important future research opportunity is the selection of genotypes that can efficiently associate with VAM for better utilization of P applied as indigenous PR.

4.6. Use of decision-support systems modelling, and geographical information systems

Farmers' production systems vary with respect to rainfall, soil type and socio-economic circumstances and, therefore, they are complex. Dealing with such complexity only by empirical research is expensive and inefficient. Use of models and geographical information systems (GIS) will facilitate the transfer of workable technologies to other similar agro-ecological zones. The use of the Decision Support System for Agrotechnology Transfer (DSSAT), Agricultural Production Systems Simulator (APSIM) and GIS will facilitate cost-effective extrapolation of findings to other agro-ecozones similar of the benchmark sites chosen for testing technologies.

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EFFECTS OF NITROGEN AND MULCHING MANAGEMENT ON RAINFED WHEAT AND MAIZE IN NORTHWEST CHINA

GUIXIN CAI
Chinese Academy of Sciences,
Nanjing, China

TINGHUI DANG, SHENGLI GUO, MINGDE HAO
Chinese Academy of Sciences,
Yangling, China

Abstract

Two field experiments were conducted in northwest China from September 1998 to June 2002. In one, the effects of three nitrogen (N)-fertilizer treatments were compared on a wheat-wheat-maize rotation. In the other, three mulching treatments were compared on continuous wheat. In an additional experiment in 2001, the effects of mulching were examined on maize. A ^{15}N micro-plot study was included with the three N treatments in the first year, and another was included, with and without mulching of wheat in the second year. Results showed that rational fertilization is an effective management practice to increase efficiency of water and nutrient utilization in rainfed farming systems of the region. Grain yields of wheat and maize were increased greatly by application of N-fertilizer: 35 to 81% for wheat and 35 to 44% for maize. Application of N fertilizer also increased water-use efficiency (WUE). An appropriate application rate for wheat was 60 to 100 kg N/ha and for maize was around 120 kg N/ha. Mulching increased maize yield from 5.1 to 7.9 t/ha, and WUE from 15 to 24 kg/ha/mm, but showed no effect on wheat. Grain yields of wheat varied greatly between years mainly as a function of rainfall. Plant recovery of applied N was in the range of 35 to 43%; 29 to 60% of applied N remained in the soil and from and 5 to 34% was unaccounted for. The efficiency of use of residual ^{15}N in the soil by the subsequent crop was 7 to 9 % and gradually decreased as cropping continued.

1. INTRODUCTION

The IAEA coordinated research project (CRP) “Management of Nutrients and Water in Rainfed Arid and Semi-Arid Areas for Increasing Crop Production” was started in 1998 and completed in 2002. The overall objective was to define management strategies that optimize and sustain the productivity of rainfed farming systems by increasing the efficiencies of water and nutrient utilization. The present research was part of the CRP.

In China, approximately 60% of cultivated land is rainfed [1]. Approximately half, including the north and northwest are semi-arid or arid regions where drought and limited soil moisture are key constraints to agricultural production. Moreover, the soils are deficient in nutrients, especially nitrogen (N) and phosphorus (P). Thus, better management of water and nutrients is especially important for increasing crop production in rainfed moisture-deficient conditions. Application of N-fertilizer is an effective means of increasing crop production in general [2] and in rainfed arid and semi-arid areas in particular [3, 4]. Mulching, a management practice for reducing soil water evaporation and increasing soil temperature, has been widely adopted in rainfed farming systems [5, 6]. Therefore, the objective of the present research was to investigate the effects of N and mulching management on efficiency of use of N and water by rainfed wheat and maize in northwest China.

2. MATERIALS AND METHODS

Field experiments, conducted at Changwu Experimental Station in the southern part of the Chinese Loess Plateau, were initiated in September 1998 and completed by the end of June 2002. The research included two experiments, each of four treatments with four replicates in a Latin square design. Each plot was 42 m^2 in area.

2.1. Experimental site

The experiment station is located in Changwu County, Shaanxi Province (35°12’ N, 107°40’ E; elevation 1,200 m). Mean annual rainfall is 580 mm, mean annual temperature is 9.1°C, annual cumulative mean daily temperature >10°C is 3030 °C, annual duration without frost is 170 days, and annual sunshine time is 2,230 h.

The Heilu soil, derived from loess, has a deep and even profile. The surface soil (0–20 cm) has a pH of 8.4, $CaCO_3$ content of 10%, total N content of 0.8 g/kg, available P of 14 mg/kg, available K of 146 mg/kg, cation exchange capacity of 13 cmol/kg, bulk density of 1.3 g/cm^3, field capacity of 27% and <0.01 mm clay of 37%.

2.2. Field experiments

2.2.1. First experiment

The crops were planted as follows:

- Wheat, 24/9/1998–24/6/1999
- Wheat, 29/9/1999–20/6/2000
- Bean, 23/6/2000–20/10/2000
- Maize, 16/4/2001–20/9/2001
- Wheat, 25/9/2001–20/6/2002

Rates of application of N in each treatment and cropping year are shown in Table I.. Since the soil was rather dry at the sowing of wheat in 1999, N-application rates were reduced. Phosphate at a rate equivalent to half of N2 was applied to all the treatments in each year. The urea, phosphate and organic manure in treatment N1O were applied as a basal dressing. Before sowing, fertilizers were broadcast followed by plowing, resulting in an application depth of 15 to 20 cm. Wheat was traditionally plane-planted; after harrowing, seeds were sown with a 20-cm row spacing at about 5-cm depth at a rate of 180 kg/ha.

In the case of maize, phosphate, organic manure and two thirds of N as urea were applied as basal dressing on April 16, 2001, and the remaining one third of N was applied by deep point-placement as top dressing on June 19, 2001. Maize was plane planted with mulching. A 60-cm wide area was covered with plastic film, and the distance between two films was 30 cm. Maize seeds were sowed under the film in two rows (45-cm row spacing, 40-cm plant spacing). No fertilizer was applied to bean in 2000.

Table I. Nitrogen application rates

Treatment	Wheat (1998–1999, 2001–2002)	Wheat (1999–2000)	Maize (2001)
	(kg N/ha)		
CK	0	0	0
N1	100 (urea)	60 (urea)	120 (urea)
N2	150 (urea)	100 (urea)	180 (urea)
N1O	100 (urea) + 50 (OM)[a]	60 (urea) + 40 (OM)	120 (urea) + 60 (OM)

[a] Organic manure.

2.2.2. Second experiment

The second experiment involved continuous wheat with treatments as follows:

- W—traditional planting i.e. plane planting with a row spacing of 20 cm,
- WM1—mulching and ridge planting 1; each ridge was 30 cm wide and covered with plastic film without planting, and four rows of wheat seeds were sown between two ridges with a spacing of 15 cm,
- WM2—mulching and ridge planting 2; each ridge was 60 cm wide and covered with plastic film and wheat seeds were sown under the film in four rows (15 cm spacing and 10 cm between 2 bunches with 8 wheat seeds in each bunch), the distance between two ridges was 30 cm without planting; however, in the fourth year (2001–2002), the 30 cm between two ridges was covered by maize straw, and the straw was removed at harvesting,
- WT—no-tillage after harvesting of the wheat and the soil mulched with wheat straw during the fallow season (late June to late September); the straw was removed before sowing.

In the first year, 150 kg N/ha as urea and 75 kg P_2O_5/ha as phosphate were applied to the four treatments. In the second, third and fourth years, 100 kg N/ha as urea and 50 kg P_2O_5/ha as phosphate were applied. The N and P fertilizers were applied as basal dressings. Application methods were the same as for the first experiment. Wheat seeds were sown at a depth of about 5 cm depth at 180 kg/ha for W and WT treatments. In the cases of WM1 and WM2, a reduced sowing rate of 160 kg/ha was used. In addition, there was a 2-week delay in sowing WM2.

2.2.3. Additional mulching study

A contrasting maize experiment with two treatments (plane planting, with and without mulching) in four replicates was set up on April 16, 2001. For the mulching, a 60-cm wide area was covered with plastic film, and the distance between two plastic films was 30 cm. Maize was planted with a 45-cm row spacing and 40 cm between plants. Plot size was 5.4 × 6 m. Urea was applied at 120 kg N/ha and phosphate at 60 kg P_2O_5/ha. Two thirds of the N and all of the P were applied as basal dressing on April 16, 2001, and the remainder of the N was applied by deep point-placement as topdressing on June 19, 2001.

2.3. Nitrogen-15 micro-plot experiment

In the first year, an ^{15}N-labeled urea study was included within the N1, N2 and N1O treatments in four replicates. The micro-plots were bounded by iron frames of 50 × 40 × 60 (depth) cm, inserted into the soil leaving 5 cm above the soil surface. The abundance of ^{15}N in the urea was 7.06 atom %. Soil and plant samples were taken at physiological maturity and analysed at IAEA's Seibersdorf laboratory for total N and ^{15}N.

In the second year, a ^{15}N-labeled urea study was set up in the W and WM1 treatments to investigate the effect of mulching on the fate of fertilizer N applied to wheat. The ^{15}N micro-plots of 1.44 m^2 (1.2 × 1.2m) were located without frames in the corresponding macro-plots. The abundance of ^{15}N in the urea was 5.34 atom %. Residual effects of applied urea-N were investigated from previous ^{15}N studies in treatments N1, N2 and N1O as well as W and WM1.

2.4. Measurement of soil-water content

At sowing and harvesting, soil samples (0–300 cm) were taken and oven dried at 105°C to constant weight to determine gravimetric water contents. Volumetric water contents were then determined according to soil bulk density. During the cropping season, soil water content was periodically measured using a neutron moisture meter which was calibrated against actual determinations of volumetric water content in the first measurement each year.

Table II. Wheat response to nutrient application

Treatment	1999 Grain yield (t/ha)	1999 Increase (%)	1999 Productivity index (kg/kg N)	2000 Grain yield (t/ha)	2000 Increase (%)	2000 Productivity index (kg/kg N)	2002 Grain yield (t/ha)	2002 Increase (%)	2002 Productivity index (kg/kg N)
CK	2.77b[a]			1.45b			0.920c		
N1	3.99a	44	12.1	2.47a	70	17.0	3.85b	318	29
N2	3.73a	35	6.40	2.62a	81	11.7	4.18ab	354	22
N1O	4.30a	55	10.2	2.23a	54	7.80	4.56a	396	24

[a] Different letters in a column denote a significant difference at the 5% level by Duncan's multiple-range test.

3. RESULTS AND DISCUSSION

3.1. Wheat and maize responses to N

Wheat yields responses to N application are shown in Table II. Yields in the control CK (zero N) were 2.77, 1.45 and 0.92 t/ha in 1999, 2000 and 2002, respectively. Grain yield in the controls decreased from 2.77 to 0.92 t/ha between 1999 and 2002, mainly due to decreasing soil mineral N; at 0- to 60-cm depth before sowing in the first and second years it was 12 to 21 mg N/kg, and 7 to 9 mg N/kg in the fourth year.

Nitrogen fertilizer significantly increased grain yields by 35 to 55% in 1999, 54 to 81% in 2000 and 3.2- to 4-fold in 2002. However, there were no significant yield differences between treatments N1 and N2, indicating that the rate of 60 to 100 kg N/ha as urea was usually sufficient under these conditions. In 1999 and 2002, the highest yields were obtained with treatment N1O; although not significantly different from the other N treatments in 1999, it was significantly higher than N1 in 2002. This result indicates the benefit of combined use of organic and inorganic N fertilizers. An even higher yield may have been obtained by increasing the N rate using additional manure.

The productivity index (PI), i.e. kg/ha of additional yield above CK per kg of plant nutrient applied, had a broad range: 6.4 to 29.3 kg/kg N (Table II). The PI values were much higher in 2002 than in 1999 and 2000 due to the very low yield in the control in 2002. The highest PI was obtained with N1 and decreased as N-application rate increased. The average PI for wheat in this experiment in 1999 and 2000 (10.9 kg/kg N) was similar to that reported by the Chinese Agricultural Academy of Science (10 kg/kg N) in 1986 [2].

Maize-yield responses to nutrient application are shown in Table III. Grain yield was 4.47 t/ha in the control CK (without N) and increased significantly to 6.32, 6.44 and 6.02 t/ha for treatments N1, N2 and N1O, respectively. However, there were no significant yield differences among the three fertilized treatments, indicating that 120 kg N/ha was sufficient for maximum yield.

Table III. Maize response to nutrient application in 2001

Treatment	Grain yield (t/ha)	Increase (%)	Productivity index (kg/kg N)	Straw weight (t/ha)	Increase (%)	Grain/ total dry matter
CK	4.47b[a]			8.09b		0.36
N1	6.32a	41	15.4	9.12a	13	0.41
N2	6.44a	44	10.9	8.85ab	9.4	0.42
N1O	6.02a	35	8.6	9.67a	20	0.38

[a] Different letters in a column denote a significant difference at the 5% level by Duncan's multiple-range test.

Table IV. Effects of mulching on wheat yield

Treatment	1998–1999	1999–2000	2000–2001	2001–2002	4-year mean
	(t/ha)				
W	4.21a[a]	2.60a	3.46a	4.04b	3.58
WM1	4.56a	2.86a	3.20a	3.77b	3.60
WM2	4.00a	2.72a	3.00a	4.68a[b]	3.60
WT	4.25a	2.93a	2.84a	3.41b	3.36
Mean	4.26±0.12[c]	2.78±0.07	3.13±0.13	3.98±0.27	

[a] Different letters in a column denote a significant difference at the 5% level by Duncan's multiple-range test.

[b] In addition to the ridge the space between two ridges was covered by maize straw.

[c] Mean±standard error of the mean of four treatments.

The harvest indices (grain yield over total dry matter yield) in the fertilized treatments were higher than for the control due to relatively less increase of straw weight in comparison with grain yield (Table III). The highest PI was obtained with N1 and the average of PI for maize obtained in this experiment (11.6 kg/kg N) was slightly lower than that obtained by the Chinese Agricultural Academy of Science (13.4 kg/kg N) [2].

3.2. Effects of mulching

Mulching is a management practice for improving water infiltration, reducing soil-water evaporation, and increasing soil temperature [7, 8]. Mulching with plastic film has increased wheat or maize grain yield by 10 to 20% [7–10], and up to >40% [6]. However, in the present experiments, mulching had no effect on wheat yields over four years (Table IV) whether with plastic during cropping (WM1 and WM2) or with wheat straw during fallow (WT). In the case of WT, it seems that no-tillage affected seedling growth due to presence of residues. As a result, grain yields in the third and fourth years were 0.6 t/ha lower than those of W (CK) although the difference was insignificant.

Factors such as crop variety, sowing time, planting density and fertilization influence the effects of mulching [4, 9, 11]. Mulching material [12] and soil-water content at sowing [13] also are important. Soil properties and environmental conditions impinge on the effectiveness of any management practice. It was concluded that the mulching techniques used on wheat in the present experiment are ineffective in this region.

In the fourth year (2001–2002) the WM2 treatment was modified; in addition to the ridge being covered by plastic film, the space between two ridges was covered by maize straw. This modification, combining plastic and straw mulching, significantly increased wheat yield, and merits further testing. Other studies showned that mulching with plastic plus straw increased grain yield in comparison with plastic or straw alone [5,14].

Table IV also shows that grain yields of wheat varied among years. Yields in 1999 and 2002 (averages of 4.26 t/ha and 3.98 t/ha for the four treatments, respectively) were significantly higher than those in 2000 (2.78 t/ha) and 2001 (3.13 t/ha). These differences probably resulted from different annual rainfall: 573 and 625 mm in the first and last years, and 412 and 389 mm in the second and third years, respectively (Table V). It seems that the rainfall in the last 3 months before sowing is important because it affects available soil water at sowing: Zhou [15] showed that soil water storage is significantly correlated to the ratio of rainfall/evaporation in the 55 days before sowing. Rainfall distribution during the wheat-cropping season also played a role. From February to May (the growing period for wheat) it was limited in 2000 (Fig. 1) and 2001, 61 and 69 mm, respectively, in comparison with 151 mm in 1999 (Fig. 1) and 160 mm in 2002.

Table V. Available soil water and rainfall

Parameter	1998–1999	1999–2000	2000–2001	2001–2002
	(mm)			
Available soil water in 0-3 m depth at sowing	282	78	144	210
Rainfall in the growing season	241	257	265	299
Rainfall in the 3 months before sowing	332	155	124	326
Rainfall in the whole year (July–June)	573	412	389	625

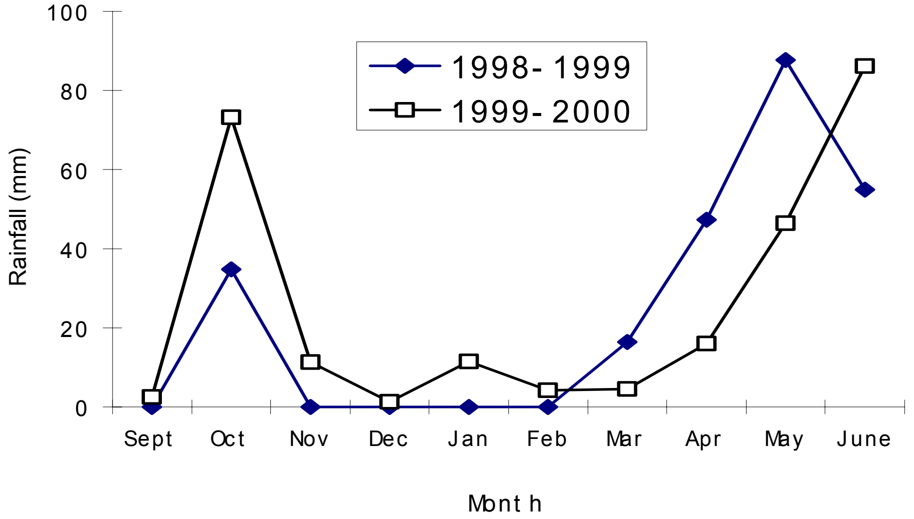

FIG. 1. Rainfall in two wheat-cropping seasons.

In contrast to the results with wheat, plastic mulching significantly affected maize (Table VI). Maize yield with normal planting was 5.12 t/ha and 7.92 t/ha with mulching, i.e. an additional 2.8 t/ha maize or 55% increase. On the other hand, mulching decreased straw weight, and thus increased the harvest index from 0.31 to 0.44. Agronomic efficiency of fertilizer N was higher with mulching.

In this region, mulching with plastic film was effective in summer but not in winter. In summer, temperatures are high as is evaporation, thus positive effects of reducing soil-water evaporation by mulching probably are easier to demonstrate.

Mulching with plastic film has been widely adopted in regions of limited water supply, where the growing season is cold, and where the soil benefits from protection. The main problems with plastic mulching are residual contamination and decreasing soil fertility. These adverse effects should be considered and resolved as components of investigations of effects of mulching on agricultural production.

Table VI. Effect of mulching on maize in 2001

Treatment	Maize yield (t/ha)	Increase (%)	Straw weight (t/ha)	Change (%)	Grain/ total dry matter
CK	5.12±0.20[a]		11.3±0.71		0.31
Mulch	7.92±0.38	55	10.2±0.51	−9.7	0.44

[a] Mean±standard error of the mean of four replicates.

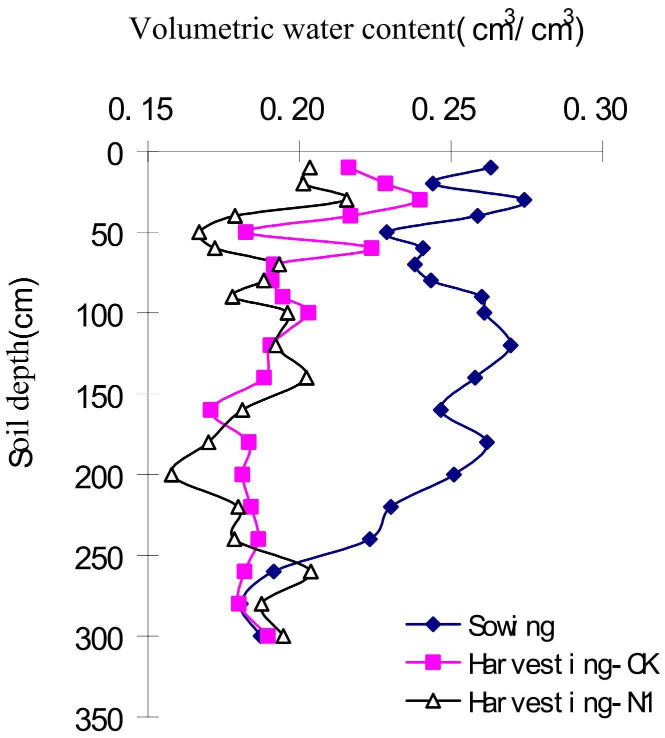

FIG. 2. Volumetric water content in the soil profile (0–300 cm) at sowing and harvesting of wheat (1998–1999).

Table VII. Water-use efficiency of wheat

Growing season	CK	N1	N2	N1O	W	WM1	WM2	WT
	(kg/ha/mm)							
1998–1999	7.6	10.2	9.7	10.5	10.5	11.7	9.9	10.2
1999–2000	8.8	13.9	12.6	14.1	11.8	14.2	13.9	11.5
2000–2001					10.2	10.8	9.4	8.5
2001 – 2002	2.5	8.3	8.7	9.8	8.6	8.5	11.3	7.4

3.3. Dynamics of volumetric soil-water content and efficiency of water use

Figure 2 shows soil-water content at harvesting and sowing in the first year of the wheat experiment (September 1998–June 1999). Soil moisture decreased greatly from sowing to harvesting. Differences among treatments were small throughout the season. In contrast, the soil-water content in the second year (1999–2000) at harvesting was higher than at sowing due to a low soil-water content at sowing and some rainfall before harvesting.

Net depletion of soil water during the cropping season can be calculated from the change in moisture content. Water-use efficiency (WUE) was calculated using total water consumption, which was calculated from the rainfall and the sum of soil-water depletion throughout the 3-m profile. Table VII provides WUE values for wheat for the 4-year period. It was lowest (2.5–8.8 kg/ha/mm) for CK, and increased to 7.4 to 14.2 kg/ha/mm, averaging 10.6 ± 1.0 for the N-fertilized treatments. Mulching did not much affect WUE (Table VII). Previous studies in the region showed low WUE values for wheat without N fertilization (2.6–6.5 kg/ha/mm), reaching 13 kg/ha/mm with fertilization [3]. Results from Zhou [15] showed that the average WUE in rainfed wheat fields in the Fengqiu region was 7.2 kg/ha/mm, increasing to 11 to 17 kg/ha/mm with fertilization.

Table VIII. Water use and yields for maize in 2001

Parameter	CK	N1	N1O	N2	No mulch	Mulch
Consumption of soil water (0–3m) (mm)	96.5	104	87.5	103	62.0	54.6
Rainfall (mm)	281					
Total water consumption (mm)	378	385	369	384	343	336
Grain yield (kg/ha)	4,473	6,318	6,438	6,024	5,122	7,915
WUE (kg/ha/mm)	11.8	16.4	17.5	15.7	14.9	23.6

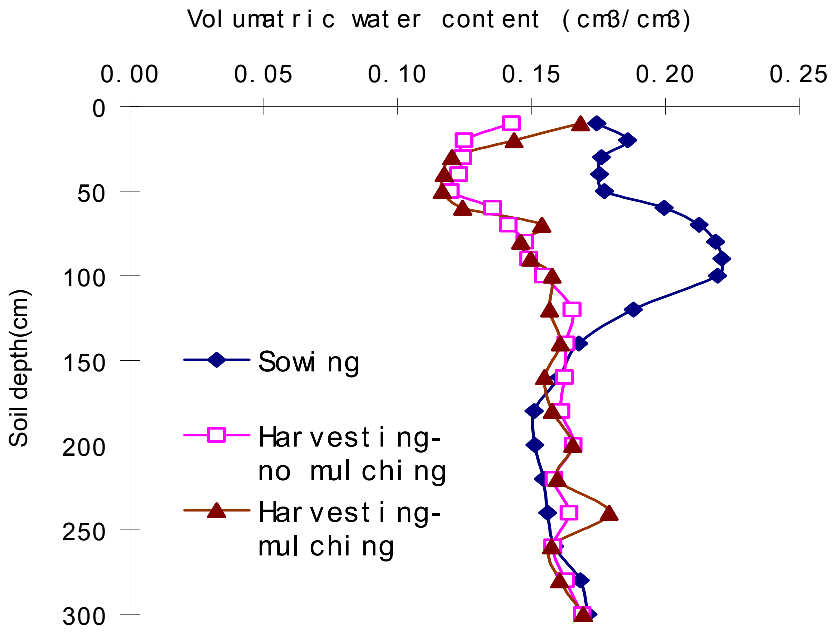

FIG. 3. Comparison of volumetric water contents (cm^3/cm^3) in the soil profile (0–300 cm) without mulching of maize in 2001 maize experiment.

Similar to wheat, the WUE of maize greatly increased with N fertilization, from 11.8 kg/ha/mm in CK to 15.7 to 17.5 kg/ha/mm (Table VIII). In contrast with the wheat experiment, mulching greatly increased WUE of maize, from 14.9 kg/ha/mm to 23.6 kg/ha/mm due to higher grain yield in the mulching treatment.

Regarding soil-water consumption, there was no significant effect of mulching (Table VIII, Fig.3). Mulching is a management practice for reducing soil water evaporation. Apparently, the maize used part of the water preserved by mulching in higher transpiration due to higher biomass. Fan et al. [10] and Ren et al. [11] also found little effect of mulching on soil-water content or water consumption.

Table IX. Fate of urea-N applied to wheat in 1998

Treatment	Plant recovery	Recovered in soil				Total recovered	Unaccounted for
		0–10 cm	10–20 cm	20–40 cm	0–40 cm		
	(% of applied N)						
N1	38a[a]	22	5.2	4.6	32a	70a	30
N2	37a	21	4.2	4.3	29a	66a	34
N1O	37a	22	6.6	4.9	34a	71a	30

[a] Different letters in a column denote a significant difference at the 5% level by Duncan's multiple-range test.

3.4. Fate of applied N

3.4.1. Wheat

The fate of urea-N applied at different rates to the Heilu-soil-wheat system is shown in Table IX. When applied as a basal dressing, recovery of N by wheat ranged from 37 to 38%, and 29 to 34% remained in the soil (0–40 cm). Thus the total recovery of the applied N ranged from 66 to 71%, and 30 to 34% remained unaccounted for. Statistical analyses indicated no significant differences between the treatments for plant recovery, soil recovery or total recovery, indicating that the fate of urea-N was not affected by the rate of applied urea or by the use of organic manure in the present study. Table IX also shows that when urea was applied as a basal dressing, the fertilizer N remaining in the soil was mostly located in the 0- to 10-cm layer and gradually decreased with depth. Fate of applied N is affected by a number of factors, such as the crop, type of soil, rate, and method and timing of application [16]. Our results are comparable with those obtained with irrigated winter wheat in China [17–20].

3.4.2. Effects of mulching

When urea was applied with traditional planting (W), recovery of the N by wheat was 43%, with 44% remaining in the soil (0–100 cm) (Table X). Thus the total recovery of the applied N was 87%, and the proportion of unaccounted-for N was 13%. The corresponding figures with mulching and ridge planting (WM1) were 35%, 60%, 95% and 4.8%, respectively, indicating that mulching greatly improved recovery in soil, but had no effect on N recovery by the crop. This is consistent with the finding that mulching had no effect on grain yield. The N residual in the soil may be overestimated by the ^{15}N technique. It should be pointed out that the ^{15}N-recovery measurements for 20 to 40 cm, 40 to 70 cm and 70 to 100 cm might be affected by sampling errors; only two to four soil cores were taken and assumed to be representative.

Figure 4 shows that when urea was applied as a basal dressing, the fertilizer N remaining in the soil was located mostly in the 0- to 40-cm layer (40–58% of applied N) and greatly decreased with depth. Only 3 to 4% of applied N remained at a depth of 40 to 100 cm, and only 1% was present between 100 to 200 cm. Figure 4 also shows that a greater proportion of N remained in the subsurface soil (20–40 cm) in treatment WM1 than W, probably due improved water infiltration by mulching.

Table X. Effects of mulching on fate of N applied to wheat

Treatment	Recovered by plants	Recovered in soil 0–100 cm	Total N recovery	Unaccounted for
	(% of applied N)			
W	43±0.9[a]	44±1.7	87±0.9	13
WM1	35±1.6	60±7.2	95±6	4.8

[a] Mean±standard error of the mean of four replicates.

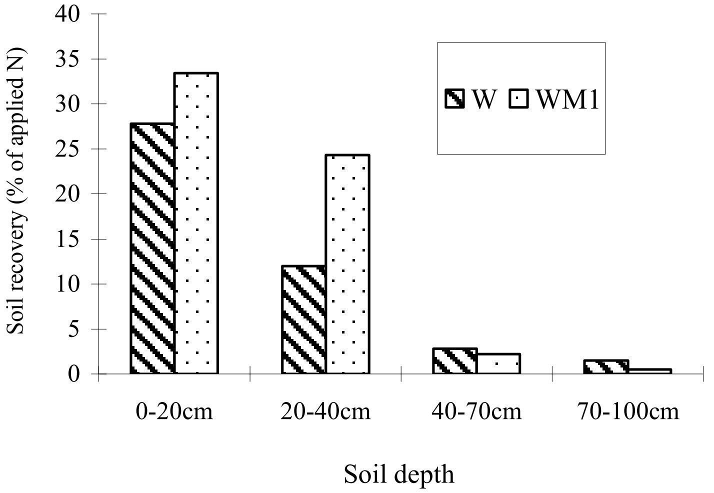

FIG. 4. Recovery in on ^{15}N at various soil delphs by conventional (W) and mulching planting (WM1).

3.4.3. Effect of residual N in soil

Table XII shows that recoveries of residual N in subsequently cropped wheat were in the range of 2.1 to 2.8% of applied N, taken up from the 6.7 to 8.7% of N remaining at 0 to 40 cm (Table XI) or 7.9 to 10% of N remaining at 0 to 20 cm. Shi et al. [21] studied residual effects from ammonium sulfate applied to rice on a bleached paddy soil in Jiangsu Province and found that the recovery of residual N by second cropping season rice was 20% of N remaining in the 0- to 20-cm layer, much higher than obtained in the present study. It was explained that the high residual effect on the bleached paddy soil was due to “newly” fixed ammonium N the availability of which was higher than that of biologically immobilized N [22]. Fertilizer N remaining in the 0- to 40-cm layer in treatment N1 was similar in 1999 (32%) and 2000 (35%) indicating that it was stable. Approximately 2.5% of the applied N was taken up by the subsequent crops of wheat and bean, and about 2% of the applied N was taken up by the fourth crop, maize.

Table XI. Recovery of residual N by wheat in the second year

Treatment	Residual N taken up by wheat		
	% of applied N	% of N remaining in soil 0–40 cm	% of N remaining in soil 0–20 cm
N1	2.5±0.3[a]	8.0±1.0	9.3±1.2
N2	2.1±0.04	6.7±0.1	7.9±0.2
N1O	2.8±0.2	8.7±0.8	10±0.9

[a] Mean of four replicates±standard error.

Table XII. Recovery of residual N by subsequent crops

Treatment	Second wheat	Third bean	Fourth maize
	(% of applied N)		
N1	2.5±0.3[a]	2.3±0.3	1.9±0.1
N2	2.1±0.04	2.3±0.4	2.2±0.2
N1O	2.8±0.2	2.8±0.4	1.6±0.2

[a] Mean of four replicates±standard error.

Table XIII. Mulching effects on recovery of residual N by wheat in the second year

Treatment	N remaining in soil in 2000	N remaining in soil in 2001	Residual N taken up by wheat in 2001	Residual N taken up by wheat in 2001
	(% of applied N)			(% of residual N)
W	44±1.7	44±2.2	3.1±0.7	7.0
WM1	60±7.2	39±2.8	16±4.0	26

Table XIII shows residual effects in the mulching experiment. With traditional planting, 3.1% of applied N, 7.0% of the residual N, was taken up by the second crop of wheat. However, with mulching-ridge planting, 16 % of applied N, 26% of residual N, was taken up by the second wheat crop, consistent with the decrease in N remaining in the soil from 2000 to 2001: N remaining in the soil in 2000 (60%) decreased to 39% in 2001, apparently taken up by the wheat crop presumably as mineral N.

4. CONCLUSIONS

Results showed that fertilization is an effective management practice to increase the efficiency of utilization of water and nutrients in rainfed farming systems in the Changwu region. Wheat and maize grain yields were increased with application of N fertilizer, i.e. 35 to 81% for wheat and 35 to 44% for maize. Urea at 60 to 100 kg N/ha was usually sufficient for the wheat. However, higher yields are possible with higher N rates using additional manure. A rate of around 120 kg N/ha was sufficient for maize in Changwu.

Mulching is a management practice that improves water infiltration and reduces soil water evaporation, which is particularly beneficial for maize production in this region. Mulching increased maize yield from 5.12 to 7.92 t/ha. In contrast, mulching had no effect on wheat over the 4 years. A modified technique, combining plastic and straw mulching, significantly increased wheat yield in the last year; this needs further testing. Wheat grain yields varied greatly from year to year, mainly due to how annual rainfall affected soil-water content at sowing.

Application of N fertilizer increased water use efficiency (WUE) for both wheat and maize: from 2.5 to 8.8 to 7.4 to 14.2 kg/ha/mm for wheat and from 11.8 to 15.7 to 17.5 kg/ha/mm for maize. Mulching did not affect WUE of wheat, but increased WUE of maize, from 14.9 to 23.6 kg/ha/mm.

Nitrogen-15 studies on wheat showed that plant recovery of applied N was in the range of 35 to 43%, N remaining in soil was in the range of 29 to 60%, and the proportion of unaccounted-for N ranged from 5 to 34%. The efficiency of use of residual N in soil by a second crop usually was 2 to 3% of applied N or 7 to 9 % of ^{15}N remaining in soil, gradually decreasing as cropping continued.

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GREEN-MANURE AND NITROGEN-FERTILIZER EFFECTS ON SOIL QUALITY AND PROFITABILITY OF A WHEAT-BASED SYSTEM IN SEMI-ARID MOROCCO

K. EL MEJAHED, L. AOURAGH
Institut National de la Recherche Agronomique,
Settat, Morocco

Abstract

The objective of this study was to assess the substitution of fallow with green manure in terms of soil properties, wheat response to nitrogen (N) fertilizer and yield as well as profitability of wheat–fallow, wheat–incorporated vetch and wheat–mowed vetch as forage. Field experiments using nuclear techniques (^{15}N, neutron probe) were conducted over five years at two experiment stations with different rainfall. Soil N, carbon (C), organic matter (OM), nitrate, stability index and water as well as wheat grain and straw yield, N uptake, %N derived from fertilizer, N-use efficiency and rain-based water-use efficiency (WUE) were used as criteria for differences among these systems. The three dry years that occurred during the period of the study affected wheat performance in all cropping systems. The wheat–fallow rotation was generally more efficient than wheat–mowed vetch and wheat–incorporated vetch, in terms of wheat yield, N uptake, N-use efficiency and WUE. Soil-water use in wheat–fallow was around 20 mm. It buffered drought, but wheat yield depended on total rainfall and its distribution, especially in February and March. Values of $\delta^{13}C$ were not consistently related to water use. Vetch production, like wheat, was affected by the frequent droughts. Incorporated vetch did not substantially increased OM, soil nitrate or stability index. The effect of applied N on wheat in different rotations differed with location and year. In general, wheat yield was highest without N application and lowest with N application at sowing and tillering or both. Nitrogen treatments had no effect on soil-water content or use. Based on cost:benefit ratio, the fallow system generated the highest benefit, while incorporation of vetch was not economically justified.

1. INTRODUCTION

Arid and semi-arid regions, devoted mainly to cereal production, represent 87% of the total arable land in Morocco. Precipitation is low (200–400 mm) and distributed erratically; droughts are frequent [1]. Stanhill [2] has shown that rainfall distribution is the main factor affecting water-use efficiency (WUE). Therefore, water is often a limiting factor in crop production and potential evaporation exceeds precipitation in these areas. Crop production under dry farming depends on water supply from current rainfall and water stored in the root zone of the soil at sowing [3–6].

Besides water, nutrient deficiencies, especially of N even after a legume crop [4,6] and to a lesser extent phosphorus (P), often limit wheat production. Substantial increases in production of rainfed cereals and food-legumes is possible with minimum inputs and improved management. The need for affordable, alternative and appropriate technologies is critical. Water-conservation techniques combined with suitable crop management, crop selection and sequencing of the crops in the rotation are necessary to increase and stabilize wheat yields through efficient use of water and N.

Wheat–fallow rotation, justified by yield stability, is dominant within the 250- to 350-mm rainfall zone. Both tilled and clean fallow are practised in deep soils in order to conserve water and sustain grain production, especially during dry years [3–5]. Fallow reduces pathogen levels and weed infestation of the wheat [7, 8] and alleviates the need for mineral N through mineralization of organic matter (OM). This mining of the soil's nutrients, besides erosion problems, is accelerated by stubble removal and grazing, and high soil N-mineralization potential [9]. In the long term, soil mineralization capacity is likely to decrease and the wheat–fallow system would require additional N to maintain yield levels [10–12]. Furthermore, conventional fallow efficiency is only around 10% compared to 20 to 32% in black or minimum-till fallow [3–5, 13]. This efficiency depends on rain intensity, timing and distribution.

Research in semi-arid Morocco has indicated that food legumes improve soil fertility and subsequent wheat yields [4, 6, 14, 15]. Concerns over degradation of this fundamental resource have led to renewed interest in use of sustainable green-manure legume-cropping systems with minimum input of chemicals [16]. Green manure might be an economical means of restoring degraded soils, increasing soil OM and nutrient availability and improving soil production [17, 18]. The use of legumes as forage and green manure, especially vetch, dates back to 300 to 800 years BC [19, 20].

The substitution of fallow with green manure may lead to a more sustainable cropping system. It has the possible advantages of reducing surface and ground-water contamination, increasing soil OM and N, improving soil structure and aggregate stability, reducing erosion, increasing aeration, water infiltration and microbial activity. It may also contribute to soil N through biological N_2 fixation, reduce fertilizer N needs by the wheat and farmer-dependence on mineral N. However, the use of green manure in low-rainfall areas might reduce soil-water availability to the following crop [21]. Green manure as a crop preceding wheat can be readily transferable and adopted by farmers, especially in shallow soils, where fallow water-storage potential is nil and continuous cereals predominate. The introduction of green manure will eliminate the need for herbicides to control weeds during the fallow period. It will also reduce need for biocides for wheat production. Green manure can be easily integrated as a forage in crop-livestock systems. Vetch is commonly used as forage, serving as a valuable source of protein. It is usually mowed early in the season (February–March) but incorporating it into the soil was seldom considered. However, wheat performance of this system and its N requirement, water- and N-use efficiencies as well as soil physical and chemical changes were not monitored and compared to those of a wheat–fallow system. Nuclear techniques (labelled N fertilizer, carbon discrimination and the neutron moisture probe) are useful tools for evaluating N and water effects in this wheat system.

The objectives of this study were to:

- evaluate rotation and fertilizer effects on wheat,
- assess the effects of green manure and fallow on soil properties,
- monitor soil-water and N use efficiencies using nuclear techniques,
- sustain soil productivity and ensure environmental protection by reducing chemical use, and
- select the most profitable system that can be easily and readily adopted by farmers and reduce farmer-dependence on the fertilizer market.

2. MATERIALS AND METHODS

Identical field trials were conducted from 1997 to 2002 at Jemaa Riah (JR) and Jemaa Shaim (JS) Agricultural National Research Institute (INRA) experimental stations, located in the Settat-Chaouia and Safi-Abda regions, respectively. The soil at JR was classified as a fine montmorillonitic, thermic Palexerollic chromoxerert with a IIe capability subclass. At JS, the soil is a fine montmorillonitic, thermic Palexerollic chromoxerert (mixed) with a IIIw capability subclass. Both soils have a petrocalcic horizon, below 1 m at JS and at 50 to 60 cm at JR. Soil profile description, for both sites, is reported in an appendix. Physical and chemical properties are given in Table I.

The experimental had a split-plot design arranged in a randomized complete block with four replicates. Rotations were assigned to main plots: wheat–fallow (W–F), wheat–vetch mowed (W–VM), wheat–vetch incorporated (W–VI), fallow–wheat and vetch–wheat. The sub-plots consisted of N split with 0 or 40 kg N/ha at planting (P), 46 kg N/ha at tillering (T) and N at planting and tillering (P+T). Therefore, N treatments were 0, 46, 0–40 and 40–46. Phosphorus and potassium were applied based on soil tests. Nitrogen-15 micro-plots of 1.5 × 1 m for ^{15}N were installed for wheat and vetch in four replicates. Urea at 2.19% ^{15}N a.e was used for all N rates. For vetch, 2.5 % ^{15}N a.e labelled urea was used at a rate of 22.3 kg/ha.

Neutron-probe access tubes were installed in four replicates in wheat plots; only four tubes were installed in the vetch and fallow phases. Soil water was monitored using a neutron probe, to a depth of

60 cm in both location during the 1998–1999, 1999–2000, 2000–2001 cropping seasons. Soil-water measurement periods were not the same for both locations; they also differed over years within each location according to rainfall pattern and wheat-germination date.

Bread wheat (cv. Achtar) and vetch (*Vicia sativa*) were sown each year in November. Weeds in wheat were chemically controlled. Wheat-grain and straw %N, as well as their ^{15}N a.e and δ^{13}C values, were determined at the IAEA laboratory at Seibersdorf, Austria.

Water use (WU) was calculated as the sum of rain and difference between soil water (R) at two different times (final and initial) as indicated below:

$$WU = Ri - Rf + Rain$$

where

Rf is the final soil-water reserve (mm),
Ri is the initial soil-water reserve (mm).

Water-use efficiency is the ratio of yield to WU (kg ha^{-1} mm^{-1}):

$$WUE = \frac{Yield}{WU}$$

Rain-water-use efficiency was also determined as:

$$RWUE = \frac{Yield}{WU}$$

The ^{15}N-enrichment data were used to calculate the % of N derived from fertilizer (%Ndff). The N-use efficiency (NUE) for wheat grain, straw and total dry matter was calculated as:

$$NUE = 100 \times \frac{N\ uptake \times \%Ndff}{labelled\ applied\ N\ fertilizer}$$

Grain and straw yield, WU, WUE, δ^{13}C, N uptake, %Ndff, NUE, as well as soil water and nitrate at different depths and OM (0–20 cm and 20–40 cm) were used to examine the effects of rotation and N fertilizer at the two sites. Analyses of variance and mean comparisons were done separately for each location and year.

3. RESULTS AND DISCUSSIONS

3.1. Rainfall quantity and distribution

There were three consecutive dry years (1998–2001). The 1997 to 2002 rainfall for both locations is reported on Table II. The amount and the distribution of received rainfall during these years are an indication of the variation in climatic conditions that prevail in semi-arid regions of Morocco. The 1998 to 1999 season was dry at the beginning and at the end. The late onset of rain affected crop establishment. The cumulative rainfall from February to May 1999 was 70 and 64 mm at JR and JS respectively (Table II). Therefore, water stress during grain filling was more severe at JS, which had a total rain of only 177 mm.

In the 1999–2000 growing season, rainfall was 236 and 199 mm for JR and JS, respectively. However, at both locations, approximately 70 mm were received in October (before planting), while 67 mm at JR and 50 mm at JS were received in April 2000 when the wheat crops were ready for harvest. Therefore, received rainfall during the 1999–2000 growing season was only 125 mm at JR and 78 mm at JS. The 30 mm received in the second decade of January 2000 at JS, compared to 15 at JR, affected wheat yield because of difference in soil depth and water-holding capacities (Table I).

Table I. soil physical and chemical properties at Jemaa Shaim (JS) and Jemaa Riah (JR)

Site	Depth (cm)	Clay	Silt	Sand	B. density (g/cm^3)	Water retention	
			(%)			0.33 bar	15 bar
JS	0–15	60	22	18	1.15	27	18
	15–30	56	27	17	1.25	27	18
	30–60	56	27	17	1.34	28	20
	60–90	55	26	19	1.46	27	15
JR	0–10	30	10	60	1.25	21	10
	10–38	32	7	61	1.64	17	11
	38–50	40	6	54	1.55	22	14
	50–60	46	6	48	1.65	20	18

Site	Depth (cm)	OM	OC	TN	NO_3	P	K	pH
			(%)			(ppm)		
JS	0–15	2.0	1.2	0.09	20	22	220	7.7
	15–30	2.0	1.2	0.06	21	5	265	8.0
	30–60	1.5	0.9	0.06	–	–	–	8.1
	60–90	1.0	0.6	–	–	–	–	8.1
JR	0–10	2.0	1.2	0.11	14	6	149	6.7
	10–38	1.7	1.0	0.09	13	2	178	6.6
	38–50	1.3	0.8	0.07	–	–	–	6.8
	50–60	1.1	0.6	0.04	–	–	–	7.1

During the 2000–2001 cropping season, 3 mm rainfall were received only at JS after the end of January. Therefore, there were three consecutive dry months (February, March and April) at both locations (Table II). The highest rainfall during the four years of the experiment, was received during the 2001–2002 cropping season: 292 and 270 mm for JS and JR, respectively (Table II). However, the 18 mm received in February at JS, coupled with greater soil depth and water-holding capacity (Table I) resulted in higher yields at JS.

At both sites, water stress occurred throughout the growing seasons, even in the wheat–fallow system where fallow efficiency and soil-water storage were also affected by rain intensity, timing and distribution. These climatic conditions resulted in crop failure, especially in the wheat–vetch system at JR during the 1999–2000 season. Analyses of variance revealed no interaction between rotation and applied N fertilizer. Therefore, the effects of rotation and fertilizer will be discussed separately.

2. ROTATION EFFECTS

2.1. Wheat grain and straw, rain-water-use efficiency and $\delta^{13}C$

2.1.1. Jemaa Riah

Except for the 2000–2001 growing season, grain and straw yields were highest in W–F, while W–VM and W–VI did not significantly differ from each other (Table III). Differences between the cropping systems in term of wheat production, were more pronounced in 1998–1999 after 311 mm had been received in the 1997–1998 fallow period (Table II). The received low rainfall in 1998–1999 coupled with the extended dry period from 1999–2000, resulted in complete crop failures (negligible grain) in the wheat–vetch system (Table III). In fact, approximately 70 mm were received in October 1999 (before planting), while 67 mm were received in April and May (Table II), when crop growth had stopped and grain was ready for harvest. Therefore, received rainfall during the growing season was only 107 mm.

Rain-water-use efficiency, based on one season rainfall for grain (RWUE grain) and straw (RWUE straw) was higher in W–F than in W–VM or W–VI, which were not significantly different from each other except for 1999–2000 (Table III). W–F was more efficient than the two other rotations because of the extreme water stress that affected all cropping systems. However, when two season rainfalls are used (data not reported), W–F system was more efficient than W–VM and W–VI in the 1998–1999 and 1999–2000 seasons. This situation resulted from the extreme water stress and the 1998–1999 and 1999–2000 rainfall amounts distributions that affected wheat yield and water storage at both locations.

The analysis of grain and straw δ^{13}C data for the 1998–1999 growing season showed more negative values for W–F that were significantly different from those of W–VM and W–VI (Table III). These values were related to water-use efficiencies. However, for the other cropping seasons, there were either no differences in δ^{13}C among cropping systems or no relationship between WUE and straw δ^{13}C(%) or both. In fact, despite differences in wheat yield and water-use efficiency in 1999–2000, straw δ^{13}C values were similar for all cropping systems (Table III), while in 2001–2002 rotations differed in WUE but not in C discrimination.

2.1.2. Jemaa Shaim

Grain and straw yields in W–F during the 1999–2000 and 2001–2002 cropping seasons were higher than in W–VM or W–VI, which did not significantly differ from each other (Table IV). Although, only 18 mm rainfall were received in January and February, the 2001–2002 yield was four- to six-fold higher than in the other best-yielding year (Table IV) because of the 292 mm of relatively well distributed rainfall (Table II).

Table II. Monthly and decadal rainfall at Jemaa Riah and Jemaa Shaim

Month	Decade	Jemaa Shaim					Jemaa Riah				
		97–98	98–99	99–00	00–01	01–02	97–98	98–99	99–00	00–01	01–02
							(mm)				
Oct	O1	11	5	0	0	0	10	18	0	0	1
	O2	0	0	31	4	0	0	0	19	24	0
	O3	30	0	40	14	0	24	0	51	1	0
Nov	N1	22	0	0	0	0	39	0	0	0	8
	N2	13	0	10	3	2	11	0	28	10	4
	N3	17	0	3	3	2	27	0	0	0	4
Dec	D1	9	23	28	4	8	20	40	40	16	8
	D2	25	0	5	5	51	54	0	11	3	50
	D3	41	32	0	86	91	30	28	2	80	78
Jan	J1	0	0	2	24	0	0	18	12	16	0
	J2	3	29	30	4	0	8	17	16	42	0
	J3	77	23	0	21	0	29	24	0	8	0
Feb	F1	99	0	0	0	0	45	0	0	0	0
	F2	0	0	0	0	18	0	0	0	0	4
	F3	0	36	0	3	0	0	23	0	0	0
Mar	M1	0	1	0	0	38	0	0	0	0	32
	M2	0	15	0	0	17	0	26	0	0	16
	M3	26	0	0	0	2	9	0	0	0	13
Apr	A1	0	0	41	0	49	2	0	43	0	35
	A2	10	0	6	0	15	6	0	12	0	17
	A3	0	13	3	0	0	0	0	3	0	0
	Total	383	177	199	171	292	311	194	236	200	270

Table III. Effects of rotation on wheat yield, rain-water-use efficiency and carbon discrimination at Jemaa Riah, 1998–2002

Parameter	1998–1999			1999–2000			2000–2001			2001–2002		
	W–F	W–VM	W–VI	W–F	W–VM	W–VI	W–F	W–VM	W–VI	W–F	W–VM	W–VI
Grain (kg/ha)	2,746a[a]	1,347b	1,154b	259a	30b	36b	1,210	1,123	1,143	689a	587a	338b
Straw (kg/ha)	3,700a	2,512b	2,482b	1,916.4a	715b	702b	2,291	2,045	2,209	1,656 a	1,226b	1,213 b
δ^{13}C grain (‰)	–22.3b	–21.9ab	–21.6a	–20.5	–	–	–21.9	–22.3	–22.2	–23.1	–23.3	–23.1
δ^{13}C straw (‰)	–25.0b	–24.5 a	–24.5a	–23.1	–23.5	–23.4	–24.5	–24.7	–24.6	–23.5	–23.7	–23.9
RWUE grain (kg/mm/ha)	14.2a	6.94b	5.96b	1.10	0.13b	0.15b	5.78	5.37	5.46	2.24a	1.90a	1.10b
RWUE total (kg/mm/ha)	30.9a	19.9b	20.5b	8.12a	3.03b	2.97b	16.7	15.1	16.0	7.61a	5.88b	5.03b

[a] Numbers in a row within a growing season followed by different letters are significantly different ($P \leq 0.05$).

Table IV. Effects of rotation on wheat yield, rain-water-use efficiency and carbon discrimination at Jemaa Shaim, 1998–2002

Parameter	1998–1999			1999–1900			2000–2001			2001–2002		
	W–F	W–VM	W–VI	W–F	W–VM	W–VI	W–F	W–VM	W–VI	W–F	W–VM	W–VI
Grain (kg/ha)	687	748	707	482a[a]	2,77b	231b	553	354	420	3,860a	2,433b	3,003b
Straw (kg/ha)	3,185	3,012	3,048	1,778a	1,493b	1,477b	2,214	1,796	1,812	5,193a	3,711b	4,556ab
δ^{13}C grain (‰)	–21.7b	–20.9a	–20.7a	–21.0	–	–	–20.4	–20.1	–20.0	–24.7b	–23.7a	–24.1a
δ^{13}C straw (‰)	–24.5b	–23.9a	–23.8a	–23.9	–23.2	–23.3	–22.8	–22.3	–22.3	–26.3b	–25.1a	–25.6a
RWUE grain (kg/mm/ha)	3.88	4.23	4.00	2.42a	1.39b	1.16b	2.05	2.44	2.84	12.7a	7.99b	9.86b
RWUE total (kg/mm/ha)	21.9	21.2	21.2	11.4a	8.81b	8.65b	12.2	12.9	14.4	29.7a	20.2b	24.8ab

[a] Numbers in a row within a growing season followed by different letters are significantly different ($P \leq 0.05$).

Despite the 383 mm received during the 1997–1998 fallow period, the differences between W–F and the other cropping systems in terms of wheat production (Table IV) were not significant because of the low rainfall (177 mm) in 1998–1999 (Tables II and IV). The same situation prevailed in 2000–2001; both previous and current rainfalls were low (199 and 171 mm). This difference was more pronounced in the 2001–2002 growing season (Table IV) when 311 mm were received during crop growth, despite the previous year's low rainfall (171 mm) (Table II).

Despite the superiority of the W–F system in terms of wheat production, low rainfall in 1998–1999 coupled with the extended dry period in 1999–2000, resulted in the lowest yield during the four years of the experiment (Table IV). Only 78 mm were received during the growing season, while 70 mm were received in October (before planting) and 50 mm in April and May when the grain was ready for harvest. The 30 mm received in the second decade of January at JS, compared to 15 at JR (Table II) coupled with soil-water holding capacity, made a big difference in wheat yield (Table III and IV).

Rain-water-use efficiencies, based on one season's rainfall for grain (RWUE grain) and straw (RWUE straw) followed the same trend as did wheat yields (Table IV). W–F was more efficient than the two other rotations because of extreme water stress that affected all of the rotations, especially during the 1998–2001 growing seasons. However, when two seasons' rainfall values are used (data not reported), the W–F system was as efficient as the others in 1999–2000, but less efficient in the other years.

The grain and straw $\delta^{13}C$ data for the 1998–1999 and 2001–2002 growing seasons showed significantly more-negative values than for W–VM and W–VI (Table IV). These values were related to both wheat grain and straw and their WUEs only in 2001–2002. However, for the other cropping seasons, there were either no differences in $\delta^{13}C$ among cropping systems (1999–2000) or no relationship between WUE and straw $\delta^{13}C$ as in 1998–1999 (Table IV). Walley et al. [22] reported that stomatal closure related to moisture deficit, reduced C discrimination and resulted in less-negative $\delta^{13}C$ values among tillage system within a rotation, but not between rotations. Other work showed effects of differing WUEs on $\delta^{13}C$ content of C_3 plants [23] especially when water was not growth-limiting [24,25].

2.2. Nitrogen uptake, percent nitrogen derived from fertilizer and nitrogen-use efficiency

2.2.1. Jemaa Riah

Nitrogen assimilated by grain (NUP grain), N uptake by straw (Nup straw) and total N uptake (Nup tot) were not affected by rotation treatment in 2000–2001. However, they were, in the other years, higher in W–F compared to the other rotations (Table V). Nitrogen uptake in W–VM and W–VI were not significantly different, except in 1998–1999 when W–VI was higher than W–VM and similar to W–F (Table V). Grain N uptake in vetch systems was nil because of lack of grain production in 1999–2000. Furthermore, the rainfall in the 1998–1999 season (218 mm) affected water storage and was beneficial as indicated by total water use (Table II).

Rotation affected the %N derived from fertilizer (%Ndff) for straw only in 1998–1999, with vetch systems having higher %Ndff values than the fallow system (Table V). The %Ndff for grain in W–F was higher in 1999–2000 and 2001–2002, but lower in 1998–1999, than W–VM and W–VI, which did not significantly differ from each other.

Grain N-use efficiency (NUE grain) and total N-use efficiency (NUE tot) were not affected by rotation treatment in 2000–2001, but in the other years they were higher in W–F (Table V). Straw NUE was affected by rotation treatment in 1998–1999 and 1999–2000; highest values were obtained with W–VI in 1998–1999 and with W–F in 1999–2000.

Table V. Effects of crop rotation on grain- and straw-N uptake, %N derived from fertilizer and N-use efficiency at Jemaa Riah, 1998–2002

Parameter	1998–1999			1999–2000			2000–2001			2001–2002		
	W–F	W–VM	W–VI	W–F	W–VM	W–VI	W–F	W–VM	W–VI	W–F	W–VM	W–VI
Nup grain (kg/ha)	63.7a[a]	30.0 b	27.8b	8.13a	0	0	32.3	28.6	30.5	19.7a	16.2a	9.56b
Nup straw (kg/ha)	20.9ab	18.4b	24.5a	26.8a	14.2b	15.2b	29.2	26.0	26.9	16.8a	10.0b	12.5b
Nup tot	84.6a	48.4b	52.3b	34.8	14.2	15.2b	61.5	54.6	57.4	36.5a	26.3b	22.1b
%Ndff grain	26b	31a	33a	15	0	–	8.2	9.0	9.8	21a	18 b	17b
%Ndff straw	27b	37a	34a	16	18	17	7.4	8.7	8.8	17	15	17.
NUE grain (%)	27a	17b	18b	8.4	–	–	6.0	6.5	7.2	7.8a	6.1a	3.0b
NUE straw (%)	9.4b	12ab	15a	8.8a	4.9b	5.3b	5.1	5.1	5.1	5.7	2.9	5.2
NUE tot (%)	37a	30b	33ab	17a	4.9b	5.3b	11	12	12	13a	9.0b	8.2b

[a] Numbers in a row within a growing season followed by different letters are significantly different ($P \leq 0.05$).

Table VI. Effects of crop rotation on grain- and straw-N uptake, %N derived from fertilizer and N-use efficiency at Jemaa Shaim, 1998–2002

Parameter	1998–1999			1999–2000			2000–2001			2001–2002		
	W–F	W–VM	W–VI	W–F	W–VM	W–VI	W–F	W–VM	W–VI	W–F	W–VM	B–VI
Nup grain (kg.ha)	20.4	22.8	21.0	11.6a[a]	5.85b	5.14b	15.3	10.9	12.94	83.7a	57.4b	68.5b
Nup straw (kg/ha)	32.8b	40.4a	37.0a	20.3	23.1	21.9	26.1	28.9	34.8	26.4a	21.3b	22.9b
Nup tot	53.2b	63.2a	58.0a	20.3	29.0	27.0	41.4	39.8	47.8	110a	78.7b	91.4b
%Ndff grain	48a	40b	39b	12	–	–	7.7	5.0	3.3	20b	27a	25a
%Ndff straw	64a	55b	52b	13	13	15	5.9	4.1	3.0	14c	22a	19b
NUE grain (%)	15	15	14	5.3	–	–	2.1	1.1	0.80	35	32	34
NUE straw (%)	37a	38a	32b	5.6	6.6	6.8	3.2	2.5	2.2	7.4b	10a	8.3ab
NUE tot (%)	53a	53a	46b	11a	6.6b	6.8b	5.2a	3.6b	2.9b	42	42	42

[a] Numbers in a row within a growing season followed by different letters are significantly different ($P \leq 0.05$).

2.2.2. Jemaa Shaim

Rotation did not affect N uptake or use efficiency in the 2001–2002 season. Nitrogen uptake by grain in W–F was higher than in the two other rotations only in 1999–2000 and 2001–2002 (Table VII). Values for %Ndff for grain and straw, as well as straw-N-use efficiency in W–F, were higher in 1998–1999, but lower in 2001–2002, than those in W–VM and W–VI. Wheat–vetch mowed (W–VM) had the highest straw and grain %Ndff in 2001–2002 (Table VI). Values for both straw- and total-N uptake followed the opposite trend: they were highest for W–F in 2001–2002 and lowest in 1998–1999. During the 1998–1999 season, total N-use efficiency was lowest in W–VI and in 1999–2000 and 2000–2001 in both vetch systems; total N-use efficiency was not affected by rotation in the other year (Table VI).

Fertilizer-use efficiency has been shown by many authors to vary widely with soil, climatic conditions and cropping systems. The NUE values for JR and JS were at the lower limits of the ranges reported in the literature. In data from the same sites NUE ranged from 25 to 35%, with that of W–F being highest [4]. Average NUE efficiency values for cereals in Greece ranged from 17 to 32% for wheat, 25 to 40% for barley and 17 to 37% for bread wheat [26]. However, values ranging from 30 to 70% have been reported by others [27,28].

2.3 Water use

Wheat yields and the other parameters differed greatly with year and location. They were higher at Jemaa Shaim than at Jemaa Riah in the 1999–2000 and 2001–2002 growing seasons (Tables III and IV).

There were no significant differences at either location between rotations or fertilizer treatments with respect to soil water at various depths within each period of measurement (data not shown). Similar results were obtained for total soil water. This was mainly due to the low rainfall over the growing seasons, especially in terms of received precipitation before harvest. Therefore, we could not evaluate soil-water conservation in the different rotations, especially W–F. Soil-water loss, before the first measurement, was probably not the same for the different rotations. However, total water use between the first measurement and harvest at JR indicates that W–F had 20 mm of water more than did the other rotations (Table VII). These results indicate that green manure depleted soil water and negatively affected soil-water availability for the following crop. Stanhill [2] and Paul et al. [21] obtained similar results in semi-arid conditions. It should be mentioned that comparison between years is not possible because of differences in times and locations of measurements from year to year due to the erratic rainfall distribution (Table II) and due to late and heterogeneous seedling emergence in 1998–1999 and 2001–2002.

At both locations, fallowing supplemented rainfall and buffered the drought period, giving plants more chance to survive until the next rainfall event. February and March rainfall, when not preceded by a long dry period, was a determinant for sustaining growth and increasing production and WUE of wheat. Paul et al. [21], Bouzza [3], Kacemi [5] and El Mejahed [4] have shown that fallow is the most convenient management system to counteract the frequent dry periods in semi-arid climates.

Table VII. Effects of rotation on water use by wheat in three rotations, 1998–2001

Growing season	Jemaa Riah			Jemaa Shaim		
	W–F	W–VM	W–VI	W–F	W–VM	W–VI
	(mm)					
1998–1999	174a	158b	157b	134	135	146
1999–2000	156a	137b	131b	125	120	112
2001–2002	116	109	112	162	167	171

[a] Numbers in a row within a location followed by different letters are significantly different ($P \leq 0.05$).

Bouzza [3] reported that water conserved by fallow is the only way to sustain grain production, especially in areas with less than 300 mm rainfall. A leguminous green manure as a preceding crop helps to alleviate erosion, fixes N_2 and reduce possible nutrient leaching, but also utilizes soil water. Paul et al. [21] and McVay et al. [29] indicated positive effects from green manure in terms of improving water infiltration, decreasing evaporation, or reducing water-logging for the following crop. However, its main negative effect in semi-arid conditions is the reduction of water storage for the following crop when compared to fallowing. Joffe [30] found that benefits from green manure depend on climatic conditions. Frye et al. [31] reported that green-manure residue, when placed on the soil surface, with no-till or conservation tillage, is probably the most efficient method of increasing water availability for the following crop. This practice decreases run-off, increases soil OM, improves soil structure and decreases soil-water evaporation. Results obtained by Zenter et al. [31] showed that wheat grain yield after green manure was generally lower than after fallow, mainly due to lower soil-water availability. Allison and Ott [32] concluded that use of a food legumes as a green manure would be profitable only if the following crop yields more than after fallow. However, economic and environment evaluations might show the green-manure system to be more sustainable in the long term.

2.4. Soil nitrate, percent nitrogen, organic matter and stability index

In the 1998–99 growing season, soil nitrate was determined at both locations for depths of 0 to 20 and 20 to 40 cm before planting (S) and 0 to 20, 20 to 40 and 40 to 60 cm at harvest (H). For the same year, total soil %N, OM and stability index (SI) were analyzed for the 0- to 20-cm soil profile at sowing and harvest (Table VIII). However, in 1999–2000, only nitrate and OM at 0–20 and 20–40 cm and nitrate at 40–60 cm were analyzed. In 2000–2001 soil analysis consisted of nitrate and OM in the top 20 cm of the soil at both locations (Table VIII).

Rotation ranking with respect to soil parameters differed with year and location. Rotations did not differ from each other with respect to the measured parameters at Jemaa Riah in 1998–1999 or at Jemaa Shaim in 2000–2001. Furthermore, except for %OM at harvest, which was lowest in W–F in 1998–1999 at Jemaa Shaim, rotations did not differ in soil SI, %OM or soil nitrate at 40 to 60 cm (Table VIII). Soil nitrate in the 0- to 20-cm layer at sowing was the highest in W–F at JR in 2000–2001, but lowest in 1999–2000, while the two other rotations did not differ from each other (Table VIII). However, at JS, the 1998–1999 soil-nitrate levels were highest in the vetch system in the 0- to 20-cm layer at sowing and at a depth of 20 to 40 cm at harvest. In 1999–2000, nitrate at 20 to 40 cm at sowing was the highest in W–VI and W–VM at Jemaa Riah and Jemaa Shaim, respectively (Table VIII).

At Jemaa Shaim in 1998–1999, fallowing resulted in less soil total %N and %OM at harvest than the with vetch (Table VIII). These differences would probably widen over time. Because of differences in soil texture, especially clay content, SI at JS was higher than at JR. It should be mentioned that vetch yield was very low during 1999–2000 and 2001–2002 seasons.

The level of nitrate in soil is affected by the cropping system, fertilizer management, soil and climatic conditions and the previous crop yield. Studies in Moroccan semi-arid regions indicated that soil nitrate after fallow was higher than after wheat, chickpea, ryegrass, vetch-oat mixture or oat [3–6].

The introduction of vetch probably increased soil nitrate through the accumulation of OM and mineralization. MacRae and Mehuys [33] reported that OM persistence and accumulation depends on many factors that affect microbial activity. Furthermore, OM accumulation is also related to green manure yields, which were low during the period of this experiment. The long-term effect of green manure on OM and soil N depends on the legume species, the period of the study, the crop rotation and soil type. Mann [34] demonstrated that, after an eighteen-year field study, soil-fertility level was not directly related to N in the crop or to the quantity of incorporated OM, but to factors such as soil type, crop rotation, initial soil N and OM and the sown species.

Table VIII. Effects of crop rotation on soil nitrate, soil P, organic matter, %N, and stability index at sowing (S) and harvest (H) at Jemaa Riah and Jemaa Shaim, 1998–2001

Growing season	Parameter	Jemaa Riah			Jemaa Shaim		
		W–F	W–VM	W–VI	W–F	W–VM	W–VI
1998–1999	NitS(0–20) (ppm)	25.8	32.89	25.9	31.9b[a]	44.5a	38.7a
	NitS(20–40) (ppm)	38.2	36.99	37.7	28.1	30.3	28.9
	NitH(0–20) (ppm)	27.6	21.6	26.6	42.2	51.9	49.4
	NitH(20–40) (ppm)	31.2	29.4	27.2	21.0b	26.7a	32.7a
	NitH(40–60) (ppm)	24.8	34.1	31.8	22.8	24.8	25.6
	OM S (%)	1.3	1.5	1.6	1.4	1.7	1.7
	OM H (%)	1.5	1.5	1.5	1.0b	1.2ab	1.3a
	Nsol S (%)	0.17	0.19	0.17	0.08	0.1	0.09
	Nsol H (%)	0.08	0.08	0.09	0.08b	0.10a	0.10a
	SI S	0.58	0.56	0.53	0.7	0.66	0.71
	SI H	0.61	0.56	0.52	0.69	0.68	0.65
	NitS(0–20) (ppm)	19.1b	19.1b	24.1a	10.1	11.3	7.53
	NitS(20–40) (ppm)	11.4b	10.3b	15.9a	12.0c	21.9a	15.7b
1999–2000	NitS(40–60) (ppm)	–	–	–	9.54	8.57	8.76
	%OM (0–20)	1.4	1.3	1.3	2.1	2.1	2.1
	%OM (20–40)	1.3	1.2	1.4	1.5	1.5	1.7
	NitS(0–20) (ppm)	17.6a	6.92b	7.22b	10.9	11.8	11.6
2000–2001	P(0–20) (ppm)	13.4a	10.7b	10.8b	3.72	5.45	4.71
	OM (%)	1.36	1.32	1.38	1.34	1.53	1.22

[a] Numbers in a row within a location followed by different letters are significantly different ($P \leq 0.05$).

Other studies over ten years in a clay soil in Holland concluded that there was no correlation between %N of incorporated material and the soil-accumulated OM. However, there was a highly significant correlation between accumulated OM and the lignin content of the plant material; soil pH and clay content were also factors determining the accumulation of OM [35]. Sowden and Atkinson [36] reported that soil OM decomposition is accelerated at lower pH. Russell [37] reported that green manure, especially legumes, is more effective as a means of increasing soil N than OM.

3. EFFECTS OF APPLIED FERTILIZER AVERAGED OVER ROTATIONS

3.1 Wheat grain and straw, rain-water-use efficiency and $\delta^{13}C$

Nitrogen did not increase grain yield, or grain or total dry matter efficiency based on annual rainfall (RWUE grain and RWUE tot) at Jemaa Shaim, during the 2000–2001 growing season (Table IX). Research in semi-arid Morocco has shown that whether to apply N-fertilizer is a dilemma because it may accelerate water deficit under severe drought conditions especially in the middle and at the end of the crop-growth cycle [38]. However, El Mejahed [4] found that a reasonable amount of applied N might only slightly affect water use but it increased WUE through increased dry-matter production before wheat-stem elongation.

Furthermore, many Moroccan farmers practice cereal–food legume and cereal–fallow rotations to compensate for low N-fertilizer application [39].

Table IX. Effects of nitrogen combinations on wheat yield, rain-water-use efficiency and carbon discrimination at Jemma Riah and Jemma Shaim, 1998–2002

Growing season	Parameter	Jemaa Riah				Jemaa Shaim			
		0–40[a]	40–0	40–46	0	0–40	40–0	40–46	0
1998–1999	Grain (kg/ha)	1,556	1,689	1,827	1,923	704	737	597	819
	Straw (kg/ha)	2,976	2,913	2,548	2,563	2,984	3,246	3,008	3,087
	RWUE gr (kg/ha/mm)	8.02	8.71	9.42	9.91	3.97	4.16	3.37	4.63
	RWUE tot (kg/ha/mm)	23.4	23.7	22.6	23.1	20.8	22.5	20.4	22.1
	$\delta^{13}C$ grain (‰)	–21.9	–22.1	–21.8	–	–20.8	–21.6	–20.9	–
	$\delta^{13}C$ straw (‰)	–24.7	–24.6	–24.6	–	–23.8	–24.4	–23.9	–
1999–2000	Grain (kg/ha)	86.0	149	106	91	365	265	284	402
	Straw (kg/ha)	1,008	1,165	942	897	1,414	1,811	1,694	1,410
	RWUE gr (kg/ha/mm)	0.36	0.63	0.45	0.39	1.83	1.33	1.43	2.02
	RWUE tot (kg/ha/mm)	4.63	5.57	4.44	4.19	8.94	10.4	9.94	9.10
	$\delta^{13}C$ grain (‰)	–		–	–	–	–	–	–
	$\delta^{13}C$ straw (‰)	–23.2	–23.3	–23.3	–23.3	–23.5	–23.5	–23.2	–23.9
2000–2001	Grain (kg/ha)	1,229	1,181	1,192	1,034	457ab	383b	3,36b	593a
	Straw (kg/ha)	2,183	2,233	2,261	2,050	1,962	1,970	2,001	1,831
	RWUE gr (kg/ha/mm)	5.87	5.64	5.69	4.94	2.69b	2.11b	1.93b	3.03a
	RWUE tot (kg/ha/mm)	16.3	16.3	16.5	14.7	13.7ab	13.1ab	11.7b	14.2a
	$\delta^{13}C$ grain (‰)	–21.9	–22.1	–22.1	–22.3	–20.1	–20.2	–20.0	–20.4
	$\delta^{13}C$ straw (‰)	–24.6	–24.6	–24.5	–24.8	–22.5	–22.3	–22.5	–22.6
2001–2002	Grain (kg/ha)	517	513	526	597	3,112	3,199	3,073	3,008
	Straw (kg/ha)	1,298	1,408	1,347	1,406	4,700	4,313	4,429	4,504
	RWUE gr (kg/ha/mm)	1.68	1.66	1.71	1.94	10.2	10.5	10.1	9.88
	RWUE tot (kg/ha/mm)	5.89	6.24	6.08	6.50	25.7	24.7	24.6	24.7
	$\delta^{13}C$ grain (‰)	–23.2	–23.2	–23.1	–23.3	–24.1	–24.3	–23.9	–24.5
	$\delta^{13}C$ straw (‰)	–23.7	–23.8	–23.5	–23.7	–25.5	–25.9	–25.6	–25.8

[a] Nitrogen treatments; see Materials and Methods.

3.2. Nitrogen uptake, percent nitrogen derived from fertilizer and nitrogen-use efficiency

The effects of N on these parameters was not consistent across years or locations. Nitrogen uptake by the grain (Nup grain) was highest in the check plot only at Jemaa Shaim in the 2000–2001 growing season. In the other situations, N uptake grain and straw (Nup straw) as well as total N uptake (Nup tot) were either not affected by applied N, as in 1999–2000 and 2001–2002 at Jemaa Riah, or increased with applied N, especially at the end of tillering or both at planting and at tillering (Table X).

Except for Jemaa Riah, where the lowest values for %Ndff for both grain and straw were obtained, dual N application at planting and the end tillering resulted in higher values than in the other treatments (Table X). Nitrogen use efficiency was not affected at Jemaa Riah in 1999–2000 or at Jemaa Shaim in 2000–2001 or at either location in 2001–2002. These parameters were highest with N applied only at the end of tillering at both locations in 1998–1999 and at Jemaa Riah in 2000–2001; however, the lowest values were obtained with the same N treatment at Jemaa Shaim in 1999–2000 (Table X).

Table X. Effect of N combinations on grain and straw N uptake and on %N derived from fertilizer and nitrogen-use efficiency at Jemaa Riah and Jemaa Shaim, 1998–2002

Growing season	Parameter	Jemaa Riah				Jemaa Shaim			
		0–40^a	40–0	40–46	0	0–40	40–0	40–46	0
1998–1999	Nup grain (kg/ha)	43.3a^b	38.9b	39.37b	–	22.9a	17.6b	18.6b	–
	Nup straw (kg/ha)	18.4b	19.6b	25.76a	–	37.4a	22.5b	35.6a	–
	Nup tot (kg/ha)	61.7a	58.5b	65.13a	–	60.3a	40.1b	54.3a	–
	%NdffG	29b	22b	39a		43a	0.10b	41a	
	%NdffP	27b	25b	45a		60a	3.9b	55a	
	NUE grain (%)	26a	18b	18b		21a	0.03c	8.9b	
	NUE straw (%)	11	12	14		49a	2.3c	23b	
	NUE tot (%)	37a	1b	32b		70a	2.3c	31b	
1999–2000	Nup grain (kg/ha)	2.27	3.48	2.77	2.32	4.18	2.86	4.07	4.3
	Nup st (kg/ha)	18.2	23.0	20.2	13.4	17.9b	25.1a	27.4a	16.8b
	Nup tot (kg/ha)	20.4	26.5	22.9	15.8	22.1b	27.9a	31.4a	21.1b
	%Ndff grain	0	0	0		0	0	0	
	%Ndff straw	18b	19b	31a		4.9b	26a	24a	
	NUE straw (%)	7.2	11	7.1		2.0c	16a	7.4b	
	NUE tot (%)	7.2	11	7.1		2.0c	16a	7.4b	
2000–2001	Nup grain (kg/ha)	32.8a	32.1a	31.8a	25.3b	13.9ab	11.1b	10.4b	16.8a
	Nup straw (kg/ha)	27.6ab	26.8ab	30.7a	24.3b	28.8ab	33.0a	34.4a	23.6b
	Nup tot	60.4a	58.9a	62.5a	49.5b	42.7ab	44.1a	44.8a	40.4b
	%NdffG	13a	8.4b	5.9c		4.5b	4.1b	7.5a	
	%NdffP	12a	7.9b	5.1c		3.4b	3.4b	6.2a	
	NUE grain (%)	11a	6.8b	2.4c		1.8	1.3	1.0	
	NUE straw (%)	8.1a	5.2b	2.0c		2.4	2.7	2.6	
	NUE tot (%)	19a	12b	4.3c		4.1	4.0	3.7	
2001–2002	Nup grain (kg/ha)	14.6	15.0	15.2	15.9	71.9a	69.8a	80.6a	57.0b
	Nup straw (kg/ha)	12.7	13.9	13.5	12.4	24.7ab	22.5bc	29.7a	17.3c
	Nup tot (kg/ha)	27.3	28.9	28.8	28.3	96.5ab	92.3b	110a	74.4c
	%NdffG	17b	15b	24a		19c	22b	31a	
	%NdffP	15b	13b	21a		14c	17b	23a	
	NUE grain (%)	6.4	5.9	4.6		32	37	31	
	NUE straw (%)	5.1	5.0	3.6		8.2	9.3	8.5	
	NUE tot (%)	12	11	8.3		40	47	39	

[a] Nitrogen treatments; see Materials and Methods.

[b] Numbers in a row within a location followed by different letters are significantly different ($P \leq 0.05$).

3.3. Soil nitrate, percent nitrogen, organic matter and stability index

Applied N did not substantially increase soil nitrate, %OM or SI at Jemaa Riah in 1998–1999, 1999–2000 or 2000–2001 (Table XI). However, at Jemaa Shaim, nitrate at sowing in the 0- to 20-cm layer [nitS(0–20)] increased with dual N application. The same results were obtained for nitrate at sowing in the 20- to 40-cm layer [nitS(20–40)] in 1999–2000 and for nitrate at harvest at 20 to 40 cm [nitH(0–20)] in 1998–1999.

Nitrogen losses probably occurred with the side-dressed N application that was followed by low rainfall and high temperature during most of the growing seasons.

Table XI. Effect of N on soil nitrate, OM, %N and stability index at sowing (S) and harvest (H) at Jemaa Riah and Jemaa Shaim, 1998–2002

Growing season	Parameter	Jemaa Riah				Jemaa Shaim			
		0–46[a]	40–0	40–46	0–0	0–46	40–0	40–46	0–0
1998–1999	NitS(0–20) (ppm)	23.7	26.8	24.5	28.3	28.8	42.1	27.0	29.8
	NitS(20–40) (ppm)	41.9	39.5	38.4	33.2	27.8	29.0	29.2	26.6
	NitH(0–20) (ppm)	20.8	29.9	30.7	29.0	35.2	23.9	68.2	–
	NitH(20–40) (ppm)	29.7	25.2	28.0	41.9	22.9	20.4	19.9	–
	NitH(40–60) (ppm)	26.6	25.4	24.5	22.8	25.1	22.7	20.6	–
	OM S (%)	1.3	1.4	1.2	1.4	1.4	1.4	1.5	1.4
	OM H (%)	1.5	1.7	1.6	1.4	1.0	1.2	1.1	–
	Nsol S (%)	0.15	0.15	0.19	0.17	0.07	0.08	0.07	0.09
	Nsol H (%)	0.09	0.09	0.09	0.07	0.09	0.08	0.08	–
	SI S	0.63	0.62	0.58	0.47	0.64	0.67	0.75	0.74
	SI H	0.55	0.68	0.57	0.64	0.93	0.9	0.92	–
1999–2000	NitS(0–20) (ppm)	20.8	17.4	21.4	16.8	11.6	4.65	21.0	3.38
	NitS(20–40) (ppm)	18.0	9.89b	9.98	7.88	11.8	9.07	19.1	8.04
	NitS(40–60) (ppm)	–	–	–	–	11.3	9.46	11.6	5.81
	OMS (0–20) (%)	1.8	1.5	1.3	0.89	2.1	2.2	2.5	2.0
	OM (20–40) (%)	1.4	1.7	1.6	1.3	2.1	1.6	0.93	1.5
2001–2002	Nit020 (ppm)	13.8	9.88	10.0	8.68	11.6	9.60	14.8	9.70
	OM (%)	1.6	1.47	1.37	1.27	1.58	1.08	1.34	1.44

[a] Nitrogen treatments; see Materials and Methods.

4. ECONOMICS

Both phases of each rotation were considered for each year. Vetch in W–VM was evaluated in terms of forage production and its revenue; incorporated vetch in W–VI required the same inputs without generating revenue. All expenses related to the various rotation phases, to fertilizer inputs and to management were accounted for (data not shown) along with revenues accrued to calculate the benefit:cost ratio.

The wheat–incorporated-vetch system had the lowest benefit:cost ratios at both locations in each of the four years (Table XII). The use of green manure in these semi-arid locations was not economically justified. Except for Jemaa Riah in the 2001–2001 season where W–VM had a better cost:benefit ratio, W–F had the highest cost/benefit ratios. The dry period of the experiment affected both wheat and, especially, vetch production.

Furthermore, soil-water conservation in W–F ensured grain production during the driest years when wheat in the other rotations failed to yield and vetch produced no dry matter. Despite these results, vetch alone or in a mixture with cereals, is still an alternative for continuous cropping in areas with more favorable rainfall and in shallow soils of low water-holding and/or storage capacities.

As discussed before, wheat responses to applied N were either negative or very low. Consequently, based on benefit:cost ratio, the application of N was not economically justified during the period of experiment (Table XIII) with three consecutive dry years.

Table XII. Benefit:cost ratios for rotations and years at Jemaa Riah and Jemaa Shaim

Growing season	Jemaa Riah			Jemaa Shaim		
	W–F	W–VM	W–VI	W–F	W–VM	W–VI
1998–1999	3.72	2.82	1.16	1.65	1.25	0.96
1999–2000	0.74	–0.24	–0.25	1.02	0.20	0.17
2000–2001	1.92	1.42	1.09	1.23	0.53	0.41
2001–2002	1.19	2.04	0.17	4.92	3.74	2.94

Table XIII. Benefit:cost ratios for various nitrogen combinations and years at Jemaa Riah and Jemaa Shaim

Growing season	Jemaa Riah				Jemaa Shaim			
	0–40[a]	40–0	40–46	0	0–40	40–0	40–46	0–0
1998–1999	2.88	2.34	2.03	3.32	1.41	1.23	0.91	1.78
1999–2000	0.09	0.06	–0.12	0.17	0.51	0.36	0.24	0.70
2000–2001	1.72	1.37	1.22	1.75	0.85	0.57	0.42	1.13
2001–2002	1.32	1.06	0.91	1.66	4.24	3.71	3.33	4.56

[a] Nitrogen treatments; see Materials and Methods.

5. CONCLUSION

The three consecutive dry years affected grain yields, even in the wheat–fallow system, at both locations. Fallowing ensured grain production in both locations, where the wheat–vetch system failed to produce grain in the driest year. Rainfall distribution affected wheat yield more did than total precipitation. Consequently N either depressed or did not affect yield in the different cropping systems. Nitrogen-use efficiency was in general highest with wheat fallow at both locations. The severe drought, coupled with bad rain distribution resulted in no yield response to N and in low NUE values. There was no difference among rotations in terms of soil %OM and only a small difference with respect to soil nitrate. This was due to low green manure production, which was nil in the driest years. Nitrogen did not affect soil water in the different profiles and rotations. Incorporated vetch is not economically justified in this semi-arid region, where water is the main limiting factor for crop production. As a forage, vetch is still a viable alternative to continuous wheat.

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APPENDIX

A1. JEMAA RIAH SOIL PROFILE

Ap: 0–13 cm:
dark reddish brown (5YR 3/3), clay loam; week subangular blocky and granular structure; firm.
A1: 13–28 cm: Dark reddish brown (5YR 3/3), clay loam; week, very coarse prismatic structure, massive to granular inside, very firm, many worm casts; many roots
Bu: 28–65 cm: Reddish brown (2.5 YR 4/4), clay; moderate, very coarse prismatic structure, parting to moderate medium and coarse angular blocky; pressure faces, wedge-shaped aggregates and parallelepipeds; dense; roots between pods.
Bk: 65–100 cm: Red (2.5 YR 4/6) clay loam; week very coarse prismatic and medium subangular blocky structure; firm; common to many carbonate accumulation, few with hard centres.

A1.1. Diagnostic features

1- Ochric epipedon
2. Calcic horizon (k)
3. Gilgai
4. Slickensides, wedge-shaped aggregates, cracks
5. Xeric moisture regime
6. Thermic temperature regime
The soil was classified as a fine montmorillonitic, thermic Palexerollic chromoxeret
Soil capability subclass: Iie

A.2. JEMAA SHAIM SOIL PROFILE

Ap: 0–10 cm:
Very dark gray (10YR 3/1), clay; moderate medium subangular blocky and granular structure; firm.
Bu: 10–75 cm:
Very dark gray (10YR 3/2), clay; moderate very coarse prismatic structure with wedge-shaped aggregates and slickensides and parallelepipeds; very firm.
Bu: 75–100 cm:

Dark gray (10YR 3/2), clay; weak very coarse prismatic structure, few wedge shaped aggregates and slickensides; firm; few to common soft powdery lime spots (white).

Buk: 75–100 cm:
Red (2.5 YR 4/6) clay loam; week very coarse prismatic and medium subangular blocky structure; firm; common to many carbonate accumulation, few with hard centres.

A2.1. Diagnostic features

1- Ochric epipedon
2. Calcic horizon (k)
3. Gilgai
4. Petrocalcic horizon (below 1 m)
5. Slickensides, wedge-shaped aggregates, parallelepipeds and deep cracks
6. Xeric moisture
The soil was classified as a very fine montmorillonitic thermic Palexerollic chromoxerert (mixed)
Soil capability subclass: IIIw

INCREASING CROP PRODUCTION IN RAINFED DRY AREAS BY IMPROVED WATER AND NUTRIENT MANAGEMENT

W. MOHAMMAD, S. MAHMOOD SHAH, M. MOHSIN IQBAL, H. NAWAZ
Nuclear Institute for Food and Agriculture,
Peshawar, Pakistan

Abstract

The responses of three cropping sequences to two tillage and nutrient-management factors with a view to improved and sustained productivity of a rainfed farming system were tested at the Nuclear Institute for Food and Agriculture (NIFA) Research Station and farmers' fields from 1998 to 2002. The tillage treatment improved grain yield of wheat at the research station, but did not improve farmers' yields significantly. Fertilizer-N utilization by wheat was greater on farmers' fields (up to 42% of applied N) than at the research station (up to 33%). Grain yield of lentil was not influenced by tillage or nutrient level, but N accumulation in grain was significantly greater at the higher P level. Nitrogen fixation was also stimulated by higher P. The lentil crop obtained 82 to 96% of its N from fixation, up to 6% from applied fertilizer and up to 12% from soil. The amounts fixed varied from 42 to 91 kg/ha in different treatments. The chickpea crop obtained 52 to 64% of its N from fixation, up to 9% from applied fertilizer and up to 39% from soil. Carbon-13 discrimination values (δ) of straw, grain and root of wheat revealed no evidence of water stress at NIFA under tillage. On a farmer's field at Urmar, tillage induced some water deficit as reflected by less-negative δ values of straw. Applied P had no significant effect on moisture availability. Intercropping of wheat, lentil and chickpea was not productive. Lentil, a legume, had a significant positive effect on yield of subsequent wheat as compared to a wheat–wheat sequence, potentially providing additional income. The %N derived from fertilizer and %N utilization from residual ^{15}N-labelled urea indicated that wheat utilized less than 1% of the N applied in the previous year. Water-use efficiency (WUE) in terms of wheat grain was improved (3.31 kg ha^{-1} mm^{-1}) in the lentil-wheat sequence and tillage treatment at NIFA as compared to no-tillage and wheat-wheat sequence. The WUE of wheat grain indicated a good correlation (R^2=0.988) with δ^{13}C values of grain.

1. INTRODUCTION

Of the total cropped area of 20.5 Mha in Pakistan, about 5 Mha (24%) is rainfed [1]. Most of the rainfed area is in the North West Frontier Province (NWFP) of Pakistan where 62% (i.e. 1.2 of 1.9 Mha) is rainfed. These rainfed areas are diverse in regard to soil, climate, resource base, production system, and socio-economic and demographic features. Their development potential, therefore, cannot be broadly grouped. Even within a defined ecological zone, strategies have to be tailored to local regional conditions.

Annual rainfall in the country varies from <100 mm (in hot deserts) to >1,500 mm (in the lower Himalayas). The pattern is bimodal with 60 to 705 mm occurring in summer, July to September, and the remainder falling in winter, December to February. The major limitation in dryland rainfed agriculture is inadequate and unpredictable precipitation, which fluctuates from season to season and year to year.

Normally, rainfall is insufficient to grow two crops per year. The farmer has to choose between growing a summer crop (millet, sorghum, mung bean or sesame) or a winter crop (wheat, chickpea, rapeseed or barley). If he chooses a winter crop, he has to conserve soil moisture from the summer rains until sowing the winter crop (November). This is traditionally done by a combination of tillage practices: deep cultivation (24–27 cm) in June every 3 years using a moldboard plough and harrowing the soil yearly to maximize water penetration. At the end of the rainy season, the soil surface is planked to prevent surface evaporation. In addition to suffering water shortages, the soils of rainfed areas of Pakistan are of low fertility. Drought and nutritional stress — including widespread nutrient deficiencies [2] and low and unbalanced use of fertilizer [3] — are the major constraints to crop production under rainfed conditions.

Adequate and proper use of fertilizer can become a major instrument of change, and coupled with improved cultural practices can double the crop yields at least in areas with rainfall >350 mm [1]. Balanced fertilizer use can also reduce the adverse effects of drought. Options to increase water-use efficiency (WUE) include conservation of rainwater, reduction in water loss and adoption of suitable and appropriate cultural practices [4, 5]. Of the cultivated rainfed areas in Pakistan, almost 50% have no inherent soil limitation except moisture shortage. Highly diverse climatic and soil conditions make possible the production of a wide range of field and horticultural crops. New techniques and innovations must be developed to increase effective and efficient use of already scarce water resources for enhancing crop production in rainfed dry areas of Pakistan.

If rainwater is utilized effectively and the existing systems improved through proper cropping sequences and fertilizer- and water-management technologies, they will enhance/sustain productivity of rainfed farming, which has high practical and economic value for rural communities. The objective of this project was to devise a profitable farming system with improved water- and fertilizer-management practices under rainfed conditions using nuclear techniques, and to extend applicability to farmers' fields. The response of three cropping sequences to two tillage and nutrient-management factors were tested at a research station and on farmers' fields under rainfed conditions.

2. MATERIALS AND METHODS

Field experiments were conducted under the framework of IAEA-Research Contract Pak.9990, 1998 to 2002, at the Nuclear Institute for Food and Agriculture (NIFA) and on farmers' fields in the rainfed area around Peshawar (34°4' N, 72°25' W). The soil of the experimental site at the institute was a silt clay, alkaline, moderately calcareous, deficient in N (0.05%), P (7.0 $\mu g\ g^{-1}$) and organic matter (OM) (0.62%) and free from salinity, with a field capacity of 0.37 $cm^3\ cm^{-3}$ and a bulk density (BD) of 1.62 $g\ m^{-3}$. The soils of the farmers fields were loams, alkaline, calcareous and very low in N (0.02–0.03%) and P (3–4 $\mu g\ g^{-1}$) and OM(0.4–0.5%) and free from salinity with a field capacity of 0.26 cm^{-3} and BD of 1.5 $g\ m^{-3}$. Details of experimental treatments are given below.

2.1. NIFA Research Station

2.1.1. Cropping sequences (main plots)

Growing season				
	1998–1999	1999–2000	2000–2001	2001–2002
(i)	Wheat (cv. Tatara)	Wheat (cv. Tatara)	Wheat (cv. Tatara)	Wheat (cv. Tatara)
(ii)	Lentil (cv. Local)	Wheat (cv. Tatara)	Chickpea (cv. NIFA-95)	Wheat (cv. Tatara)
(iii)	Wheat intercropped with lentil and chickpea in alternate rows during 1998–1999 and 2000–2001. In 1999–2000 and 2001–2002, wheat was grown in the rows occupied by lentil and chickpea during 1998–1999 and 2000–2001 respectively, and vice-versa.			

2.1.2. Water management (sub-plots)

Soil water was managed via tillage: (i) conventional tillage (Farmers' practice), and (ii) no tillage. The water contents of the soil profiles in these treatments were determined at regular intervals with a neutron moisture probe.

2.1.3. Nutrient management (sub-plots)

Two nutrient levels were applied in 1998–1999 and 2000–2001. These plots were further sub-divided into two portions making four nutrient levels in 1999–2000 and 2001–2002, as follows.

1998–1999	1999–2000	2000–2001	2001–2002
i. N_{60}[a] + P_{30}	i. $N_{30} + P_{30}$	i. $N_{60} + P_{30}$	i. $N_{30} + P_{30}$
	ii. $N_{60} + P_{30}$		ii. $N_{60} + P_{30}$
ii. $N_{60} + P_{60}$	iii. $N_{30} + P_{60}$	ii. $N_{60} + P_{60}$	iii. $N_{30} + P_{60}$
	iv. $N_{60} + P_{60}$		iv. $N_{60} + P_{60}$

[a] Nitrogen at 60 kg ha^{-1}, etc.

The experiments were laid out in a split-split-plot design with cropping sequences forming the main plots, tillage treatment forming the sub-plots and nutrient ratios forming the sub-sub-plots. The row-to-row distance was kept at 30 cm.

2.2. Farmers' fields

The experimental plan for farmers' fields was the same as at NIFA Research Station except that the plots were bigger and there were two replications. In response to termite attacks on some of the experimental plots, Furadan granules were applied.

2.3. Nuclear techniques

At NIFA, ^{15}N-labelled fertilizer was used to determine efficiency of utilization of applied N as influenced by tillage and P fertilization (N:P ratio) during 1998–1999 and 2000–2001. Labelled urea (1% ^{15}N a.e.) was applied to the nutrient sub-sub-plots of the tillage/no-tillage treatments of wheat (in 1 × 1 m micro-plots in four replications). In order to study the residual availability of N, ^{15}N-urea (1% a.e.) was applied during 1998–1999 and 2000–2001 to nutrient sub-plots of wheat; no labelled urea was applied during 1999–2000 or 2001–2002, when ordinary urea was used.

On farmers' fields, labelled fertilizer was used to assess fixation of atmospheric N_2 by lentil during 1998–1999 and by chickpea during 2000–2001. For this purpose, lentil and chickpea crops were fertilized with ^{15}N-urea (5% ^{15}N a.e., at 20 kg N/ha). The lentil seed was inoculated with *Rhizobium leguminosarum* by a seed-pelleting technique before sowing; no inoculant was applied to chickpea. Wheat, as a reference crop, was fertilized at 60 kg N/ha with urea labelled at 1% ^{15}N a.e. The labelled fertilizer was applied to all crops as an aqueous solution, in 1 × 1 m micro-plots in all replicates. In order to study the residual availability of ^{15}N applied in 1998–1999 and 2000–2001 to nutrient sub plots of wheat, lentil and chickpea, no labelled urea was applied during 1999–2000 or 2001–2002.Instead, ordinary urea was used.

The soil-water profiles down to 90 cm under tillage and no tillage and cropping-sequence treatments were determined by neutron moisture probe. A single light irrigation (6 cm), to facilitate seedbed preparation, was given at NIFA Research Station; no irrigation was applied to the farmers' fields. However, during 2000–2001 due to a prolonged dry spell, one more irrigation was applied at the flowering stage to preclude complete crop failure. After this, the crops at NIFA as well as on the farmers' fields solely depended on rainfall. Total rainfall during the growing season was 268 mm in 1998–1999, 158 mm in 1999–2000, 85 mm in 2000–2001 and 142 mm in 2001–2002.

2.4. Sampling

Samples of wheat, lentil, and chickpea at harvest were separated into straw and grain. These samples were finely ground in a Wiley mill and analysed by the IAEA for ^{15}N and ^{13}C content and total N. The data for calculating N yield, fertilizer-N yield, N utilization, etc., were recorded on the main (non-labelled) plots. For intercropping (main plot iii), land usage was determined to see whether it improved when wheat and lentil, wheat and chickpea were intercropped or otherwise. For this, relative yields (intercrop yield/sole-crop yield) were calculated for wheat, lentil and chickpea, and then were added to provide land equivalent ratio (LER) values, i.e. productiveness per unit area.

Table I. Effects of tillage and nutrient treatment on grain yields of wheat, lentil and chickpea

Crop	Location	Tillage	Grain yield					
			1998–1999			2000–2001		
			P_1[a]	P_2[b]	Till.-mean	P_1	P_2	Till.-mean
			(kg ha^{-1})					
Wheat	NIFA Res. Stn.	T_1[c]	4,666ab	4,883a	4,774a	2,067	2,100	2,083
		T_0[d]	4,000c	4,100bc	4,050b	1,200	1,333	1,267
		P-mean	4,333a	4,491a		1,633	1,717	
	Urmar	T_1	1,917	2,067	1,992a	443b	433b	439b
		T_0	1,683	1,850	1,766a	500b	800a	650a
		P-mean	1,800a	1,958a		472b	617a	
	Jalozai	T_1	2,667	2,767	2,717	–	–	–
		T_0	2,867	3,033	2,950	–	–	–
		P-mean	2,767	2,900		–	–	
Lentil	NIFA	T_1	1,447a	1,200a	1,327a			
		T_0	1,380a	1,547a	1,467a			
		P-mean	1,413a	1,373a				
Chickpea		T_1				2,000	1,934	1,967
		T_0				1,767	1,900	1,833
		P-mean				1,880	1,913	
Lentil	Urmar	T_1	1,016	1,050	1,033a			
		T_0	783	783	783a			
		P-mean	899a	916a				
Chickpea		T_1				56.7d	177c	66.7b
		T_0				114.3a	97.7b	106a
		P-mean				85.3b	87.0a	
Lentil	Jalozai	T_1	1,100	1,267	1,183	–	–	
		T_0	1,267	1,133	1,200	–	–	
		P-mean	1,183	1,200		–	–	

[a] $N_{60} + P_{30}$. [b] $N_{60} + P_{60}$. [c] Conventional tillage. [d] No tillage.

3. RESULTS AND DISCUSSION

The results are discussed under two main headings with respect to the crops and treatment effects at the three experimental sites, i.e. at NIFA Research Station and at farmers' fields from 1998 to 2002.

3.1. Effects of tillage and nutrient management on yield and fertilizer N utilization

3.1.1. Wheat

3.1.1.1. Yield

At NIFA, tillage increased grain yield significantly (Table I). The higher P level also led to higher yields. The interaction between nutrient level and tillage was significant, showing that the highest yield was obtained under tillage treatment at N:P of 60:60; the lowest yield was obtained under no tillage at N:P of 60:30.

On farmers' fields, yields of wheat (Table I) were not improved by tillage; neither did N:P at 60:60 increase yield. At Urmar, tillage and the higher P level appeared to improve grain yield, but the effect was not significant. At Jalozai, on the other hand, grain yield was markedly increased under no-tillage and at higher P. These results indicate that tillage is not beneficial under farmers' conditions. Overall higher yields were obtained during the 1998–1999 growing season, due to a prolonged dry spell during 2000–2001, which resulted in crop failure at Jalozai.

Considerable work has been done to elucidate the effects of various tillage systems on productivity of dryland agriculture. However, yield responses have not been clear-cut. Some workers have reported beneficial effects of no-tillage, whereas others have found no differences between conventional tillage, reduced tillage and no-tillage (NT). Yields of wheat have tended to be greater under no-tillage whereas those of spring barley have been greater under conventional tillage (moldboard ploughing to about 150 mm depth followed by at least two secondary tillage operations) [6]. In contrast, higher wheat yields have been obtained with reduced tillage (one ploughing in spring) than with conventional tillage (CT) (one ploughing in autumn and two in spring) or zero tillage (ZT) (harrowed + herbicide), although differences were not always significant [7].

On the other hand, it has also been reported that winter wheat consistently yielded less under no-tillage than conventional tillage regardless of fertility [8, 9] and lower wheat yields in NT were attributed to poor tiller initiation and lower tiller survival [10]. Plant development was also delayed in NT compared with CT. In India, grain yields of wheat were 14% higher in CT than NT plots [11]. In a 2-year study in West Africa, tillage increased grain yield of pearl millet by 68 to 70%, by increasing soil moisture storage in the upper 1.4 m [12]. However, no differences were found in yields of wheat, sorghum or maize due to tillage method (no-till vs. chisel-till) or fertilizer treatment [13]. Similar yields of wheat, rape and barley were obtained under CT, NT and minimum-tillage systems [14]. In that experiment, the effects of tillage and cropping system on spring soil moisture, which was responsible for observed differences in crop water use and consequently in yield, were dependant on soil type. Likewise, similar wheat yields were obtained in Israel with both NT and CT in a normal year whereas in drought years, NT management increased yield relative to CT [15]. In summary, tillage effects on yield depend on conditions such as agro-climatic zone, rainfall, crop and soil type.

Table II. Effects of tillage and nutrient treatment on utilization of fertilizer N by wheat as influenced by tillage and nutrient treatments at NIFA Research Station and on farmers' fields, 1998–1999

Location	Tillage	P level	Fertilizer-N yield				N utiliz'n (%)	Means
			Straw	Grain	Root	Total		
			(kg ha^{-1})					
NIFA Res. Stn.	T_1[a]	P_1	8.48	10.2	0.34	19.0	32	T_1: 32a
		P_2	9.00	10.4	0.38	19.8	33	T_0: 26b
	T_0	P_1	6.69	8.02	0.42	15.1	25	P_1: 28a
		P_2	6.50	8.68	0.31	15.5	26	P_2: 29a
Urmar	T_1	P_2	8.16	16.8	0.49	25.5	42	T_1: 39a
		P_2	6.73	14.4	0.42	21.6	36	T_0: 32a
	T_0	P_1	8.31	9.53	0.51	18.4	31	P_1: 37a
		P_2	6.78	12.6	0.52	19.9	33	P_2: 35a
Jalozai	T_1	P_2	7.26	11.6	0.21	19.1	32	T_1: 32
		P_2	5.15	13.5	0.20	18.8	31	T_0: 34
	T_0	P_1	5.28	10.8	0.24	16.3	27	P_1: 30
		P_2	8.03	15.8	0.17	24.0	40	P_2: 36

[a] Conventional tillage; T_0= No tillage; $P_1 = N_{60} + P_{30}$; $P_2 = N_{60} + P_{60}$.

Table III. Effects of tillage and nutrient treatment on utilization of fert. nitrogen by wheat, 2000–2001

Location	Tillage	P level	Fertilizer-N yield			N utiliz'n (%)	Means
			Straw	Grain	Total		
			(kg ha^{-1})				
NIFA	T_1[a]	P_1	2.45	9.67	12.1	20	T_1: 12
Res. Stn.		P_2	2.71	9.76	12.5	21	T_0: 8.7
	T_0	P_1	2.15	6.20	8.36	14	P_1: 10a
		P_2	1.62	7.38	9.00	15	P_2: 11a
Urmar	T_1	P_2	3.86	1.37b	5.24	8.7	T_1: 6.1a
		P_2	5.62	1.36b	6.98	12	T_0: 6.2a
	T_0	P_1	3.98	1.58b	5.56	9.3	P_1: 5.4a
		P_2	4.53	2.39a	6.92	12	P_2: 7.0a

[a] Conventional tillage; T_0= No tillage; $P_1 = N_{60} + P_{30}$; $P_2 = N_{60} + P_{60}$.

3.1.1.2. Fertilizer-nitrogen utilization

At NIFA, up to 33% of fertilizer N was utilized by wheat during the 1998–1999 season (Table II), whereas only up to 21% of fertilizer N was utilized at NIFA by wheat during 2000–2001 (Table III). The tillage treatment led to significantly greater N utilization (32% in 1998–1999 and 12% in 2000–2001) compared to NT (26% in 1998–1999 and 8.6% in 2000–2001) when averaged over P levels. Nutrient level, however, exerted no effect. Grain utilized more N than straw and root combined.

On the farmer's field at Urmar, the amount of N taken up by wheat was the highest of the three experimental sites (up to 42% during 1998–1999). As at NIFA, the tillage treatment led to greater N utilization than did the no-tillage treatment during 1998–1999 but no significant effect of tillage on N utilization was found during 2000–2001. Over all, higher amounts of N were utilized during the 1998–1999 season as compared to 2000–2001, both at the research station and on farmer fields. The low N utilization during 2000–2001 was due to low yield and early maturity of crops because of a prolonged dry spell. Results from forty-three fertilizer trials in the Punjab (Pakistan) also showed that fertilizer-use efficiency decreased in a no-tillage system [16], and N, S deficiency were more severe under no-tillage whereas P deficiency was less affected by tillage [8]. On the other hand, at Jalozai (Table II), no-tillage contributed to slightly higher N utilization, as did the higher P level. The magnitude of accumulation of N by wheat plant parts, particularly grain, was higher on farmers' fields than at NIFA Research Station. This could have been due to nutrient deficiency in the farmers' soils where the amounts of fertilizers applied were much below the recommended levels. Usually one 50-kg bag of urea (23% N) only is applied to wheat at sowing time.

3.1.2. Lentil

3.1.2.1. Yield

At Urmar (Table I), tillage and the higher P level individually produced higher yields of lentil grain though not significantly so. At Jalozai, however, yield was unaffected by tillage or nutrient treatment. The results obtained at both locations indicate that tillage practices slightly improved the grain yield of lentil. Similarly, Lampurlanes et al. [17] reported that the grain yield (4 year) of barley was similar between no tillage and minimum tillage and significantly lower for subsoil tillage under semi-arid conditions. Although the yield data from our experiments showed that the difference between P levels was found non-significant, N_2 fixation was improved by the higher P level. The results of Idris et al. [18] showed that application of P at 40 and 60 kg ha^{-1} to an inoculated treatment increased grain yield of lentil by 17 to 18.5%, and significantly improved nodulation of lentil. These results are in agreement with our findings.

Table IV. Effects of tillage and nutrient treatments on nitrogen derived by wheat and lentil from fertilizer, and sources of nitrogen for lentil, on farmers' fields, 1998–1999

Location	Tillage	P level	Nitrogen derived from fertilizer (weighted average)					
			Non-fixing system (wheat)			Fixing system (lentil)		
			Total N yield	Total fert. N yield	Ndff[b] (%)	Total N yield	Total fert. N yield	Ndff (%)
			($kg\ ha^{-1}$)			($kg\ ha^{-1}$)		
Urmar	T_1[a]	P_1	64.9	25.5	39	69.8	2.84	4.1
		P_2	60.7	21.6	36	78.3	4.36	5.6
	T_0	P_1	62.7	18.4	29	50.9	2.57	5.1
		P_2	56.2	19.9	35	54.7	1.65	3.0
Jalozai	T_1	P_1	80.1	19.1	24	74.1	1.00	1.4
		P_2	74.2	18.8	25	84.0	1.05	1.3
	T_0	P_1	78.2	16.3	21	95.3	0.88	0.92
		P_2	80.1	24.0	30	73.3	0.77	1.1

Location	Tillage	P level	Nitrogen sources for lentil						
			Proportion			Amount			
			Ndff[b]	Ndfa	Ndfs	Ndff	Ndfa	Ndfs	Total
			(%)			($kg\ ha^{-1}$)			
Urmar	T_1[a]	P_1	4.1	90	6.3	2.84	62.6	4.39	69.8
		P_2	5.6	84	10	4.36	66.1	7.90	78.3
	T_0	P_1	5.1	83	12	2.57	42.1	6.21	50.9
		P_2	3.0	91	5.5	1.65	50.0	3.02	54.7
Jalozai	T_1	P_1	1.4	94	4.3	1.00	69.9	3.90	74.1
		P_2	1.3	95	3.7	1.05	79.9	3.10	84.0
	T_0	P_1	0.92	96	3.5	0.88	91.1	3.32	95.3
		P_2	1.1	97	2.5	0.77	70.7	1.79	73.3

[a] Conventional tillage; T_0= No tillage; $P_1 = N_{60} + P_{30}$; $P_2 = N_{60} + P_{60}$.

[b] Nitrogen derived from fertilizer; Ndfa = nitrogen derived from the atmosphere (i.e. from fixation); Ndfs = nitrogen derived from soil.

3.1.2.2. Nitrogen fixation by lentil on farmers' fields

At Urmar and Jalozai, only a small proportion (up to 6%) of its lentil N was derived from applied fertilizer (Table IV). In comparison, wheat derived up to 39% of its N from fertilizer. The major proportion of lentil N (82 to 96%) was derived from fixation; the remaining proportion (up to 12%) was taken up from the soil. Similarly, Shah et al. [19] reported that in a rainfed area of the Swat River Valley (NWFP-Pakistan), lentil fixed 37 to 45 kg N ha^{-1} and values for P fixed were 85% in control and 93 to 97% in inoculated treatments. In rainfed areas of Jordan also, two lentil cultivars obtained 80 and 83% of their N requirements from fixation [20]. The proportions and quantities of N fixed were higher at Jalozai than at Urmar.

Effect of tillage and nutrient treatment on N_2 fixation were not pronounced at Jalozai, whereas at Urmar, the quantities of N fixed were higher under N_{20}:P_{60} and with tillage. This can be explained by the fact that leguminous crops have greater P requirements compared to cereals and tillage makes the soil environment more conducive to N_2 fixation.

3.1.3. Chickpea

3.1.3.1. Yield

Tillage increased grain yield of chickpea though the effect was nonsignificant (Table I). The higher P level also led to higher yields. The interaction between nutrient level and tillage was significant, showing that the highest yield was obtained with tillage with N:P at 20:60 and the lowest with no tillage and N:P at 20:30. At Urmar, chickpea yields were not improved by tillage, whereas N:P of 20:60 did increase yield. These results indicate that tillage was not beneficial under farmers' conditions and P significantly enhanced yield on the research station as well as under farmers' conditions. Overall, chickpea yields were low on farmers' fields because of a prolonged dry spell.

3.1.3.2. Nitrogen fixation by chickpea

Chickpea derived up to 8.6% of its plant-N from fertilizer (Table V). In comparison, wheat derived up to 19% of its N from fertilizer. A major proportion of N (52 to 64%) was derived by chickpea from fixation; the remaining proportion (up to 36%) was taken up from the soil. The chickpea crop fixed less N_2 than did lentil (Table V). This was due to lower chickpea yields because of a prolonged dry spell. The effect of tillage on N_2 fixation was not pronounced; it was higher under N_{20}:P_{60}.

3.1.3.3. Carbon-isotope discrimination

At NIFA, the ^{13}C-discrimination (δ) values were more negative in wheat straw and grain under tillage than no tillage, but the effect was not statistically significant (Table VI). However, the values for root were significantly more negative under tillage than under no-tillage. The tillage × P-level interaction was also non-significant for δ values of the three plant parts. The more-negative ^{13}C discrimination values for roots under tillage indicate that wheat roots discriminated against this heavier isotope to a greater degree than when under no-tillage, implying that relatively greater amounts of water were taken up with tillage. These values showed a positive relationship: wheat grain yield was higher with tillage.

The general condition of the wheat crop under tillage at NIFA was very good despite absence of rains from November 1998 to January 1999. A light pre-sowing irrigation was given to optimize sowing time. The experimental soil being clayey in texture, the water-holding capacity was high, so no adverse effect of the dry spell was noted. Rains were frequent from January onwards. The less-negative ^{13}C discrimination values and low yield under tillage and no tillage found during the 2000–2001 season (Table VII) as compared to the values for 1998–1999 could be due to the adverse effects of the prolonged dry spell during 2000–2001.

However, on the farmer's field at Urmar, ^{13}C values were not influenced by tillage, nutrient level or their interactions except in straw where P level × tillage interactions were significant (Tables VI and VII). These interactions showed that δ values were less negative under no-tillage at both P levels indicating that tillage exerted more influence on δ values than did P levels. It is probable that stomatal closure in no-tillage plots, related to moisture stress, reduced ^{13}C discrimination resulting in less-negative values. This agrees with the findings of Walley et al. [21].

On the farmer's field at Jalozai also, straw and grain exhibited slightly less-negative ^{13}C-discrimination values under no-tillage, whereas P level had no effect. The differences in δ^{13}C values for lentil were not significantly influenced by tillage or nutrient treatments for straw, grain or roots but the value in grain at Jalozai tended to be less negative under P_2 compared to P_1. However, in the case of chickpea, the values for straw were significantly increased by tillage. The grains generally had less-negative ^{13}C-discrimination values than did straw or roots indicating a greater effect of moisture stress on grains. The overall differences in ^{13}C discrimination were not significant and did not show any relationship to grain yield.

Table V. Effects of tillage and nutrient treatment on nitrogen derived from fertilizer by wheat and chickpea, and on sources of nitrogen for chickpea at Urmar, 2000–2001

Tillage	P level	Nitrogen sources (weighted average)					
		Wheat			Chickpea		
		Total N yield (kg ha^{-1})	Total fert. N yield (kg ha^{-1})	Ndff[b] (%)	Total N yield (kg ha^{-1})	Total fert. N yield (kg ha^{-1})	Ndff (%)
T$_1$[a]	P$_1$	29.3	5.24	16	10.3	0.67	6.5
	P$_2$	37.5	6.98	19	11.0	0.74	6.7
T$_0$	P$_1$	31.1	5.56	18	7.72	0.66	8.6
	P$_2$	37.4	6.92	19	7.20	0.62	8.7

Tillage	P level	Nitrogen sources for chickpea			
		Ndff[b] (%)	Ndfa (%)	Ndfs (%)	Total fixed (kg ha^{-1})
T$_1$[a]	P$_1$	8.6	52	40	3.99
	P$_2$	8.6	55	37	3.91
T$_0$	P$_1$	6.5	63	30	6.53
	P$_2$	6.7	64	29	7.11

[a] Conventional tillage; T$_0$= No tillage; P$_1$ = N$_{60}$ + P$_{30}$; P$_2$ = N$_{60}$ + P$_{60}$.

[b] Nitrogen derived from fertilizer, Ndfa = N derived from the atmosphere (fixation); Ndfs = N derived from soil.

Table VI. Effects of tillage and nutrient treatments on carbon-isotope discrimination in straw, grain and roots of wheat and lentil at NIFA Research Station and on farmers' fields, 1998–1999

Crop	Loc'n	Till.	Carbon discrimination (‰)								
			Straw			Grain			Roots		
			P$_1$	P$_2$	Mean	P$_1$	P$_2$	Mean	P$_1$	P$_2$	Mean
Wheat	NIFA	T$_1$[a]	-28.6	-28.7	-28.6a	-28.2	-27.9	-28.1a	-29.0	-28.8	-28.9a
		T$_0$	-28.5	-28.7	-28.6a	-28.0	-28.0	-28.0a	-28.1	-28.3	-28.2b
		Mn	-28.6a	-28.7a		-28.1a	-28.0a		-28.5a	-28.6a	
	Urm.	T$_1$	-28.5a	-28.5a	-28.5a	-25.9	-26.2	-26.1a	-28.4	-28.2	-28.3a
		T$_0$	-27.8b	-27.9b	-27.9a	-26.2	-26.3	-26.2a	-28.5	-28.6	-28.5a
		Mn	-28.2a	-28.2a		-26.0a	-26.3a		-28.4a	-28.4a	
	Jaloz.	T$_1$	-28.2	-27.8	-28.0	-26.8	-26.4	-26.6	-28.5	-28.2	-28.3
		T$_0$	-28.1	-28.4	-28.3	-26.6	-27.0	-26.8	-27.5	-27.6	-27.6
		Mn	-28.1	-28.1		-26.7	-26.7		-28.0	-27.9	
Lentil	Urm.	T$_1$	-27.6	-27.7	-27.7a	-24.8	-24.9	-24.8a	-28.0	-27.9	-27.9a
		T$_0$	-27.8	-27.6	-27.7a	-25.4	-25.06	-25.2a	-27.8	-28.0	-27.9a
		Mn	-27.7a	-27.7a		-25.1a	-25.0a		-27.9a	-27.9a	
	Jaloz.	T$_1$	-27.3	-28.0	-27.7	-24.9	-26.1	-25.5	–	–	
		T$_0$	-27.9	-27.3	-27.6	-25.8	-25.4	-25.6	–	–	
		Mn	-27.6	-27.7		-25.3	-25.8				

[a] Conventional tillage; T$_0$= No tillage; P1 = N$_{60}$ + P$_{30}$; P$_2$ = N$_{60}$ + P$_{60}$.

Table VII. Effects of tillage and nutrient treatments on carbon-isotope discrimination in straw and grain of wheat and chickpea at NIFA Research Station and on farmers' fields, 2000–2001

Crop	Location	Tillage	Carbon discrimination					
			Straw			Grain		
			P_1	P_2	Mean	P_1	P_2	Mean
			(‰)					
Wheat	NIFA	T_1[a]	–28.26	–28.35	–28.30a	–26.43ab	–26.50a	–26.47a
		T_0	–27.94	–28.42	–28.14a	–26.52a	–26.35b	–26.44a
		Mean	–28.10a	–28.38a		–26.48a	–26.42a	
	Urmar	T_1	–25.83a	–25.85a	–25.89a	–25.27	–25.25	–25.26a
		T_0	–25.80a	–24.76b	–25.28a	–25.23	–25.15	–25.19a
		Mean	–25.81a	–25.30a		–25.25a	–25.20a	
Chickpea	Urmar	T_1	–25.61a	–25.56a	–25.59a	–25.89	–25.69	–25.79
		T_0	–25.34b	–25.32b	–25.33b	–25.89	–25.92	–25.90
		Mean	–25.48a	–25.44a		–25.89a	–25.80a	

[a] Conventional tillage; T_0= No tillage; P1 = N_{60} + P_{30}; P_2 = N_{60} + $P_{60.}$

Table VIII. Effects of tillage on water- and rain-use efficiency of grain and straw of wheat and lentil at NIFA Research Station and a farmer's field, respectively, 1998–1999

Parameter	Location	Tillage	Wheat		Lentil	
			Grain	Straw	Grain	Straw
			(kg ha^{-1} mm^{-1})			
WUE	NIFA	T_0[a]	9.91	26.3	3.04	12.3
		T_1	12.3	29.3	3.39	12.4
		T_0	4.16	11.2	2.01	3.21
		T1	4.69	11.1	2.58	3.89
RUE	Jalozai	T_0	11.0	26.3	4.42	8.15
		T_1	10.1	22.0	4.48	8.40

[a] No tillage; T_1 = Conventional tillage.

3.1.3.4. Water-use efficiency

At NIFA Research Station, water-use efficiency (WUE) was improved by tillage as compared to no-tillage (Table VIII). The WUE values were higher than on the farmer's field. The higher values are due to higher fertility status, better water-holding capacity and higher potential productivity of the research-station soil. On the farmers' fields, water- and rainwater-use efficiency were enhanced slightly by tillage. Soil-surface conditions are of major importance in determining the water content of soil under various tillage systems. No-tillage is potentially better for semi-arid conditions because it maintains greater water content in the soil and supports better root growth, especially in years of low rainfall [17].

3.1.3.5. Intercropping

Monocrop yields were greater than intercrop yields both at NIFA and on farmers' fields (data not shown). This indicates that combination of wheat and lentil did not generally result in more-efficient land use than did sole cropping. However, combination of wheat and chickpea did result in better LERs (1.10–1.19) than did the sole cropping at the research station. The LER were relatively improved at the higher nutrient level, but the effect of tillage was mixed. Also, LER was higher at NIFA than on farmers' fields (data not shown).

3.2. Effect of cropping sequence, tillage and nutrient management on yield, nitrogen uptake and water use efficiency of wheat.

3.2.1. Yield

Lentil had a pronounced effect on yield of the following wheat crop at NIFA Research Station (Table IX). A similar positive effect on farmers' fields was not statistically significant. The effects of lentil on yield were more promising at zero tillage and low N-level (30 kg N ha^{-1}) treatments as compared to with-tillage and 60 kg N ha^{-1}. Lentil caused a net increase in grain yield of 0.93 and 0.54 t ha^{-1} at NIFA and 0.52 and 0.21 t ha^{-1} on farmers' fields in zero-tillage and tillage treatments, respectively. Increases in wheat yield (straw + grain) caused by the legume in the sequences (Table X) were equivalent to (on a per-ha basis) Rs.12,280 (US$204) and Rs.13,152 (US$219) at the NIFA Research Station, and Rs.6,020 (US$100) and Rs.2,600 (US$43) on farmers' fields in zero-tillage and tillage treatments, respectively. These results indicate legume inclusion in the cropping system would provide additional income to farmers under rainfed conditions. Beneficial effects of legume cultivation on subsequent cereal yields has been reported in many studies [22–27]. Besides water, N deficiency is the most important limiting factor for production of wheat and other cereals in Pakistan. For continuous cropping, the N must be supplemented as organic matter and other sources. Next to soil and fertilizer, biological N_2 fixation (BNF) is to be considered as an extremely important source of N [28].

Table IX. Effects of cropping sequence, tillage and nutrient treatments on wheat yields at NIFA Research Station and on farmers' fields, 1999–2000

Location	Previous crop	Tillage	P_1	P_2	P_3	P_4	Sequence mean
			(kg ha^{-1})				
NIFA	Wheat	T_0[a]	3,154g	3,954ef	3,692fg	4,000ef	4,252b
		T_1	3,538fg	5,261abc	5,077abc	5,338abc	
	Lentil	T_0	4,723bcd	4,692cd	4,415de	4,692cd	4,986a
		T_1	5,108abc	5,461a	5,415a	5,385ab	
		P-mean	4,131b	4,842a	4,649a	4,853a	
		T-mean	T_0=4,165b	T_1=5,073a			
Urmar	Wheat	T_0	1,311e	1,726d	1,704d	2,052abc	1,763a
		T_1	1,385e	2,000bc	1,852cd	2,074abc	
	Lentil	T_0	2,074abc	2,274a	2,296a	2,222ab	2,124a
		T_1	1,704d	2,222ab	2,074abc	2,126ab	
		P-mean	1,618c	2,055ab	1,981b	2,118a	
		T-mean	T_0=1,957a	T_1=1,929a			
Jalozai	Wheat	T_0	1,407	1,550	1,626	1,481	1,503
		T_1	1,450	1,481	1,500	1,530	
	Lentil	T_0	1,704	1,581	1,860	1,852	1,718
		T_1	1,560	1,570	1,690	1,925	
		P-mean	1,530	1,546	1,669	1,697	
		T-mean	T_0=1,633	T_1=1,588			

[a] No tillage, T_1=Conventional tillage. P_1= N_{30} + P_{30}, P_2 = N_{60} + P_{30}, P_3= N_{30} + P_{60}, P_4 = N_{60} + P_{60}.

Table X. Net increases in wheat yields from previous lentil and their value

Location	Treatment	Increased grain yield	Increased straw yield	Value[a] of increased yield (grain + straw) (Rs. ha^{-1})
		(kg ha^{-1})		
NIFA	Lentil effect, zero tillage	930	2,420	12,280
	Lentil effect, with tillage	539	4,420	13,152
Urmar	Lentil effect, zero tillage	520	930	6,020
	Lentil effect, with tillage	210	460	2,600

[a] Price of wheat = Rs.400/50 kg for grain and Rs.100/50 kg for straw; Rs 60.00 = US$1.

In Southern and Western Australia, the principal source of N for cereal crops is BNF, either from forage legumes or grain legumes in rotation. The most widespread and consistent effect of legumes is to improve the N economy of soil through BNF. The N balance of a legume-cereal sequence in most cases is more positive than that of a cereal-cereal sequence in the same soil. Thus, the inclusion of legumes in cropping systems can arrest decline of soil-N fertility and reduce requirements for fertilizer N. Similarly, our results indicate that the with-legume sequence enhanced the yield and reduce the fertilizer-N requirement of succeeding wheat at the NIFA Research Station and farmers' fields under rainfed conditions, possibly due to improvement in soil-N-fertility status and other associated benefits from legumes.

Tillage significantly improved wheat grain yield at NIFA, but did not improve yields on farmers' fields. This difference may be due to soil texture. The results of Ali [29] support our findings. He observed that deep tillage improved grain yield and WUE of wheat over minimum and zero tillage and the deep tillage impact was significant in a silt-loam but not a sandy soil. The added nutrients significantly improved yields on farmers' fields and NIFA Research Station; however, the effect was more pronounced on the farmers' fields. The highest yield was recorded with 60 kg N + 60 kg P ha^{-1}.

A residual effect of nutrient applied the previous year was noted only in plots that received 60 kg P ha^{-1} in combination with N. These plots produced higher yields than those plots previously fertilized with 30 kg P ha^{-1}. The residual effect of nutrients on yield was clearer in wheat–wheat sequences as compared to legume–wheat sequences. In the legume–wheat sequence, 30 kg N along with 30 or 60 kg P ha^{-1} was found sufficient at the research station to meet N and P requirements of the wheat crop previously fertilized with 60 kg N + 60 kg P ha^{-1}. However, on farmers' fields, 60 kg N was needed along with 30 or 60 kg P ha^{-1} for higher yields.

The interaction between nutrient level, tillage and cropping sequence was significant, showing that the highest yield was obtained with tillage treatments and N:P levels of 60:30 and 30:60 in lentil–wheat sequences previously fertilized with 60:60, and lowest in zero tillage and N:P of 30:30 in wheat–wheat sequences. However, on farmers' fields, highest yields were obtained under zero tillage and N:P levels of 30:60, and 60:30 in lentil–wheat sequences previously fertilized with 60:60.

3.2.2. Intercropping.

Wheat was grown in the alternate rows previously occupied by lentil during the 1998–1999 season. Intercropped wheat production on a unit-area basis was higher than for sole wheat, although it received 40 kg N ha^{-1} compared to 60 kg N ha^{-1} applied to the sole crop (Table XI). Cereals intercropped with grain legumes generally benefit from the association in terms of increased grain and N per unit area compared to monocropped cereals [30]. The N benefit derives from the N-sparing effect of the legume, rather than from concurrent transfer of biologically fixed N to the cereal.

Table XI. Effects of intercropping and tillage on wheat grain yield at NIFA Research Station and on farmers' fields, 1999–2000

Location	Cropping system	Tillage T_0[a]	Tillage T_1	Mean
		(kg ha^{-1})		
NIFA	Intercrop[b]	2,667	3,267	2,967
	Monocrop (wheat followed by lentil)	4,631	5,342	4,986
	Monocrop (wheat followed by wheat)	3,700	4,804	4,252
Urmar	Intercrop	1,083	1,450	1,267
	Monocrop (wheat followed by lentil)	2,044	2,032	2,038
	Monocrop (wheat followed by wheat)	1,698	1,828	1,762
Jalozai	Intercrop	933	900	916
	Monocrop (wheat followed by lentil)	1,749	1,686	1,718
	Monocrop (wheat followed by wheat)	1,516	1,490	1,503

[a] No tillage; T_1 = Conventional tillage.

[b] Intercropped yield was obtained from half of the area as 50% was lentil.

One of the commonly reported advantages of intercropping (legumes with cereals) over monocropping is higher productivity. This is sometimes attributed to transfer of fixed N to the non-N_2-fixing crop [31]. Higher nutrient-utilization efficiency has been observed in intercropped than in pure-stand maize [32].

It was reported that when wheat was grown with various legumes (pure or intercropped), pigeon pea preceding wheat did not leave much residual fertility whereas black gram, groundnut and cowpea for fodder gave benefits equivalent to 40 to 80 kg N ha^{-1} to wheat [33]. However, several studies have failed to demonstrate significant transfer of N from a legume to an associated cereal [34,35]. Thus, contributions from the soil N-sparing effect have been shown in crop-rotation experiments to be more important than N-transfer [24,36].

3.2.3. Nitrogen uptake.

At NIFA, N uptake by wheat straw and grain was significantly influenced by cropping sequence, tillage and nutrient level (Table XII). The interaction between cropping sequence, tillage and nutrient level was significant, showing that the lentil–wheat sequence with tillage led to higher N uptake at all nutrient levels as compared to no-tillage and wheat followed by wheat. Maximum N uptake by grain was recorded in the plots receiving 60 kg N ha^{-1} in combination with 30 or 60 kg P ha^{-1}.

On farmers' fields, N uptake by wheat grain was not significantly influenced by tillage, but it was improved by increased nutrient level and by the lentil–wheat as compared to wheat–wheat sequence (Table XII). Higher N-uptake values in wheat straw and grain were recorded under the lentil–wheat sequence at all nutrient levels. Grain- and straw-N yields were least in the continuous wheat sequence both at the research station and on the farmers' fields and greatest in the lentil–wheat sequence. The amounts of N in grain were greater than in straw, probably due to translocation of N from straw to grain. Similarly, Strong et al. [37] found that uptake of N by wheat was higher in a legume–wheat sequences compared with cereal–wheat sequences.

3.2.4. Utilization of residual nitrogen

Less than 1% of the fertilizer applied the previous year (1998–1999) was utilized at the NIFA Research Station by the subsequent wheat crop (data not shown). Tillage led to greater utilization of N than no-tillage, but higher %Ndff values were recorded in no-tillage treatments at all N and P levels.

Table XII. Effects of cropping sequence, tillage and nutrient treatment on wheat-grain nitrogen yield, 1999–2000

Location	Previous crop	Tillage	P_1	P_2	P_3	P_4	Sequence mean
					(kg ha^{-1})		
NIFA	Wheat	T_0[a]	64.7g	83.2ef	69.0fg	81.8ef	88.2b
		T_1	71.4fg	122ab	104bcd	109bcd	
	Lentil	T_0	93.4de	104cd	85.6ef	104cd	107a
		T_1	107bcd	128a	114.9abc	118abc	
		P-mean	84.1c	109a	93.5b	103a	
		T-mean	T_0=85.8b	T_1=109a			
Urmar	Wheat	T_0	28.7	37.2	35.7	45.2	39.0
		T_1	32.9	44.3	39.9	48.3	
	Lentil	T_0	43.2	59.3	49.9	58.3	50.5
		T_1	36.6	52.8	50.6	53.9	
		P-mean	35.3b	48.4a	44.0a	51.4a	
		T-mean	T_0=44.7a	T_1=44.9a			
Jalozai	Wheat	T_0	31.0	43.5	34.1	40.9	37.9
		T_1	30.5	43.4	40.9	39.2	
	Lentil	T_0	39.2	39.5	44.6	49.4	41.4
		T_1	37.4	37.7	42.3	41.3	
		P-mean	34.5	41.0	40.5	42.7	
		T-mean	T_0=40.3	T_1=39.1			

[a] No tillage; T_1=Conventional tillage; P_1= N_{30} + P_{30}; P_2 = N_{60} + P_{30}; P_3= N_{30} + P_{60}; P_4 = N_{60} + P_{60}.

On farmers' fields at Urmar and Jalozai, the %Ndff, fertilizer-N yield and %N-utilization values for residual ^{15}N-urea were lower than at NIFA Research Station. A greater %N utilization at Urmar was recorded for the lentil–wheat sequence than for wheat–wheat. However, tillage and nutrient level had no clear effect.

3.2.5. Carbon-isotope discrimination

The ^{13}C-discrimination data revealed that, at NIFA Research Station, the values for straw and grain were more negative under tillage than zero-tillage (Table XIII). However, for nutrient level the values were very close in both grain and straw. These data indicate that higher amounts of water were taken up under tillage. This is confirmed by the WUE data and the moisture status of the soil profile as determined at successive growth stages under tillage and zero-tillage; water contents were higher in tilled plots (Fig. 1). The WUE values of grain indicated a good correlation (R^2=0.988) with $\delta^{13}C$ values, which became more negative as WUE increased.

Any factor that affects either stomatal conductance or photosynthetic capacity, such as photosynthetically active radiation, water deficit, atmospheric humidity, nutrition, salinity and air pollution will influence $\delta^{13}C$ [38,39]. On farmers' fields, the values were less negative under zero-tillage and lentil–wheat crop sequences as compared tillage and wheat–wheat, but the tillage and zero-tillage values were similar. These results support the yield and rain-use-efficiency data obtained from the farmers' fields.

Table XIII. Effects of tillage and nutrient level on carbon-isotope discrimination in wheat straw and grain at NIFA Research Station and of farmers' fields, 1999–2000

Location	Tillage/ Previous crop	Carbon discrimination					
		Straw			Grain		
		P_1	P_3	Mean	P_1	P_3	Mean
		(‰)					
NIFA	T_0[a]	–27.4	–27.7	–27.5	–27.2	–27.1	–27.1
	T_1	–28.1	–28.0	–28.1	–27.5	–27.7	–27.6
	Mean	–27.8	–27.8		–27.4	–27.4	
		T_0	T_1		T_0	T_1	
Urmar	Wheat	–26.5	–26.6	–26.6	–24.5	–24.3	–24.4
	Lentil	–26.0	–26.1	–26.1	–24.0	–24.2	–24.1
	Mean	–26.3	–26.4		–24.2	–24.2	
Jalozai	Wheat	–26.1	–26.6	–26.3	–24.4	–23.7	–24.1
	Lentil	–25.8	–27.0	–26.4	–24.3	–25.2	–24.7
	Mean	–26.0	–26.8		–24.4	–24.5	

[a] No tillage; T_1 = Conventional tillage; $P_1 = N_{30} + P_{30}$ in 1999–2000 (received $N_{60} + P_{30}$ in 1998–1999); $P_3 = N_{30} + P_{60}$ in 1999–2000 (received $N_{60} + P_{60}$ in 1998–1999).

3.2.6. Water-use efficiency.

The WUE was improved by tillage and the lentil–wheat sequence at the NIFA Research Station as compared to no tillage and the wheat–wheat sequence (Table XIV). The WUE values were higher than other reported values, possibly due to higher fertility status, water-holding capacity and potential productivity of the NIFA soil. Ali [29] also reported higher water use efficiency by wheat due to tillage and NPK application in comparison with zero and minimum tillage in Pakistan.

On farmers' fields, rainwater use efficiency was enhanced by the lentil–wheat sequence (Table XIV). However, tillage treatment did not exert any effect. The values ranged between 9.60 to 13.4 kg ha^{-1} mm^{-1}. The lentil–wheat sequence increased the rainwater use efficiency by 2.28 kg ha^{-1} mm^{-1} over the wheat–wheat sequence at Urmar and by 1.36 kg ha^{-1} mm^{-1} at Jalozai. The no-tillage treatment showed higher rain use efficiency on both farmers' fields.

Soil-water content data under wheat at different growth stage — as influenced by tillage treatment and cropping sequence — are summarized in Figs. 1 and 2, respectively. Tillage showed higher moisture content in the soil profile (0–90 cm) at all growth stages except during stem elongation (Fig. 1). Although the moisture content was higher with tillage treatments, it was very close to the zero-tillage treatment at seedling, tiller initiation and the first tillering stage. However at the second tillering, ear and milky stages, the tillage treatment contained 38.0, 7.95, and 19.7 mm more water, respectively, in the profile than did zero tillage. These higher moisture contents at lower depths in the tillage treatment showed that tillage helped to control 2nd stage evaporation by breaking the capillaries as compared to the no-tillage treatment. Cropping sequence did not have a pronounced effect on the soil moisture content as recorded at different growth stages (Fig. 2). However wheat–wheat and intercropping systems showed higher moisture contents at all growth stages than did lentil–wheat, except at the milky stage. This indicates that legumes may contribute little to the maintenance of higher moisture content in the soil profile for a subsequent crop. The positive effects of lentil on subsequent wheat may be due to other associated benefits from the legume.

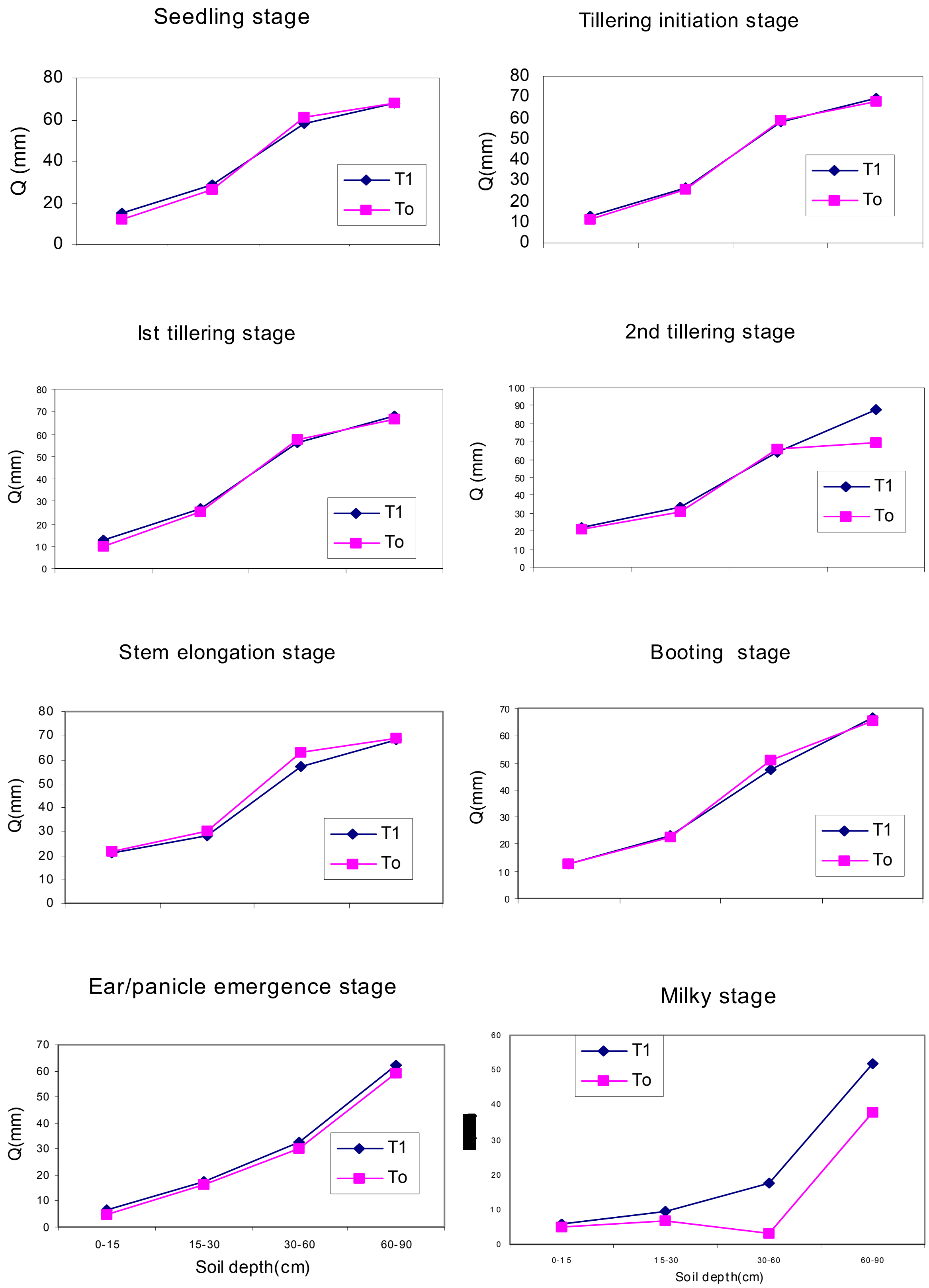

FIG. 1. Effect of tillage on soil moisture content under wheat at various growth stages at NIFA Research Station, 1999–2000 (T_1=conventional tillage, T_0=no tillage).

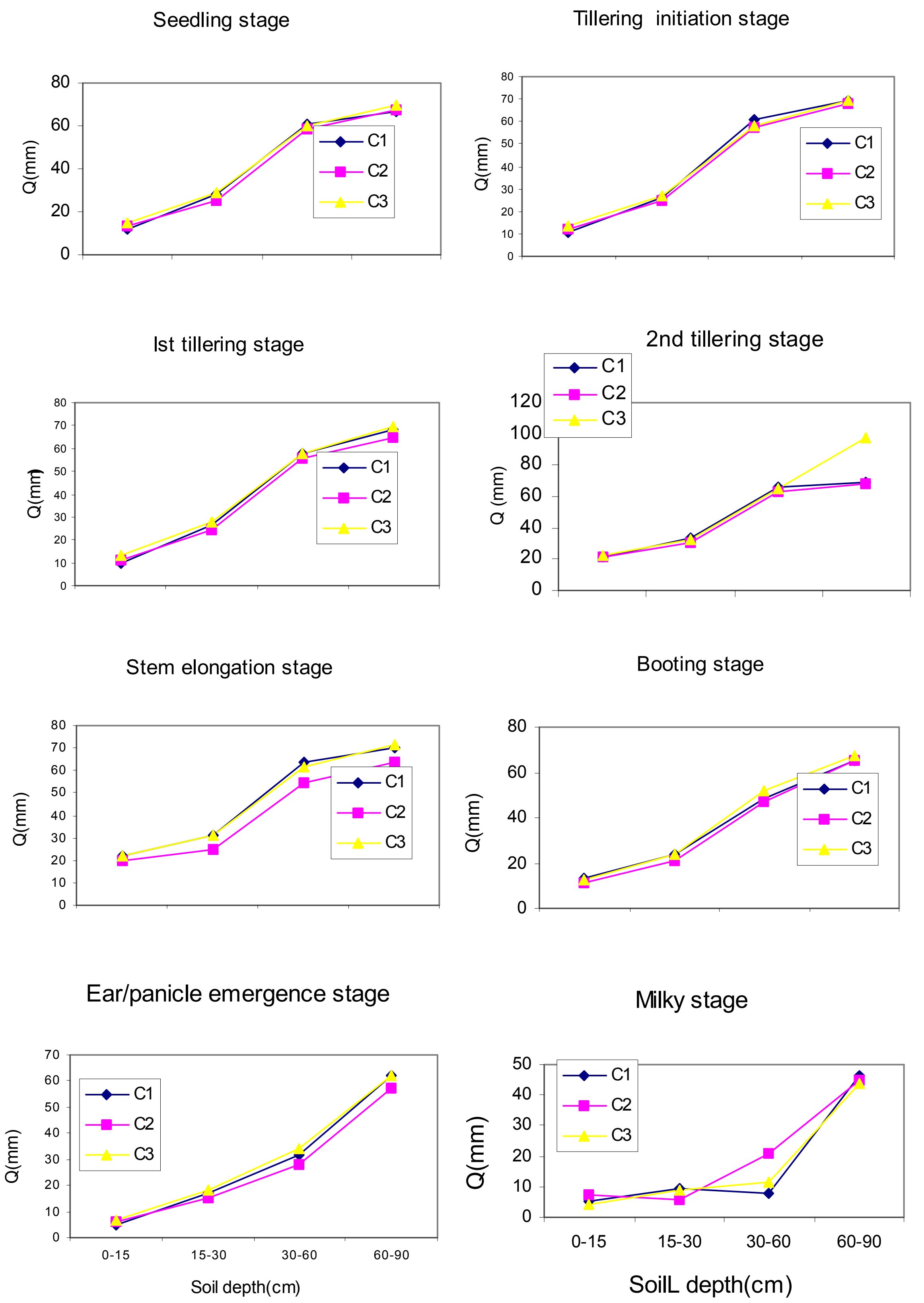

FIG. 2. Effect of cropping sequence on soil-moisture content under wheat at various growth stages at NIFA, 1999–2000 (C1 = wheat–wheat, C2 = lentil–wheat, C3 = intercropped lentil/wheat).

Table XIV. Effects of cropping sequence and tillage on wheat-grain water-use efficiency at NIFA and rainwater use efficiency on farmers' fields, 1999–2000

Location/ Parameter	Previous crop	T_0[a]	T_1	Mean	Remarks
		(kg ha^{-1} mm^{-1})			
NIFA/	Wheat	14.5	21.0	17.7	3.31 kg ha^{-1} mm^{-1} increase in
WUE	Lentil	18.7	23.4	21.0	WUE due to legume
	Mean	16.6	22.2		5.6 kg ha^{-1} mm^{-1} increase in
					WUE due to tillage
Urmar/	Wheat	10.7	11.6	11.1	2.28 kg ha^{-1} mm^{-1} increase in
RWUE	Lentil	14.0	12.8	13.4	RWUE due to legume
	Mean	12.4	12.2		0.18 kg ha^{-1} mm^{-1} decrease in
					RWUE due to tillage
Jalozai/	Wheat	9.60	9.43	9.51	1.36 kg ha^{-1} mm^{-1} increase in
RWUE	Lentil	11.1	10.7	10.9	RWUE due to legume
	Mean	10.3	10.1		0.28 kg ha^{-1} mm^{-1} decrease in
					RWUE due to tillage

[a]No tillage; T_1 = conventional tillage.

Soil-surface conditions are a major influence on water content of soil. Bouzza [40] found that water storage increased from 50 to 85 mm as a result of surface-applied straw as compared to treatments in which straw was deeply incorporated. The improved moisture conservation was due to better infiltration and reduced evaporation. Wheat grain yield was higher under no-tillage than clean tillage because of better utilization of growing-season precipitation in residue-covered plots. Similarly, in our experiments on farmers' fields, the lentil residues (leaves, etc) on the soil surface at maturity worked as a mulch with zero tillage and thus helped reduce surface evaporation and improved utilization of growing season rainfall.

4. CONCLUSIONS

Tillage treatment improved the grain yield of wheat at NIFA Research Station but did not improve yields on farmers' fields. Fertilizer-N utilization by wheat was greater on farmers' fields (up to 42% of applied N) than at NIFA (33%). In the case of lentil, grain yield was not influenced by tillage or nutrient level, although N_2 fixation was stimulated by the higher P level. Lentil obtained 82 to 96% of its N from fixation and chickpea 52 to 64% under farmers' conditions. The ^{13}C-discrimination data for wheat grain indicated a positive relationship with grain yield. Lentil exerted a significant effect on the yield of subsequent wheat as compared to a wheat–wheat sequence. Wheat utilized less than 1% of the N applied to the previous year's crop. Water-use efficiency was improved in the lentil–wheat sequence with tillage at NIFA as compared to no-tillage of the wheat–wheat sequence. However, on farmers' fields, no-tillage showed higher rainwater-use efficiency.

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HELPING SMALL-SCALE FARMERS IN THE SEMI-ARID TROPICS: LINKING PARTICIPATORY RESEARCH, TRADITIONAL RESEARCH AND SIMULATION MODELLING

R.J.K. MYERS*
ICRISAT-Bulawayo,
Bulawayo, Zimbabwe

Abstract

The aim was to link necessary research skills to increase the range of options available to resource-poor farmers in the study area. The research consisted of on-station research to evaluate and understand cropping-system options resulting from insertion of a legume crop into the sorghum and castor system, on-farm research whereby farmers evaluate cropping-system options that are of interest to them, use of ^{15}N as a label to help understand the nitrogen (N) balance of the various options, and cropping-systems simulation to examine long-term climatic risks from possible options. Particular attention was placed on the option of sorghum/pigeon pea intercrops, and on quantifying the inputs of N from animal manure and by the pigeon-pea component. We were also interested in the process of linking on-station to on-farm research, and simulation modelling to the cropping system research. One important outcome was that different groups identified different problems and posed different questions. The problems identified and questions raised were examined by use of scenario analyses run for ten to thirty years which contrasted the existing practice with a range of alternative practices. The simulations were useful in guiding the design of on-farm experiments. Other likely outcomes are the setting of low-rate fertilizer recommendations specifically for the semi-arid tropics, the marketing of small packs of fertilizers, and increased use of manure resources for crop production.

1. INTRODUCTION

Despite low soil fertility and crop productivity in the semi-arid tropics (SAT), smallholder farmers have been reluctant to invest in methods of improving soil fertility; recommendations for fertilizer use remain irrelevant to most farmers. In order to overcome the reluctance to invest in soil fertility, the International Centre for Research in the Semi-Arid Tropics (ICRISAT) and its partners have been examining ways of using more effective participatory research methods in combination with new tools such as simulation. The systems simulator APSIM [1]was used in this work since it can simulate the main crops grown in this region, and can simulate the effects of water, nitrogen (N) and manure.

Models can help researchers and farmers evaluate and interpret variable responses due to season, soil and management factors, and, in conjunction with long-term climate data, they allow analysis of production risk of a technology under variable rainfall patterns. APSIM is a farming-systems simulator that combines climatic risk analysis with prediction of long-term conservation of farming practice on the soil resource, and has the capacity to be applied to questions concerning crop rotations and intercropping, organic and inorganic inputs, and crops (including sorghum and pigeon pea) grown in the SAT. It is a tool that can simulate fertility and cropping-technology options relevant to dryland farming. Therefore, APSIM can contribute to the farmer/researcher dialogue for developing technology options and recommendations from participatory research.

Recently, in research projects in India and Zimbabwe, ICRISAT and partners in the national agricultural research systems (NARS), working with smallholder farmers, have been using participatory methods to identify better soil-fertility options. In India, this research involves the Regional Agricultural Research Station (RARS), Acharya N. G. Ranga Agricultural University ANGRAU at Palem in Mahabubnagar District, Andhra Pradesh, and, in Zimbabwe, it involves the Soil Productivity Research Laboratory at Marondera, the Agricultural Production Research Unit (APSRU), the International Maize and Wheat Improvement Center (CIMMYT) and the Department of Research and Extension.

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[*] Present address: 31 Woonalee Street, Kenmore, Queensland 4069, Australia.

This report includes an example of how simulation has been used to examine options for improving productivity in smallholder farming in semi-arid lands in Zimbabwe, how isotopes are being used to test options for improved management of N and water in Zimbabwe and India, and how simulation can be used to add value to results from more traditional research experimentation. It gives examples from collaborative workshops in Zimbabwe, and research in progress in smallholder farming districts near Masvingo in Zimbabwe, and in the Mahabubnagar District of Andhra Pradesh in India.

Sorghum systems are predominant in the semi-arid areas of the southern Telengana region of Andhra Pradesh, India, and in the Matabeleland provinces of Zimbabwe. These regions are characterized by relatively high population density, low-fertility soils, and long distances to markets. The productivity of these systems is very low (around 0.5 t ha^{-1}) and limited by low and highly variable rainfall with a 3- to 4-month growing season, and nutrient-poor soils. The annual rainfall is 600 to 800 mm with frequent dry spells causing yield losses and sometimes crop failure. The land is best suited for grazing, but farmers need to grow food to feed themselves and their families. Some families have cattle or goats, but many do not, so draft power can be a problem. Many farmers are women, either without husbands or whose husbands are absent, working elsewhere. The majority of households do not achieve food sufficiency. Farmers prefer to grow maize supplemented with some sorghum, millet, cowpea, bambara nut, groundnut, etc. Sorghum and millet tend to be grown as "insurance" crops. Sowing starts after the first significant rain, and additional areas are sown after further rains; usually there are several sowings.

Farmers identify their major problems as low-yielding varieties, lack of draft power, low soil fertility, drought, weeds (striga is important) and pests. Often extension agents have difficulty in helping farmers because recommendations were initially set for commercial farming and are inappropriate for small-scale farming on poor soils in dry areas where markets are poorly developed. Understanding trade-offs is critical to understanding farmers' problems and constraints. There are competing demands for their scarce resources. Should the farmer invest in fertilizer in the hope of obtaining a high-yielding crop, or should the investment be in paying for the education of one or more of the children? Change agents need to be considered, i.e. extension agents for technical advice and recommendations, traders and companies who supply inputs such as seed, fertilizer and crop-protection materials, banks that can supply credit, companies that can purchase crop products, and others.

Many potential interventions may be considered by farmers: seed of improved varieties, fertilizers, farmyard manure, green manures or crop residues, weeding strategies, insect- and disease-control agents, methods of water management, and many others. The main questions regarding their use are whether they are attractive to small-scale farmers, what is the risk associated with their use, and what are the alternative uses for the money or the time? This means that farmer decision-making is a complex process, and there are many factors in a farmer decision to invest in crop production and soil fertility.

The Mahabubnagar District has been studied by ICRISAT and ANGRAU, and the soils in farmers fields have been shown to be poor in organic carbon (C), and the two main limiting factors for crop production are low and variable rainfall, and lack of N. The nutrient balance of sorghum and castor crops in farmers' fields is negative. If the nutrient (mainly N, phosphorus (P) and potassium) mining of these poor soils continues, they will become so infertile as to be unsuitable for crop production. Nitrogen-fertilizer application under this situation is recommended to increase the yields of sorghum and castor. However, the N-fertilizer-rate recommendation, based on research in Mahabubnagar District for optimum yields of castor and sorghum, is 60 to 80 kg ha^{-1} depending on cultivar used. Such a recommendation is not attractive to resource-poor farmers.

In communal farming lands in areas of low rainfall in Zimbabwe, the soils are mostly low-fertility sands and productivity is, therefore, very low (around 0.5 t ha^{-1}). Within this region, ICRISAT and the Soil Productivity Research Laboratory have been conducting on-station and on-farm research to help farmers achieve food sufficiency. Nitrogen-fertilizer application is officially recommended to increase the yields of maize, but few farmers have the resources to invest in soil fertility.

Household livelihoods in these locations cannot be expected to change without nutrient inputs that can lead to increased water-use efficiency, which in turn leads to stable and sustainable higher yields and income. Potential nutrient options are likely to be based on modified fertilizer recommendations, use of legumes such as pigeon pea in the cropping system, use of available livestock manures, and maintaining a focus on marketable crops such as castor that can provide the cash flow necessary for investment in soil fertility.

The research reported here is the result of a desire of scientists at ICRISAT and their NARS partners to link necessary skills to conduct research that will increase the range of options available to resource-poor farmers in the study area. The research consists of on-station efforts to evaluate and understand cropping-system options resulting from insertion of a legume into sorghum and castor systems, on-farm research whereby farmers evaluate options that are of interest to them, use of ^{15}N as a label to help understand the N balance of the various options, and cropping-systems simulation to examine long-term climatic risk of possible options. In India, particular attention was placed on the option of sorghum/pigeon pea intercrops, and on quantifying the inputs of N from animal manure and by the pigeon-pea component. In Zimbabwe, attention was placed on combinations of farmyard manure and mineral fertilizer, and on attempting to improve water-use efficiency by the use of tied ridges. We were also interested in the research-process aspects of linking on-station to on-farm research, and of linking simulation modelling to the cropping-system research. First we report efforts to use simulation to explore management options that could not be looked at in the field experiments.

2. MATERIALS AND METHODS

2.1 Initial workshop to examine alternative management scenarios

In 1999, modellers from APSRU, ICRISAT and CIMMYT, and researchers and extension specialists from the NARS of Zimbabwe combined to examine the scope for utilizing modelling to assist farmers improve their production systems. The process consisted of identifying possible best-bet management practices, compiling sets of weather, crop and soil data to run the APSIM model, then running multiple-season simulations to determine the likely outcome of alternative management practices. Long-term rainfall, solar radiation and temperature data were obtained from diverse locations in Zimbabwe. The simulation tool was used first to confirm that the model gave reasonable outputs as judged by the local knowledge of the Zimbabwean participants. Having agreed that we could reasonably accurately simulate the growth and yield of some components of the various rotations with the different inputs, we then planned to examine two scenarios, namely how various inputs affect cropping systems production over a period of ten years, and also the consequence of low (less than currently recommended) rates of fertilizer for production from cropping systems during that ten years.

2.2. Research in India

2.2.1. The environment

Starting in 1999, the researchers conducted experiments on a shallow-medium Alfisol (Typic Haplustalfs) in the Mahabubnagar District, Andhra Pradesh. It is a semi-arid tropical environment with 540 mm rain in the July to December growing season. On-station research was at the Regional Agricultural Research Station, Palem, also in the Mahabubnagar District (16.35° N, 642 masl). The soil’s 0- to 15-cm layer contained 3.2 g kg^{-1} organic C, 0.405 g kg^{-1} total N, and pH (soil:H_2O 1:5) 4.93. The soil profile had an available water storage of 84 mm/90 cm depth. Seven farmers in the area within 20 km of the research station voluntarily selected management options to test on their own farms by comparing those options with their normal practices. The soils were similar to those of the research station.

2.2.2. On-station research

The main experiment had two two-year rotations, sorghum-castor (together with its mirror image castor-sorghum) and sorghum/pigeon pea intercropped-castor (together with its mirror image castor-sorghum/pigeon pea) as main treatments, and four soil-fertility input combinations, zero input control, farmyard manure (FYM) at 1.5 t ha^{-1}, 60 kg N ha^{-1} as urea, and combined FYM and 45 kg N ha^{-1} urea. There were three replicates. In order to track the use of N applied in FYM and urea, ^{15}N-labelled manure and fertilizer were applied to separate micro-plots within the relevant plots. The micro-plots (1.5 × 0.75 m) were bordered by aluminium sheeting embedded to 15 cm. Labelled urea (5.571 atom % excess) was banded to crop rows within the micro-plots at the same rate and time as the unlabelled urea applied to the remainder of the plot. Labelled FYM was prepared by adding labelled urea and incubating at an optimum moisture level for 4 months under polythene covers with regular mixing. The final product was labelled at 1.272 ^{15}N atom % excess. Subsidiary experiments gathered information on the N contribution of pigeon-pea crop residues, to assess the amount of biological N fixation (BNF) by sole and intercropped pigeon pea, and to determine the value of soil-moisture conservation on traditional and improved cropping systems. Castor var. Kranti, sorghum var. PSV-1 and pigeon pea var. PRG-100 were used, having been developed and released from RARS Palem as highly suitable for the southern Telengana region.

2.2.3. On-farm research

Farmers selected variations on rotating a sorghum/pigeon pea intercrop with sole castor, the variations being either the input of urea or a combination of urea and FYM. Seed and fertilizer were provided to farmers for the improved practice treatments; they used their own resources for the traditional practice.

APSIM's sorghum, pigeon pea, intercropping, N, and manure modules provided a means to examine many issues relevant to the experiments being conducted, and, therefore, data were collected to permit scenario analysis of these issues. Lack of a castor module meant that simulation of the full rotation options was not possible. Long-term rainfall and temperature data were obtained from RARS Palem; solar radiation data were obtained from an automatic weather station installed at RARS Palem for the duration of the on-station research; solar radiation data were supplemented from the ICRISAT Centre at Patancheru, approximately 100 km from Palem. The simulation tool was used here to confirm that we could reasonably accurately simulate the growth and yield of some components of the various rotations with the different inputs, and then to examine two scenarios, namely how do various inputs affect cropping-systems production over a period of ten years, and also what is the consequence of low (less than currently recommended) rates of fertilizer for production from cropping systems over twelve years.

2.3. Research in Zimbabwe

2.3.1. The environment

Starting in the 1998–1999 growing season, the researchers conducted experiments on an acid fersiallitic coarse sand derived from granite [Matopos 5G.1 series, classified as Ferralic Arenosol (FAO) or Ustic Quartzipsamment (USDA)] at Makaholi Research Station near Masvingo in semi-arid Zimbabwe (19.80° S, 1204 masl). It is a tropical environment with 583 mm average annual rainfall. The soil's 0- to 15-cm layer contained 3.2 g kg^{-1} C and pH ($CaCl_2$) was 4.5. The soil profile had an available water storage of 59 mm/100 cm depth. Several farmers in the area within 20 km of the research station voluntarily agreed to test management options on their own farms by comparing those options with their normal practice. The soils were similar to those of the research station.

2.3.2. On-station research

The experiment had continuous cropping of maize and tested three soil-fertility inputs (F1, 15 t ha^{-1} FYM; F2, 200 kg ha^{-1} single superphosphate, 100 kg ha^{-1} urea and 50 kg ha^{-1} KCl; and F3, 7.5 t ha^{-1} FYM, 100 kg ha^{-1} single superphosphate, 50 kg ha^{-1} urea and 25 kg ha^{-1} KCl), and two water-management practices (W1, tied ridging between crop rows; and W2, open furrows between crop rows). There were three replicates with a randomized complete block design. In order to track the use of N applied in urea, ^{15}N-labelled fertilizer was applied to separate micro-plots within the relevant plots. This was done in unconfined micro-plots (1.0 × 1.0 m). The urea was labelled at 5.571 atom % excess, and applied at the same time as the unlabelled urea applied to the remainder of the plot.

2.3.3. On-farm research

This was conducted at a location named Buhera that had similar soil and rainfall to Makaholi. The same six treatments were tested.

2.3.4. Scenario analysis using the APSIM simulator

APSIM has suitable modules to examine many issues relevant to the experiments being conducted, and data were collected to permit scenario analysis. Lack of a surface-management module that specifically addressed tied ridging meant that simulation of these treatments had to be achieved by setting different curve numbers for the universal soil-loss equation (USLE) for open furrows and tied ridging. Long-term rainfall, solar radiation and temperature data were obtained from Makaholi Research Station. The simulation tool was used first to confirm that we could reasonably accurately simulate the growth and yield of some components of the various rotations with the different inputs. Then two scenarios were examined, namely how various inputs affect cropping systems production over a period of seven years, and the consequence of low (less than currently recommended) rates of fertilizer for production from cropping systems during those seven years.

3. RESULTS

3.1. Scenario testing using APSIM

Four simulation workshops were conducted to evaluate responses to low rates of N, manure and legumes. APSIM was used to examine scenarios to contribute analyses and insights for fertility management. The exercise also provided participants with exposure to system analysis using simulation, and showed how APSIM can answer resource allocation questions relevant to resource-poor farmers. Trade-offs in allocating limited capital resources were examined. One scenario involved a typical farm household with a shallow, infertile sand, and moderate weed pressure. The farmer plants in stages to avoid risk of crop failure and because of labour constraints. Household labour can control weeds in only half of the area because of children’s education demands. Funds are sufficient to purchase fertilizer or to hire labour for weeding or to hire a draft animal to prepare additional area for earlier sowing. Given the unreliable rainfall and its influence on such decision-making, the question relevant to a resource-poor farmer is, “On average, which allocation of resource offers the best prospects?”

Investment scenarios simulated included none (baseline), purchase of fertilizer, splitting the investment between fertilizer and labour hire for weeding, and investment only in labour for weeding. Different strategies for targeting the fertilizer were also simulated and subjected to economic analysis. Eleven seasons were simulated.

Simulated baseline yields were low and variable and in line with participants’ expectations. Figure 1 shows the response for whole-farm production when fertilizer is either used on the earliest sown crop or split between the first two sown fields, both of which were weeded. The simulation shows a large benefit from fertilizer investment: the average yield increase would give a good return. In four of eleven seasons, there would be little if any return. There was a marginal advantage to splitting the small fertilizer input over a larger area. The 0N-treatment data represent the baseline household maize production with no investment in fertility. In only two seasons was the household food requirement exceeded, in line with the type of subsistence living faced by households in these situations.

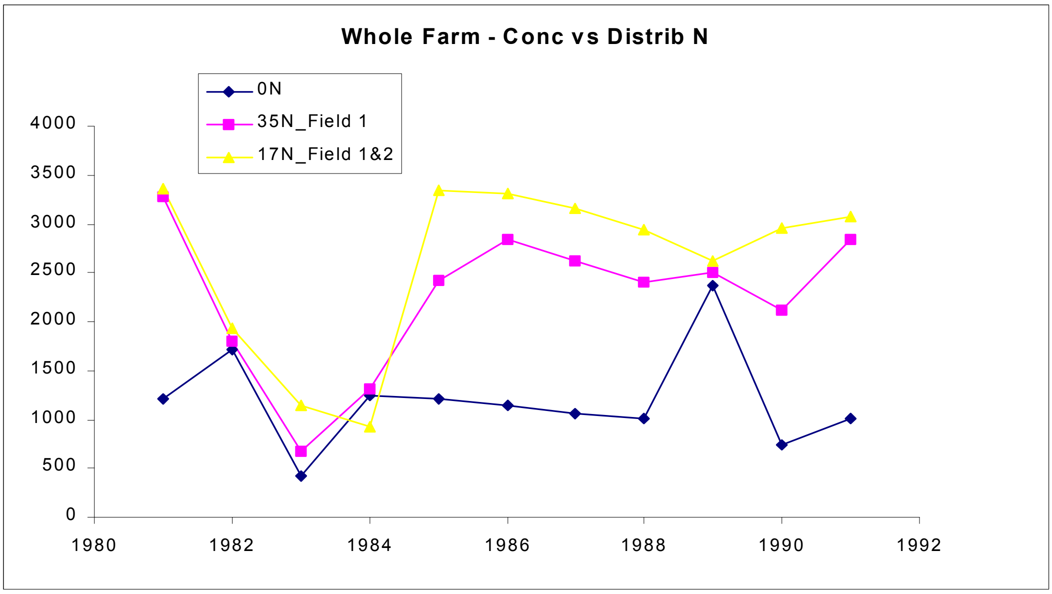

FIG. 1. Simulated whole-farm production (kg grain ha^{-1}) for different inputs and distribution of N (35 kg N ha^{-1} on earliest sown field or 17.5 kg N ha^{-1} on first two sown fields) on an infertile sand, Bulawayo, Zimbabwe.

Table I. Simulated whole-farm production statistics (eleven years of data) for three investment scenarios

Investment scenario	Mean yield	St. dev.	Minimum
	(kg grain ha^{-1})		
None	1,190	505	413
Buy/apply N on first two sowings	2,620	883	923
Hire labour for weeding/apply N on first two sowings	2,410	500	1,580

Overall, the highest expected return (Table I) was from applying fertilizer on the two early-sown, weeded fields. Splitting the investment between fertilizer and labour hire to weed field 3 was almost as good, but had lower risk expectation.

The scenario analyses have been effective in showing how simulation can contribute to researcher learning about fertility management technologies in small-scale farming. For example, one collaborating project has now included extra weeding as an experimental treatment in its on-farm testing. Another project included low rates of N as part of its on-farm experimentation. The key ingredient missing at that time was direct input from farmers. A subsequent workshop in September 2000 focused on the sharing of on-farm experimental data and using simulation with farmers, thus obtaining farmer input in formulating scenarios and feedback on simulated, as well as experimental, results.

In October 2001, the knowledge gained from these new approaches to linking simulation to participatory research was extended through an international workshop, Linking Logics — Taking Simulation Models to the Farmers. This was a joint venture between a participatory research and gender analysis (PRGA) group and a soil-water and nutrient-management (SWNM) programme together with ICRISAT, CIMMYT and APSRU and, importantly, farmer groups in the Zimbabwean SAT. The combination of workshop sessions that brought together the participatory research and simulation scientists, and the on-farm field sessions that brought those groups together with the farmers, proved challenging and exciting, and produced new insights into the problems of resolution of smallholders' production constraints.

3.2. Research in India

Detailed results are reported elsewhere in this volume by Venkata Ramana [2]. The years were drier than average; July to December growing-season rainfall was 445 mm in 1999 and 500 mm in 2000, compared with the long-term average of 540 mm. Crop yields of the order of 1.5 t ha^{-1} are respectable considering the degraded nature of the Mahabubnagar-District soils, and the below-average rainfall. Intercropping sorghum with pigeon pea resulted in sorghum production similar to that by a sole sorghum crop, and production of additional good quality pigeon pea grain, plus (according to the chosen experimental protocol) a return to the soil of about 2 t ha^{-1} of legume residue. The pigeon pea crop took little N (<1.5%) either from fertilizer or from FYM. Using the ^{15}N-dilution method, the N derived from the atmosphere was 43% in sole pigeon pea and 65% in intercropped pigeon pea.

Applying FYM provided additional N to the crops, with 6 to 11% of its N being released and taken up in the first season. This was a consequence of the quality of the FYM (Table II), which was relatively high in total N and P with high concentrations of nitrate and ammonium. Urea N was more available: castor retrieved 26 to 30% of applied N in the first season; pigeon pea took up 25 to 26%, and sorghum 29 to 38%. Associated growth increases were substantial, with FYM doubling grain yields, whereas urea and FYM plus urea each increased grain yields five-fold.

The second cropping season provided the opportunity to contrast the traditional system in which castor follows sorghum with an alternative of castor following a crop with a legume component. However, in this case, castor yield was not influenced by the preceding cropping system, being similar to that in 1999, though sorghum yield was substantially higher. Farmyard manure was effective in that it almost doubled yield, and urea, either with FYM or alone, more than doubled yields.

A group of local farmers selected and tested some alternative systems in their own fields. The traditional system of rotating sorghum and castor without inputs of fertilizer or FYM was invariably out-yielded by the intercropping alternative or by sole crops with inputs. The yields of these farmers and the yield increases obtained with alternative treatments were similar to those obtained on-station, indicating that the farmers had managed these crops carefully. They reported to the researchers that they were impressed by the improved systems, but it is too early to report if there has been any adoption at a larger scale or by other farmers in the district.

Table II. Quality and quantity of farmyard manure applied to plots in the on-station experiment at Palem in 1999, 2000 and 2001

Year	Org C	Total N	Total P	NO_3-N	NH_4-N
		(%)		(mg kg^{-1})	
1999	17.7	1.96	1.02	2720	102
2000	20.5	2.20	1.04	82	237
2001	16.0	1.80	1.02	2290	210
	Org C	Total N	Total P	NO_3-N	NH_4-N
			(kg ha^{-1})		
1999	265	29.4	15.3	4.08	0.15
2000	307	33.0	15.6	0.12	0.36
2001	240	27.0	15.3	3.43	0.32

Table III. Does APSIM adequately simulate sorghum and pigeon-pea yields at Palem?

Crop	Treatment	Observed yield	Simulated yield
		(t ha^{-1})	
Sorghum	Control (0N)	0.47	0.65
	FYM	1.26	1.49
	60N	2.69	1.97
	FYM + 45N	2.14	1.16
Pigeon pea	I/crop with sorghum	0.56	0.24

Table IV. What are the longer-term implications of soil-fertility inputs for crops at Palem? — means of APSIM-simulation outputs for eleven years

System	0N	FYM	60N	FYM + 45N
		(t ha^{-1})		
Continuous sorghum	1.33	1.91	3.13	3.08
Intercrop				
Sorghum	2.18	2.28	2.58	2.56
Pigeon pea	0.40	0.40	0.39	0.39

Table V. What is the likely outcome of farmers applying less than the recommended fertilizer-N rate of 60 kg N ha^{-1} to sorghum at Palem? — means of APSIM-simulation outputs for twelve years

Parameter	0N	10N	20N	30N	60N
Grain yield (t ha^{-1})	1.03	2.04	2.63	2.88	3.13
Crop failure (years)	6/12	2/12	0/12	0/12	0/12

The third component of this work was the use of cropping-systems simulation to add value to the on-station and on-farm trials by exploring wider options than could be studied in trials. This component of the work lagged behind the field research, partly because data from the field were needed as inputs, and because there is still a tendency to leave modelling to the end of the project. With the APSIM simulator, sorghum can be simulated readily. Pigeon pea can also be simulated using the new pigeon pea module [3](Robertson et al., 2001). Fertilizer and FYM inputs can be simulated using the relevant soil-fertility modules. The missing capability is the absence of a module for castor growth and development.

APSIM did a reasonable job of simulating sorghum and pigeon pea yields at Palem (Table III), though the number of comparisons was still limited. The responses to N fertilizer and FYM inputs were encouraging.

Eleven-year simulation runs of continuous sorghum and sorghum/pigeon pea, with four soil-fertility inputs, are summarized in Table IV. On average, this predicts that the modest FYM inputs should significantly increase yields of continuous sorghum, and that N fertilizer should raise sorghum yield to about 3 t ha^{-1}. Intercropping sorghum and pigeon pea should enhance sorghum yield even without N inputs, and with FYM and N fertilizer, yields of 2.5 t ha^{-1} sorghum and 0.40 t ha^{-1} pigeon pea should be possible.

Simulation also showed that N fertilizer at fractions of the recommended rate could be attractive to resource-poor farmers (Table V); 10 kg N ha^{-1} could double sorghum yield from 1.03 to 2.04 t ha^{-1}. Even more interesting, without N application, sorghum would fail to produce grain in 50% of years, yet crop failure would be reduced to zero with an annual application of only 20 kg N ha^{-1} of urea.

3.3. Research in Zimbabwe

The first year of this research was one of high rainfall: 140% of normal. The overall mean maize yield of 1.1 t ha^{-1} was respectable, and the fertilizer treatment yielded 23% more grain than the manure treatment. As a result of the high rainfall, the water-management treatment yielded the same as the control treatment. No further results were available to this author at the time of writing.

The on-farm component of this work did not provide conclusive results in the first season.

With the simulations, the same set of six treatments were tested using weather data from the 1991–1992 season to the 1997–1998 season. The outputs are summarized in Table VI.

Some initial model runs were conducted using an assumed treatment of growing the crop with and without soil-fertility inputs. It is desirable to verify adequate model performance without inputs, then to determine whether the model responds to manure and fertilizer inputs in an acceptable manner. As often happens, the initial experience raised questions regarding the quality of the inputs, and this has meant some further characterization of inputs, which is now in progress. This work is continuing with inputs from J.P. Dimes and N. Nhamo.

In Zimbabwe, the 1990s were notable for frequency of drought years, particularly in 1991–1992. The simulations can be interpreted to indicate that tied ridging did not improve yields, and this is likely to be true in such a light soil with low water-holding capacity. Manure alone was not predicted to improve grain yield. Fertilizer inputs remained as the only input to substantially improve maize grain yield. The simulations indicated also that fertilizer inputs reduce the frequency of crop failures due to dry years, and this confirms observations in field trials that so far have not been given the publicity that they deserve.

4. DISCUSSION

This work has not yet identified alternatives to traditional sorghum-castor rotations on the degraded lands in the Mahabubnagar District of Andhra Pradesh. India. The indications are that it might be agronomically useful to insert pigeon pea into sorghum-castor rotations, and to try inputs of FYM and urea. These recommendations could have been made by an experienced agronomist without huge inputs of research, so what was the value of using ^{15}N labelled materials? And why would the use of a simulation tool add further value to the exercise?

Table VI. Simulated maize grain yield as affected by inputs of farmyard manure, fertilizer and water management between 1991–1992 and 1997–1998, Makaholi, Zimbabwe

Treatment	91–92	92–93	93–94	94–95	95–96	96–97	97–98	Mean
	(t ha^{-1})							
FYM-TR[a]	0	4.97	0	0.02	0.04	0.03	0.04	0.73
FYM-OF[b]	0	5.01	0	0.02	0.04	0.03	0.04	0.73
Fert-TR[b]	0	7.23	4.95	4.18	6.33	0.09	4.77	3.95
Fert-OF	0	7.45	4.86	4.31	6.14	0.08	4.60	3.96
Comb-TR	0	7.33	0.04	4.46	0.07	4.55	4.29	2.96
Comb-OF	0	7.45	0.04	4.42	0.06	4.69	4.25	2.99

[a] Tied ridge.

[b] Open furrow.

The case for using isotopic methods is that N management is a critical factor in any farming system used in the study area, but simply adding fertilizer at a recommended rate is not a solution for a resource-poor farmer, particularly when choices for making N inputs also include animal manures, crop residues, and BNF. The value of the different sources varies considerably in this semi-arid situation with large seasonal variation in rainfall. The use of ^{15}N permits researchers to quantify the value of the different N inputs, showing for example that sole pigeon pea obtained 57% of its N from the soil, whereas pigeon pea intercropped with sorghum took only 35% of its N from the soil. According to a recent evaluation of published work on the effect of drought on BNF, pigeon pea's symbiosis with rhizobia is more sensitive to drought than is the pigeon pea plant itself [4] (Serraj et al. 1999), and these simulations support that observation. Dealing with FYM has been difficult because of the magnitude of variation in its quality factors which is now becoming evident as information accumulates on animal manures in countries of the south. Similar problems have occurred with crop residues, though usually it has been assumed that crop residues are of little consequence because of burning or of total harvest and removal. While it is true that burning is still widespread in some regions (e.g. the Punjab of India), and total grazing occurs in many African and Asian countries, there are signs that the use of crop residues in the management of crop nutrition may achieve more importance in the future, as is now being seen with mucuna residues in Malawi (J. Rusike, personal communication). It is clear that in countries of the south, sources of N for crops will need to include BNF, crop residues and animal manures in addition to (or instead of) fertilizer, and that assessment of quality factors of different inputs will be needed. There is a clear indication that input combinations will be increasingly used, for example small inputs of fertilizer in combination with FYM. The simulation results indicate that a re-evaluation of fertilizer recommendations is needed; no farmer in the study districts would apply the recommended rate of N, and there are likely to be large yield benefits from fractions of the recommended rate.

The simulation analysis provided an opportunity to test alternative rates of application of fertilizers, and also to examine the likely outcome of combinations of sources of N. The outcome was a clear indication that small fertilizer inputs could greatly increase crop yields, and that such small inputs could be more attractive to smallholder farmers than the much higher recommended rates. Subsequent on-farm experimentation (G.M. Heinrich et al., personal communication) supports this idea, and has led to further on-farm testing in other districts of the drier parts of Zimbabwe. The research here has also indicated that modest N inputs not only increase yield, but also reduce the risk of crop failure. Given that the monsoon has not failed in India during the period from 1990, it can be suggested that the frequent "droughts" experienced in Mahabubnagar District are more due to N deficiency than shortage of water. In Zimbabwe, this idea is not yet likely to find acceptance because of the highly skewed relationship between fertilizer cost and availability, and the value of grain produced.

Given the importance of N deficiency, how do we researchers make recommendations for management when there are several potential sources of input material, and also very fluid economic conditions? Good experimentation is still needed, but simulation tools are now available that permit us to examine a range of options more efficiently than could be done by traditional experimentation. In these studies, the modelling outputs suggest that we should question some established beliefs about crop production in the study areas.

Production of the SAT crops sorghum and millet has been declining in terms of total product and area sown. Sixteen years of the Sorghum and Millet Improvement Program has resulted in the release of numerous improved varieties but has not resulted in higher yields. These varieties perform well in good soils on research stations, but are no better than traditional cultivars on degraded lands. Improved management options are generally not adopted because of a combination of lack of knowledge, shortage of labour, lack of funds for investment, difficulty in marketing, perception of risk, alternative investment priorities, etc. ICRISAT and its partners have tackled this question in several ways, including the use of improved dissemination methods [better farmer-participatory research (FPR), farmer field schools], focus on more relevant options (modified tied ridges, legumes for farming systems, seed priming, small packets of seed and fertilizer, improved use of FYM, easier striga management), and use of new tools for helping farmers (linking simulation to FPR, engaging change agents through simulation).

4. CONCLUSIONS

- In India, use of ^{15}N has helped understand the role of BNF in pigeon pea, the modest recycling of N from FYM, and the efficiency of N uptake from fertilizer.
- In India, dealing with crop production where the major growth constraint is nutritional rather than water (as appears to be the case at Palem), it is important to have a good understanding of the efficiency of crop use of soil-fertility inputs, and equally important for researchers to engage with farmers so that the farmers become involved in conducting their own research.
- Systems simulation, for example APSIM, is now sufficiently advanced to be useful in looking at a wider range of options over longer periods than can be achieved by traditional research alone.
- In future, systems simulation should be used to help engagement with farmers, as has already been done in Australia and Zimbabwe.
- In view of the clients of this research not having funds to invest in soil fertility, fertilizer rates tested should be lower than those locally recommended.
- To break away from the present poor adoption of soil-fertility technologies, future experimentation should utilize new tools, such as isotopes, residue-quality evaluation, modern on-farm methods and systems simulation to make faster impact on farmer household livelihoods in tropical semi-arid regions.

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MANAGEMENT OF NITROGEN AND EVALUATION OF WATER-USE EFFICIENCY IN TRADITIONAL AND IMPROVED CROPPING SYSTEMS OF THE SOUTHERN TELANGANA REGION OF ANDHRA PRADESH, INDIA

M.V. RAMANA, K.M. KHADKE,
Acharya N.G. Ranga Agricultural University,
Palem, India

T.J. REGO, J.V.D.K. KUMAR RAO, R.J.K. MYERS,
G. PARDHASARADHI, N. VENKATA RATNAM
International Crops Research Institute for the Semi-Arid Tropics,
Patancheru, India

Abstract

A collaborative research project among the International Atomic Energy Agency, Acharya N.G. Ranga Agricultural University and the International Crops Research Institute for the Semi-Arid Tropics, was initiated in 1999 with the objective of developing a set of options for improving the nitrogen (N) nutrition of dry-land cropping systems by use of N from biological N_2 fixation, fertilizer and organic matter at the Regional Agricultural Research Station, Palem, Mahabubnagar District, Andhra Pradesh. The main experiment consisted of traditional (sorghum–castor) and improved (sorghum/pigeon pea-castor) cropping systems on a two-year rotation cycle with four N-management options. Nitrogen-15-labelled fertilizer and farmyard manure (FYM) were included as sources of N. In spite of low rainfall (390 mm in1999; and 450 mm in 2000) both sorghum and castor responded to applied N. Intercropped pigeon pea had beneficial effects on the succeeding castor crop. A grain yield advantage of 88 kg ha^{-1} was obtained with castor following sorghum/pigeon pea compared to that following sole sorghum. In on-farm participatory trials, the yields of sorghum, castor and pigeon pea were substantially higher with improved practice compared to farmers' practice. There was no significant difference between urea alone and urea plus FYM as a source of N to sorghum and castor-based cropping systems.

1. INTRODUCTION

Alfisols are widely distributed in the semi-arid tropics of India, as well as in East Africa, Australia, and South America. Sorghum and pigeon pea are the important food grain crops in semi-arid tropical areas of India. In the southern Telangana region of Andhra Pradesh (AP), India, sorghum and castor based systems are predominant in rainfed agriculture. The productivity of these systems is very low (around 0.5 t ha^{-1}) and limited by low and variable rainfall and nutrient-poor soils. The rainy season in this region starts in June and the monsoon ends by September/October thereby limiting the crop-growth period to 3 to 4 months. Annual precipitation varies from 600 to 800 mm with frequent dry spells causing yield losses and, at times, crop failures. Earlier studies in Mahabubnagar District conducted by scientists at the International Centre for Research in the Semi-Arid Tropics (ICRISAT) [1] in farmers' fields indicate that the soils are poor in organic carbon (C) and that nitrogen (N) is the factor most limiting crop production in addition to low and variable rainfall. Nutrient balance for both sorghum and castor crops in farmers' fields was found to be negative and consequently for the cropping system as a whole. If nutrient (NPK) mining of these poor soils continues, then they may become unsuitable for crop production.

Nitrogen-fertilizer application under this situation is a standard practice to increase yields of sorghum and castor. The recommended N-fertilizer rates, based on research at the Regional Agricultural Research Station (RARS), Palem, Mahabubnagar District, AP, for optimum yields of castor and sorghum vary from 60 to 80 kg ha^{-1} depending on cultivars used.

For stable and sustainable higher yields and maintenance of soil fertility, growing pigeon pea as an intercrop with sorghum and application of organic manures like farmyard manure play a significant role in those low-input farming systems involving sorghum and castor. Although many papers have reported yield advantage with cereal/legume intercropping systems [2, 3, 4] few have dealt with N economy within the system and contribution of the legume to succeeding non-legumes.

This paper reports the results of a collaborative project between Acharya N. G. Ranga Agricultural University (ANGRAU) and ICRISAT funded by FAO/IAEA, Vienna, Austria, conducted at RARS, Palem. The objectives were to quantify:

- to quantify N recoveries from different sources in two cropping systems (two-year rotations) and their mirror images namely sorghum–castor; castor–sorghum; intercropped sorghum/pigeon pea (2:1)–castor rotation and castor–sorghum/pigeon pea,
- to quantify biological N_2 fixation (BNF) by pigeon pea, and
- to determine the direct, residual and combined effects of N sources on crop yields and N recoveries.

2. MATERIALS AND METHODS

The experiment was conducted during the 1999 and 2000 rainy seasons on a shallow-medium Alfisol (Typic Haplustalfs) at RARS, Palem. Composite samples of soil from 0- to 15-cm had the following properties, organic C, 0.40%; total N, 498 ppm; pH (soil H_20 1:5), 4.93. The experimental site had an available water storage of 84 mm/90 cm depth (Table I)

The experimental field was fallow during 1997 and maize was grown as a cover crop during the 1998 rainy season. The experiment was laid out in a split-plot design with three replicates. Main treatments were four cropping systems (two-year rotations) namely: sorghum–castor, castor–sorghum, sorghum/pigeon pea(2:1)–castor, and castor–sorghum/pigeon pea (2:1). The sub-plot treatments were: no N (control), farmyard manure (FYM) at 1.5 t ha^{-1}, 60 kg N ha^{-1} as urea, and FYM at 1.5 t ha^{-1} + 45 kg N ha^{-1} as urea. All of the N fertilizer was applied by opening the furrows and banding at a depth of 5 to 8 cm. In the intercropping treatment (sorghum/pigeon pea in a 2:1 ratio), N was applied only to sorghum. Farmyard manure was broadcast basally to the plots and incorporated. Nitrogen was applied in two equal splits to sorghum; for castor, three equal splits were used. Where both organic and inorganic sources of N were applied, urea was added as a basal treatment to sorghum of 20 kg N ha^{-1} and at 25 kg N ha^{-1} at 30 days after sowing.

Phosphorus at 40 kg P_2O_5 ha^{-1} as single superphosphate and potassium at 30 kg K_2O ha^{-1} as muriate of potash were applied basally to all plots. The crop varieties were castor, Kranthi; sorghum, PSV-1; and pigeon pea, PRG-100. They were sown on 8 July in 1999 and 2 July in 2000, respectively. The spacings were 75 × 75 cm for castor and 50 × 15 cm for sole sorghum. In the sorghum/pigeon pea intercrop, sorghum was sown at a spacing of 50 × 10 cm, while pigeon pea had a spacing of 150 × 15 cm. This arrangement gave an identical number of plants per unit area for sorghum in the sole and intercropping systems. The experiment consisted of a total of forty-eight sub-plots, each measuring 7.5 × 9.0 m. Two seeds of pigeon pea and castor and five of sorghum were sown at precisely the required distances. Seedlings were thinned to one per hill 10 days after emergence.

Table I. Water-storage capacity of the experimental soil

Depth (cm)	Water at 0.33 bar	Water at 15 bar	Available water	Gravimetric water (%)	Bulk density	Available water (mm)
	(g g^{-1})					
0–15	0.14	0.10	0.04	6	1.50	13.5
15–30	0.22	0.16	0.06	6	1.45	13.1
30–45	0.24	0.17	0.07	7	1.47	15.4
45–60	0.25	0.18	0.07	7	1.36	14.3
60–75	0.22	0.15	0.07	7	1.32	13.9
75–90	0.23	0.16	0.07	7	1.32	13.9

All sowing and fertilizer applications were done by hand in open furrows between 10 cm ridges. Pigeon pea seeds were inoculated at sowing with a culture of rhizobial strain IC 3195. Nitrogen-15 was applied to micro-plots measuring 1.5 × 0.75 m, demarcated with aluminium sheeting embedded 15 cm deep and leaving 15 cm above the soil surface.

Farmyard manure was labelled with ^{15}N by adding an equal amount of N as that contained in the manure (N content, 1.0 %) as urea (5 atom % excess) and incubating it. The ^{15}N-labeled FYM was placed in polythene bags, and mixed at regular intervals over 4 months while maintaining optimum moisture content. Thus, treatments with FYM (1.5 t ha^{-1}) received 30 kg N ha^{-1} and N recoveries were estimated accordingly. In the treatment where FYM + urea were applied, two micro-plots were demarcated, one for labelled urea and the other for labelled FYM.

The ^{15}N-labelled urea (5.571 and 5.214 atom % excess during the first and second years) was applied by banding to crop rows in the micro-plots, at the same time and rate as for the surrounding ^{14}N-urea. The ^{15}N-labelled FYM (1.272 and 1.651 ^{15}N atom % excess during the first and second years) was broadcast as basal and incorporated into micro-plots as per sub-plot treatments.

During the second year (2000), other micro-plots adjacent to the 1999 micro-plots were enclosed in earthen bunds and labelled FYM/urea was applied as per N options. In the micro-plots laid out in the first year (1999), ^{14}N-urea/non-labelled FYM was applied during the second phase (2000) of the two-year rotation as per treatments to study the residual effects of different sources.

The proportion of N derived from the residual N of a preceding legume component in the system was calculated as the %N derived from an unlabelled source (%Ndfu) [5]:

$$\%Ndfu = (1 - \frac{atom\ \%\ excess\ for\ castor\ following\ sorghum / pigeon\ pea}{atom\ \%\ excess\ for\ castor\ following\ sole\ sorghum}) \times 100 \qquad (1)$$

During the 1999 and 2000 growing season (July–December/January) 390 mm of rain were received in 21 and 28 rainy days, respectively, against the normal 540 mm received in 36 rainy days. Insecticides and fungicides were applied as necessary to minimize damage caused by shoot fly and stem borer in sorghum, pod borer in pigeon pea and wilt in castor. Weeds were controlled manually and by running three-tined push hoes during the experimental period. Sorghum plants from within the micro-plots were harvested in 1999 and 2000 on 27 October and 17 October, respectively, while pigeon pea was harvested on 27 December 1999 and 3 January 2001. Since castor is indeterminate, capsules were harvested three times. Primary and secondary spikes were harvested on 15 October and 2 November in 1999, while in 2000 they were harvested on 11 and 31 October. Final harvesting was done from tertiary spikes on 22 December and 20 December, respectively, and plants were cut and oven-dried.

Samples from the micro-plots were analysed at the FAO/IAEA Soil Science Laboratory at Seibersdorf for N content and ^{15}N atom % excess by continuous-flow mass spectrometry. Grain yields were estimated by harvesting 40% of each plot area (including micro-plots) (67.5 m^2) and used to calculate fertilizer recoveries.

As a part of the research project, on-farm research was conducted within a radius of 15 km of the research station at Palem. Farmers selected variations on rotating sorghum/pigeon pea intercrop with sole castor on a two-year rotation basis. The variations were either urea or a combination of urea and FYM. The seed (high-yielding varieties used in on-station research) and fertilizer were provided to farmers for the improved practice; farmers used their own resources for the traditional/farmers' practice. Each was grown in an area of 2,000 m^2.

Table II. Effects of cropping system and nitrogen-management options on grain and total dry matter yields of sorghum (1999)

N option	Grain				TDM			
	Sole crop	Inter-crop	Mean		Sole crop	Inter-crop	Mean	
	(kg ha^{-1})							
Control	458	480	469		5,069	5,256	5,163	
FYM	854	906	880		6,936	6,392	6,664	
FYM+urea	2,259	1,748	2,003		8,431	7,072	7,751	
60N urea	2,326	1,847	2,087		9,121	6,824	7,973	
Mean	1,474	1,245			7,389	6,386		
	CS[a]	N[b]	N×CS	CS×N	CS	N	N×CS	CS×N
F test	**[c]	***	**	**	**	***	**	**
SEM±	7	55	78	68	32	165	233	204
C.D.(0.05)	43	171	241	210	196	507	717	626
C.V.(%)	10				6			

[a] Cropping system.

[b] Nitrogen option.

[c] *, ** and *** denote significance at P= 0.05, 0.01 and 0.001, respectively.

3. RESULTS AND DISCUSSION

3.1. Dry matter and grain yield

3.1.1. Sorghum

Cropping system did not affect the grain yield or total dry matter production of sorghum except during the first year when the sole-crop yields were significantly greater than intercrop (Table II).

The N-management options, synthetic and organic sources of N and their combination, had a significant influence on yields of sorghum during the first year of the two-year rotation. A similar response to N treatments was noticed with sorghum under sole and intercropping in the second year preceded by castor (Table III).

In both years, the least grain and total dry-matter yields (kg ha^{-1}) of sorghum were obtained from control plots (469 and 961; 5,163 and 6,488) (Tables II and III). Application of FYM significantly improved grain yield (880, 1,325) and total dry matter (6,664; 7,631) during both years over no N applied. The treatment involving integrated use of FYM and urea gave greater yields of grain (2,003; 2,512) and dry matter (7,751; 9,936) over FYM application alone. These yields were on par with those obtained with 60 kg N ha^{-1} as urea.

The interactive effect of N options and cropping system was significant for total dry matter production and grain yield during the first year. In the second year, for sorghum preceded by castor, the interaction was significant only for total dry matter (Table III). Sole sorghum produced significantly higher dry matter yields compared to that of the intercrop only with higher N treatments, viz. FYM + urea and 60 kg N ha^{-1} as urea. They were found to be similar with FYM at 1.5 t ha^{-1} alone and also with the control plot.

3.1.2. Castor

There was no effect of cropping system on castor during the first year (1999) (Table IV). The second cropping season (2000) provided an opportunity to contrast the traditional system in which castor follows sorghum with the alternative of castor following sorghum with a legume component. The results indicated no influence of the preceding cropping system (Table V).

Table III. Effects of nitrogen-management options on grain and total dry matter yields of sorghum preceded by castor (2000)

N option	Grain				TDM			
	Sole crop	Inter-crop	Mean		Sole crop	Inter-crop	Mean	
	(kg ha^{-1})							
Control	982	939	961		7,394	5,581	6,488	
FYM	1,454	1,196	1,325		7,603	7,658	7,631	
FYM+urea	2,814	2,210	2,512		11,339	8,532	9,936	
60N urea	2,666	2,056	2,361		11,412	8,456	9,934	
Mean	1,979	1,600			9,437	7,557		
	CS[a]	N[b]	N×CS	CS×N	CS	N	N×CS	CS×N
F test	NS	***[c]	NS	NS	NS	***	*	*
SEM±	137	101	144	185	520	331	468	659
C.D.(0.05)	–	313	–	–	–	1020	1442	2416
C.V.(%)	14				10			

[a] Cropping system.

[b] Nitrogen option.

[c] *, ** and *** denote significance at $P = 0.05$, 0.01 and 0.001, respectively.

Table IV. Effects of nitrogen-management options on grain and total dry matter yields of castor (1999)

N option	Grain				TDM			
	C–S[a]	C–S/PP	Mean		C–S	C–S/PP	Mean	
	(kg ha^{-1})							
Control	1,137	857	997		2,335	1,906	2,121	
FYM	1,280	1,399	1,339		2,953	3,327	3,140	
FYM+urea	1,452	1,550	1,501		3,314	3,518	3,416	
60N urea	1,623	1,622	1,622		3,696	3,619	3,658	
Mean	1,373	1,357			3,075	3,092		
	CS[c]	N	N×CS	CS×N	CS	N	N×CS	CS×N
F test	NS	***[e]	NS	NS	NS	***	NS	NS
SEM±	38	52	73	73	89	102	144	153
C.D.(0.05)	–	160	–	–	–	314	–	–
C.V.(%)	9				8			

[a] Castor–sorghum rotation.

[b] Castor–sorghum/pigeon-pea intercrop rotation.

[c] Cropping system.

[d] Nitrogen option.

[e] *, ** and *** denote significance at the $P = 0.05$, 0.01 and 0.001 levels, respectively.

Table V. Effects of previous crop and nitrogen-management options on grain and total dry matter yields of castor (2000)

N option	Grain				TDM			
	Previous crop							
	S[a]	S/PP[b]	Mean		S	S/PP	Mean	
	(kg ha^{-1})							
Control	764	795	780		2,037	2,065	2,051	
FYM	1,007	1,171	1,089		2,358	2,864	2,611	
FYM+urea	1,282	1,478	1,380		3,189	3,588	3,388	
60N urea	1,482	1,442	1,462		3,653	3,514	3,584	
Mean	1,134	1,222			2,809	3,008		
	CS[c]	N[d]	N×CS	CS×N	CS	N	N×CS	CS×N
F test	NS	***[e]	NS	NS	NS	***	NS	NS
SEM±	38	48	68	70	117	143	202	210
C.D.(0.05)	–	148	–	–	–	439	–	–
C.V.(%)	10				12			

[a] Sole sorghum.

[b] Sorghum/pigeon pea intercrop.

[c] Cropping system.

[d] Nitrogen option.

[e] *, ** and *** denote significance at the $P = 0.05$, 0.01 and 0.001 levels, respectively.

Although there was no influence of the preceding cropping system on castor, an additional mean grain yield of 88 kg ha^{-1} was obtained with castor preceded by sorghum/pigeon pea compared to that following sole sorghum (Table V).

The castor crop responded significantly to applied N during both years, and 60 kg N ha^{-1} as urea gave the highest grain yields (kg ha^{-1}) (1,622; 1,462) and total dry matter (3,658; 3,584), followed by application of FYM + urea (grain yield 1,501; 1,380 and total dry matter 3,416; 3,388) which were superior to FYM alone (grain yield 1,339; 1,089and total dry matter 3,140; 2,611). The former two differed significantly only during the first year. The least grain and TDM yields of castor were obtained from the control plots during both years.

3.1.3. Pigeon pea

Intercropped pigeon pea was not affected by the N options imposed on sorghum during either year. The total dry matter and grain yields were substantially higher during the second year. Grain yield varied from 345 to 475 kg ha^{-1} in 1999, while during 2000 it ranged between 777 and 871 kg ha^{-1} (data not shown).

3.2. Direct effects of nitrogen source on nitrogen yield and recovery

3.2.1. Sorghum

There was no effect of crop rotation in 1999, except in terms of grain and TDM yields of sole compared with intercropped sorghum (Table VI). Nitrogen yields, fertilizer N used and consequently the N recoveries in grain and total dry matter were similar in the two cropping systems (Tables VI and VII). Similar trends were observed with sorghum during the second phase of the rotation, proceeded by castor (Tables VIII and IX), except that fertilizer N used and N recovery in grain, and consequently the total fertilizer N used and total N recovery, were greater with the sole crop than the intercrop.

The N options had significant effects on N yield, fertilizer N used and N recovery. In the first year, the total N yield for sorghum, averaged over sole and intercrops, significantly increased with FYM + urea (52.6) over FYM alone (40.9) (Table VI). Application of 60 kg N ha^{-1} as urea resulted in significantly higher N yield (69 kg ha^{-1}) over the FYM + urea treatment. The total N yield of sorghum was significantly greater with application of 60 kg N ha^{-1} as urea (80.8 kg N ha^{-1}), compared to FYM + urea, and both were superior to FYM at 1.5 t ha^{-1} (39.0 t ha^{-1}) under sole crop, whereas in the intercrop all three were similar.

During the second year, higher total-N uptake was observed with urea at 60 kg N ha^{-1} (87.7 kg ha^{-1}) followed by the FYM + urea treatment over FYM alone (43.6 kg ha^{-1}) (Table VIII). When intercropped, N treatments had no effect on sorghum N yield.

Cropping system had no influence on fertilizer N from different sources in sorghum stalk or chaff (data not shown); for grain and total fertilizer N used during the second year, higher values were obtained for the sole crop than the intercrop (Table IX).

In both years, N yield of sorghum from urea was significantly greater than from FYM (Tables VII and IX). The total fertilizer N used from FYM when applied with urea was similar to that as a sole application. Application at 60 kg N ha^{-1} gave higher values for total fertilizer N used over that of urea used in combination with FYM.

Higher recoveries of N were observed in stalk and grain of sorghum compared to that of chaff. In sole-cropped sorghum, the N recovery in grain from FYM varied from 1.7% when used alone to 4.2% in combination with urea during the first year and from 2.4% to 4.0% in the second year, respectively. The grain N recovery from urea at 60 kg N ha^{-1} was lower (14%) compared to that of urea (17%) used at 45 kg N ha^{-1} in conjunction with FYM.

Similarly, with intercropping, N recovery from urea at 60 kg N ha^{-1} was lower (11%) compared to that from urea used along with FYM (14%). The same was the case with FYM (data not shown).

We estimated total N recoveries of 34% and 23% in sole and intercropped sorghum from 60 kg N ha^{-1} as urea, respectively. With FYM + urea, the N recoveries in sole and intercropped sorghum from urea were 34% and 28% during the first year (Table VII).

The N recovered from FYM in sole sorghum ranged between 5.9% with FYM alone to 7.8% in combination with urea (Table VII). Intercropped sorghum recovered 6.2% of the FYM N when combined with urea and 5.4% from FYM alone (Table VII).

During the second year a similar trend was observed in sorghum recoveries when preceded by castor. However cropping system had a significant effect on N recovery (%) in grain and total N recovery (Table IX).

The grain and total N recoveries (over N treatments) by sole sorghum were higher than those of the intercrop. Higher total N recovery (28%) was obtained when urea was applied in combination with FYM than when applied alone at 60 kg N ha^{-1} (23%). The N-recovery percentages from FYM in stalk, chaff and grain (data not shown) and total recovery were similar whether applied alone or in conjunction with urea (Table IX).

The total N recovery from urea was higher in the sole crop (27%) than in the intercrop (19%) at 60 kg N ha^{-1}. Similarly, in the FYM + urea treatment, the sole-cropped sorghum recorded higher total N recovery (30%) from urea than did the intercrop (27%). The contribution from FYM when used in combination with urea was greater than when applied along to the sole crop (Table IX).

Table VI. Effects of cropping system and nitrogen-management options on dry matter and nitrogen yields of sorghum (1999)

N option	Grain				TDM				Grain N				Total N			
	Sole crop	Inter-crop	Mean		Sole crop	Inter-crop	Mean		Sole crop	Inter-crop	Mean		Sole crop	Inter-crop	Mean	
	(kg ha^{-1})															
FYM	854	906	880		6,936	6,392	6,664		13.9	15.2	14.5		39.0	42.8	40.9	
[φ]FYM+urea	2,259	1,748	2,003		8,431	7,072	7,751		13.1	26.4	29.2		57.8	47.4	52.6	
FYM+[φ]urea	2,259	1,748	2,003		8,431	7,072	7,751		32.0	25.7	29.9		61.1	47.0	54.0	
60N urea	2,326	1,847	2,087		9,121	6,825	7,973		39.5	30.6	35.1		80.8	57.2	69.0	
Mean	1,924	1,562			8,230	6,840			29.4	24.5			59.7	48.6		
	CS[a]	N[b]	N×CS	CS×N	CS	N	N×CS	CS×N	CS	N	N×CS	CS×N	CS	N	N×CS	CS×N
F test	*[c]	***	**	**	**	***	**	**	NS	***	NS	NS	NS	***	**	**
SEM±	27.2	52.0	73.5	69.2	72.4	146.4	207.1	193.4	1.36	1.52	2.15	2.31	2.38	2.02	2.86	3.44
C.D.(0.05)	165	160	226	210	441	451	638	587	–	4.67	–	–	–	6.23	8.81	11.4
C.V.(%)	7.3				4.8				14				9.1			

Table VII. Effects of cropping system and nitrogen-management on fertilizer nitrogen used, total nitrogen recovery and soil contribution in sorghum (1999)

N option	Fertilizer N used in grain				Total fertilizer N used				Total N recovery				Soil N contribution			
	Sole crop	Inter-crop	Mean		Sole crop	Inter-crop	Mean		Sole crop	Inter-crop	Mean		Sole crop	Inter-crop	Mean	
	(kg ha^{-1})								(%)				(kg ha^{-1})			
FYM	0.52	0.55	0.53		1.77	1.65	1.71		5.9	5.5	5.7		37.2	41.2	39.2	
[φ]FYM+urea	1.25	1.02	1.14		2.35	1.87	2.11		7.8	6.2	7.0		55.5	45.5	50.5	
FYM+[φ]urea	7.63	6.39	7.01		15.2	12.4	13.8		34	28	31		45.9	34.6	40.2	
60N urea	8.45	6.68	7.57		20.2	14.0	17.1		34	23	29		60.6	43.2	51.9	
Mean	4.46	3.66			9.89	7.48			20	16			49.8	41.1		
	CS[a]	N[b]	N×CS	CS×N	CS	N	N×CS	CS×N	CS	N	N×CS	CS×N	CS	N	N×CS	CS×N
F test	NS	***[c]	NS	NS	NS	***	NS	NS	NS	***	NS	NS	NS	**	*	*
SEM±	0.22	0.25	0.34	0.38	0.70	0.83	1.17	1.23	1.3	1.5	2.2	2.3	1.8	2.17	3.07	3.23
C.D.(0.05)	–	0.74	–	–	–	2.55	–	–	–	4.7	–	–	–	6.69	9.47	10.09
C.V.(%)	15				23				21				12			

[φ]Labelled source. [a]Cropping system. [b]Nitrogen option. [c]*, ** and *** denote significance at $P= 0.05$, 0.01 and 0.001, respectively.

Table VIII. Effects of nitrogen-management options on grain, TDM and nitrogen yields of sorghum preceded by castor (2000)

N option	Grain				TDM				Grain N				Total N			
	Sole crop	Inter-crop	Mean		Sole crop	Inter-crop	Mean		Sole crop	Inter-crop	Mean		Sole crop	Inter-Crop	Mean	
	(kg ha^{-1})															
FYM	1,454	1,196	1,325		7,603	7,658	7,631		16.3	16.3	16.3		43.6	57.8	50.7	
[φ]FYM+Urea	2,814	2,210	2,512		11,339	8,532	9,936		34.5	25.5	30.0		79.6	57.8	68.7	
FYM+[φ]Urea	2,814	2,210	2,512		11,339	8,532	9,936		34.9	24.6	29.8		84.9	58.4	71.6	
60N Urea	2,666	2,056	2,361		11,412	8,456	9,934		32.9	25.7	29.3		87.7	60.4	74.0	
Mean	2,437	1,918			10,423	8,295			29.6	23.0			73.9	58.6		
	CS[a]	N[b]	N×CS	CS×N	CS	N	N×CS	CS×N	CS	N	N×CS	CS×N	CS	N	N×CS	CS×N
F test	NS	***[c]	NS	NS	NS	***	**	**	NS	***	*	*	NS	**	**	**
SEM±	149	91	129	186	541	325	207	193	3.3	1.1	1.6	3.6	9.3	4.0	5.7	10.5
C.D.(0.05)	–	281	–	–	–	1,002	638	5867	–	3.5	5.0	17.2	–	12.4	17.5	45.3
C.V.(%)	10				8.5				11				15			

Table IX: Effects nitrogen-management options on fertilizer nitrogen used, total nitrogen recovery and soil contribution in sorghum preceded by castor (2000)

N option	Fertilizer N in grain				Total fertilizer N used				Total N recovered				Soil contribution			
	Sole crop	Inter-crop	Mean		Sole crop	Inter-crop	Mean		Sole crop	Inter-crop	Mean		Sole crop	Inter-crop	Mean	
	(kg ha^{-1})								(%)				(kg N ha^{-1})			
FYM	0.71	0.50	0.60		2.00	1.94	1.97		6.7	6.5	6.6		41.6	55.9	48.8	
[φ]FYM+Urea	1.20	0.81	1.00		2.86	1.86	2.36		9.5	6.2	7.9		76.7	56.0	66.3	
FYM+[φ]Urea	5.48	4.50	4.99		13.4	11.9	12.7		30	27	28		71.5	46.4	58.9	
60N Urea	5.91	4.93	5.42		15.9	11.7	13.8		27	19	23		71.8	48.7	60.2	
Mean	3.33	2.68			8.54	6.84			18	15			65.4	51.8		
	CS[a]	N[b]	N×CS	CS×N	CS	N	N×CS	CS×N	CS	N	N×CS	CS×N	CS	N	N×CS	CS×N
F test	*[c]	***	NS	NS	**	***	NS	NS	*	***	NS	NS	NS	NS	*	*
SEM±	0.10	0.38	0.54	0.48	0.06	0.59	0.83	0.72	0.40	1.3	1.8	1.6	9.21	3.98	5.63	10.42
C.D.(0.05)	0.62	1.18	–	–	0.36	1.81	–	–	2.4	4.0	–	–	–	–	17.3	45.0
C.V.(%)	31				19				19				17			

[φ] Labelled source. [a] Cropping system. [b] Nitrogen option. [c] *, ** and *** denote significance at P= 0.05, 0.01 and 0.001, respectively.

3.2.2. Castor

The total N yield in the aboveground parts at harvest during the first year increased from 60.5 kg ha^{-1} with FYM to 78.3 kg ha^{-1} at 60 kg N ha^{-1} as urea. The N yield from urea (76.2 kg ha^{-1}) used along with FYM was similar to that obtained with urea at 60 kg N ha^{-1}(Table X). A similar trend was seen with regard to N yield in grain (Table X).

The N used from FYM (3.11 kg ha^{-1}) and consequently the manure-N recovery (10%) were slightly higher when applied in combination with urea at 45 kg N ha^{-1} over FYM applied alone (2.18 kg ha^{-1}; 7.3%). The total N recovered from urea was significantly greater (27%) when used along with FYM over that when urea was applied alone (22%) (Table XI).

Grain-N and total-N accumulations by castor averaged over N treatments were higher in 2000 when preceded by sorghum/pigeon pea (38.5; 57.1 kg ha^{-1}) compared to those preceded by sole sorghum (35.0; 52.3 kg ha^{-1}), although the differences were not significant (Table XII). Similar trends were seen in N yield of stalk and chaff (data not shown). The N-management options combining organic and chemical sources had a significant influence on N yield, fertilizer N used and fertilizer N recovery values (Table XII and XIII). Significantly greater values for urea N used were obtained for grain as well as for total fertilizer-N when applied alone at 60 kg N ha^{-1} over those obtained when applied with FYM. However, the N recoveries were similar in both treatments.

3.2.3. Pigeon pea

The pigeon pea crop took little N (<1.0%) from either urea or from FYM. The %N derived from fixation (%Ndfa) determined using the ^{15}N-dilution method (using a long-duration sorghum as the reference crop) was estimated as 43% and 65% in sole and intercropped pigeon pea, respectively (data not shown).

3.3. Residual effects of nitrogen sources on nitrogen yield and recovery

The residual effects of different N sources applied to sorghum and sorghum/pigeon pea in the first year were estimated during the second year with castor and vice versa. Generally there was more recovery of residual N by sorghum than by castor (Table XIV).

The legume component had no effect on the total N yield, fertilizer N used or total N recovery (%) of the succeeding castor, although higher values were obtained with castor after sorghum/pigeon pea compared to after sole sorghum (Table XIV). However grain N yield was significantly higher in castor preceded by sorghum/pigeon pea compared to that preceded by sole sorghum.

Castor took more residual N from manure than from urea. In contrast, sorghum was found to be more efficient in extracting residual N from urea than from manure. The residual-N recovery from FYM by castor was significantly higher (3.6%) when used in combination with urea than when applied alone (3.0%). These recoveries were significantly greater than from urea used alone (2.2%) or from urea used in conjunction with FYM (2.3%).

Also in sorghum, the residual N recovery from FYM was higher (4.5%) when used with urea than alone (3.5%). The residual N recovery by sorghum from urea (applied at 60 kg N ha^{-1} during the first year) was significantly higher (5.5%) compared to that from FYM.

Table X. Effects of nitrogen-management options on grain and total dry matter and nitrogen yields of castor (1999)

N option	Grain				TDM				Grain N yield				Total N yield			
	C–S	C–S/PP	Mean		C–S	C–S/PP	Mean		C–S	CS/PP	Mean		C–S	CS/PP	Mean	
	(kg ha^{-1})															
FYM	1,280	1,399	1,339		2,953	3,327	3,140		32.1	44.1	38.1		52.3	68.7	60.5	
[φ]FYM+Urea	1,452	1,550	1,501		3,314	3,518	3,416		44.8	51.4	48.1		66.3	81.3	73.8	
FYM+[φ]Urea	1,452	1,550	1,501		3,314	3,518	3,416		44.5	52.9	48.7		72.7	79.6	76.2	
60N Urea	1,623	1,622	1,622		3,696	3,619	3,658		50.8	50.8	50.8		79.1	77.4	78.3	
Mean	1,452	1,530			3,319	3,495			43.0	49.8			67.6	76.7		
	CS[a]	N[b]	N×CS	CS×N	CS	N	N×CS	CS×N	CS	N	N×CS	CS×N	CS	N	N×CS	CS×N
F test	NS	***[c]	NS	NS	NS	**	NS	NS	NS	*	NS	NS	NS	*	NS	NS
SEM±	52.7	32.4	45.8	66.0	101.5	68.2	96.4	131.4	3.55	2.59	3.66	4.76	5.94	3.72	5.26	7.48
C.D.(0.05)	–	99.8			–	210	–	–	–	7.97	–	–	–	11.5	–	–
C.V.(%)	5.3				4.9				14				13			

Table XI. Effect of nitrogen-management option on fertilizer nitrogen used, total nitrogen recovered and soil nitrogen contribution in castor (1999)

N option	Fertilizer N used in grain				Total fertilizer N used				Total N recovered				Soil contribution			
	C–S	C–S/PP	Mean		C–S	C–S/PP	Mean		C–S	C–S/PP	Mean		C–S	C–S/PP	Mean	
	(kg ha^{-1})															
FYM	1.11	1.68	1.39		1.77	2.60	2.18		5.89	8.65	7.27		50.5	66.1	58.3	
[φ]FYM+Urea	1.91	2.26	2.09		2.80	3.43	3.11		9.33	11.4	10.4		63.5	77.9	70.7	
FYM+[φ]Urea	7.32	6.80	7.06		13.8	10.7	12.3		30.8	23.	27.3		58.9	68.9	63.9	
60N Urea	7.69	7.89	7.79		13.3	13.2	13.2		22.1	21.9	22.0		65.9	64.3	65.1	
Mean	4.51	4.66			7.91	7.47			17.0	16.5			59.7	69.3		
	CS[a]	N[b]	N×CS	CS×N	CS	N	N×CS	CS×N	CS	N	N×CS	CS×N	CS	N	N×CS	CS×N
F test	NS	***[c]	NS	NS	NS	***	NS	NS	NS	***	NS	NS	NS	NS	NS	NS
SEM±	0.18	0.41	0.58	0.53	0.36	0.56	0.79	0.77	1.09	1.30	1.84	1.93	5.64	3.48	4.92	7.07
C.D.(0.05)	–	1.26	–	–	–	1.71	–	–	–	4.01	–	–	–	–	–	–
C.V.(%)	21.8				18				19				13			

[φ] Labelled source. [a] Cropping system. [b] Nitrogen option. [c] *, ** and *** denote significance at P= 0.05, 0.01 and 0.001, respectively.

Table XII. Effects of crop rotation and nitrogen-management options on grain, dry matter and nitrogen yields of castor (2000)

N option	Grain				TDM				Grain N				Total N			
	Previous crop															
	S	S/PP	(Mean)		S	S/PP	(Mean)		S	S/PP	(Mean)		S	S/PP	(Mean)	
	(kg ha^{-1})															
FYM	1,007	1,171	1,089		2,358	2,864	2,611		26.2	30.7	28.4		38.3	45.6	42.0	
$^{\varphi}$FYM+urea	1,282	1,478	1,380		3,189	3,588	3,388		34.3	44.7	39.5		54.2	64.3	59.3	
FYM+$^{\varphi}$urea	1,282	1,478	1,380		3,189	3,588	3,388		38.3	39.8	39.1		55.0	60.1	57.5	
60N urea	1,482	1,442	1,462		3,653	3,514	3,584		41.0	39.0	40.0		61.8	58.5	60.1	
Mean	1,263	1,392			3,097	3,388			35.0	38.5			52.3	57.1		
	CS	N	N×CS	CS×N	CS	N	N×CS	CS×N	CS	N	N×CS	CS×N	CS	N	N×CS	CS×N
F test	NS	***	NS	NS	NS	***	NS	NS	NS	**	NS	NS	NS	**	NS	NS
SEM±	32	41	58	60	104	136	193	196	1.7	1.8	2.6	2.8	2.1	3.0	4.3	4.2
C.D.(0.05)	–	127	–	–	–	420	–	–	–	5.6	–	–	–	9.3	–	–
C.V.(%)	7.6				10				12				14			

Table XIII. Effects of rotation and N-management on fertilizer N used, total N recovery and soil N contribution in castor (2000)

N option	Fertilizer N used in grain				Total fertilizer N used				Total N recovered				Soil contribution			
	Previous crop															
	S	S/PP	(Mean)		S	S/PP	(Mean)		S	S/PP	(Mean)		S	S/PP	(Mean)	
	(kg ha^{-1})								(%)				(kg N ha^{-1})			
FYM	1.20	1.28	1.24		1.66	1.78	1.72		5.6	5.9	5.7		36.7	43.9	40.3	
$^{\varphi}$FYM+urea	1.31	1.75	1.53		1.90	2.38	2.14		6.3	7.9	7.1		52.3	61.9	57.1	
FYM+$^{\varphi}$urea	8.10	7.77	7.94		10.8	11.3	11.03		24	25	25		44.2	48.8	46.5	
60N urea	8.17	10.1	9.13		12.5	14.3	13.4		21	24	22		49.3	44.1	46.7	
Mean	4.69	5.22			6.71	7.45			14	16			45.6	49.7		
	CS	N	N×CS	CS×N	CS	N	N×CS	CS×N	CS	N	N×CS	CS×N	CS	N	N×CS	CS×N
F test	NS	***	NS	NS	NS	***	NS	NS	NS	***	NS	NS	NS	**	NS	NS
SEM±	0.17	0.35	0.50	0.46	0.26	0.53	0.75	0.70	0.49	1.1	1.5	1.4	1.8	2.7	3.8	3.7
C.D.(0.05)	–	1.08	–	–	–	1.64	–	–	–	3.3	–	–	–	8.2	–	–
C.V.(%)	17				18				18				14			

$^{\varphi}$ Labelled source. [a] Cropping system. [b] Nitrogen option. [c] *, ** and *** denote significance at P= 0.05, 0.01 and 0.001, respectively.

Table XIV. Residual nitrogen recoveries from different nitrogen sources as influenced by crop rotation

Crop	Component	Treatment	Total N yield	Total fertilizer N used	Total N recovered (%)
			(kg ha^{-1})		
Recovery of residual N by castor preceded by sorghum	Previous crop	Sole sorghum	47.7	1.06	2.7
		Sorghum/PP	57.6	1.11	2.9
		F test	NS	NS	NS
		SEM±	2.1	0.08	0.21
		C.D.(0.05)	–	–	–
	N option	FYM	41.1	0.91	3.0
		$^{\varphi}$FYM+urea	55.3	1.08	3.6
		FYM+$^{\varphi}$urea	57.4	1.05	2.3
		60N Urea	56.8	1.29	2.2
		F test	*[a]	**	***
		SEM±	3.5	0.06	0.16
		C.D.(0.05)	10.7	0.18	0.51
		Interaction	NS	NS	NS
		C.V.(%)	16	13	15
Recovery of residual N by sorghum preceded by castor	Cropping system	Sole sorghum	76.1	2.40	5.5
		Sorghum/PP	58.1	1.56	3.7
		F test	NS	NS	NS
		SEM±	7.8	0.27	0.63
		C.D.(0.05)	–	–	–
	N option	FYM	45.0	1.05	3.5
		$^{\varphi}$FYM+urea	70.4	1.34	4.5
		FYM+$^{\varphi}$urea	75.4	2.24	5.0
		60N urea	77.6	3.29	5.5
		F test	***	***	**
		SEM±	3.6	0.15	0.30
		C.D.(0.05)	10.9	0.46	0.93
		Interaction	*	*	*
		C.V.(%)	13	18	16

$^{\varphi}$ Labelled source.

[a] *, ** and *** denote significance at the $P = 0.05$, 0.01 and 0.001 levels, respectively.

3.4. Residual effect of pigeon pea grown as an intercrop on the succeeding nitrogen yield of castor

The ^{15}N enrichment of castor grown after sole sorghum was higher than that of castor grown after sorghum/pigeon pea, although not significantly so. Thus, it was possible to calculate the proportion of N derived from the residual effect of previous pigeon pea in the system according to Eq. (1) for the stalk, chaff and grain. The proportion of N in castor stalk derived from the previous intercropped pigeon pea varied from 9.2 to 17% with different sources of N. Similarly it varied from 13 to 34% in chaff and from 4.0 to 20% in grain (Table XV). On the whole, it was calculated that 6.0 to 9.0 kg N ha^{-1} in castor were derived from the preceding legume in the rotation.

Table XV. Percentage and amount of nitrogen derived by castor from preceding pigeon pea as an intercrop, calculated using sorghum–castor as a control [Eq. (1)]

Part	N treatment	Previous crop		Ndfu (%)	N yield	Ndfu
		Sole sorghum	Sorghum/PP			
		(% ^{15}N atom excess)			(kg ha^{-1})	
Stalk	FYM	0.027	0.024	11	8.3	0.9
	[φ]FYM+urea	0.024	0.021	12.5	11.6	1.5
	FYM+[φ]urea	0.097	0.113	N/D	8.9	–
	60N urea	0.131	0.119	9.2	9.7	0.9
Chaff	FYM	0.038	0.025	34	7.6	2.6
	[φ]FYM+urea	0.031	0.022	29	8.5	2.5
	FYM+[φ]urea	0.101	0.087	14	8.7	1.2
	60N urea	0.147	0.123	16	11.3	1.8
Grain	FYM	0.030	0.027	10	32.8	3.3
	[φ]FYM+urea	0.025	0.024	4.0	42.2	1.7
	FYM+[φ]urea	0.115	0.092	20	41.4	8.3
	60N urea	0.140	0.125	11	39.5	4.2
Total	FYM				48.7	6.8
	[φ]FYM+urea				62.2	5.7
	FYM+[φ]urea				59.0	9.5
	60N urea				60.4	6.9

[φ] Labelled source.

3.5. On-farm research

The results of on-farm research indicated that the traditional system of rotating sorghum and castor without or with limited inputs of fertilizer was out-yielded by the intercropping alternative or by sole crops with inputs (Tables XVI and XVII).

Table XVI. Grain yields of sorghum, pigeon pea and castor in farmers' fields, sorghum/pigeon pea intercrop–castor rotation

1999 (sorghum/pigeon pea)					2000 (castor)			
Site	Crop	Grain yield (kg ha^{-1})		Increase over FP (%)	Crop	Grain yield (kg ha^{-1})		Increase over FP (%)
		IP[a]	FP[b]			IP	FP	
				60 kg N ha^{-1} as urea				
1	Sorghum/	1,444	637	126	Castor	970	735	32
	pigeon pea	220	112	96				
2	Sorghum/	1,728	1,010	71	Castor	680	535	27
	pigeon pea	352	135	160				
				FYM at 1.5 t ha^{-1} + 45 kg N ha^{-1} as urea				
3	Sorghum/	1,611	543	196	Castor	1,060	370	186
	pigeon pea	326	118	176				

[a] Improved practice.

[b] Farmer's practice.

TableXVII. Grain yields of sorghum, pigeon pea and castor in farmers' fields, castor–sorghum/pigeon pea intercrop rotation

		1999 (castor)			2000 (sorghum/pigeon pea)			
Site	Crop	Grain yield (kg ha^{-1})		Increase over FP (%)	Crop	Grain yield (kg ha^{-1})		Increase over FP (%)
		IP[a]	FP[b]			IP	FP	
				60 kg N ha^{-1} as urea				
4	Castor	1,038	636	63	Sorghum/	765	325	–
					pigeon pea	300	(green chillies)	–
5	Castor	798	506	57	Sorghum/	–	–	–
					pigeon pea	–	–	–
				FYM at 1.5 t ha^{-1} + 45 kg N ha^{-1} as urea				
6	Castor	1,387	880	57	Sorghum/	785	2050	–
					pigeon pea	600	(maize)	–
7	Castor	850	410	107	Sorghum/	1,306	365	257
					pigeon pea	760	690	10

[a] Improved practice.

[b] Farmer's practice.

4. CONCLUSIONS

Among the N-management options studied, application of FYM + urea was on a par with urea alone. Nitrogen recovery from urea was significantly higher compared to that of FYM. Greater N recoveries from these sources were seen when used in combination. Intercropped pigeon pea had a beneficial effect on succeeding castor.

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ENHANCEMENT OF NITROGEN- AND WATER-USE EFFICIENCY BY OPTIMIZING THE COMBINED MANAGEMENT OF SOIL, CROP AND NITROGEN

M.J.M. RUSAN, A. BATTIKHI,
Jordan University of Science and Technology,
Irbid, Jordan

S. ZURAIQI
National Centre for Agricultural Research and Technology Transfer,
Baqa, Jordan

Abstract

Maru Agricultural Research Station (1998–2000) Two field experiments were carried out at Maru Agricultural Research Station 100 km north of Amman, to investigate the role of wheat-crop residues and levels of nitrogen (N) fertilizer on subsequent wheat in three rotations. Nitrogen was applied at 40 and 80 kg/ha as urea enriched with ^{15}N. Lentil plots were treated with 20 kg N/ha as urea similarly enriched with ^{15}N. In the first season, half of the lentil plots did not germinate due to very low rainfall (184 mm) and growth of wheat was poor. Biological and grain yields, in addition to harvest and N indexes and amounts of N derived from fertilizer (Ndff) were very low. Nitrogen recovery was less than 2.5%. Most of the N in the biological and grain yields was derived from soil. Residual N fertilizer was not detectable in the soil. Wheat residues at the high level of N resulted in decreased uptake of N. In the second season, wheat was grown on all of the plots, after a previous crop of lentil, wheat or fallow. Plant height, number of plants per ha, number of tillers per plant and shoot dry matter at tillering were increased with N application. Crop rotation and crop-residue application had no significant effects. At anthesis, the general trend was similar to that observed at tillering. At harvest, yield tended to increase with increasing N rate regardless of the effects of other factors, but the 100-seed weight, and the dry weight were affected significantly only by the interaction between crop residue and N rate. Dry weight tended to decrease with crop-residue incorporation, but stayed higher with N applied. Harvest index tended to decrease with increased N rate and when crop residue was removed or not incorporated. An expected positive effect of the legume as a previous crop was not observed. The N contents of the grain and shoot, as expected, increased with increasing rates of N applied. There was no clear trend for the effect of crop rotation or crop residue. The N derived from fertilizer by the grain and shoot increased with increasing N rate. Nitrogen-utilization efficiency tended either to stay about the same or increase with increasing N rates. Carbon-13 values tended to be more negative for shoot than for grain. No clear patterns were observed for effects of crop rotation or crop residue on N utilization or on ^{13}C values. Soil N was very low at all depths tested. If not taken by the crops, the applied N tended to be lost by denitrification or volatilization, which decreases N-utilization efficiency in arid and semi-arid environment.

Jordan University of Science and Technology Agricultural Centre (2000–2002) Two field experiments were carried out in the 2000–2001 and 2001–2002 growing seasons at the Agricultural Research Centre of the Jordan University of Science and Technology, 80 km northeast of Amman. Three crop rotations were investigated: barley–fallow; barley–barley and barley–vetch. Three rates of N were investigated: 0, 40 and 80 kg N/ha. Nitrogen-15 enriched fertilizer was applied to micro-plots. Soil moisture was monitored with a neutron probe. Plant samples were taken during the growing season and soil samples were collected at the end of the experiment. Due to cessation of rainfall in the first season, irrigation water was applied at 250 m^3/ha in January, 200 m^3/ha in March and 200 m^3/ha in April, 2001, as supplemental irrigation. Number of tillers per plant was increased with N application compared to the zero treatment. The above-ground biomass of barley was increased when the highest rate of N (80 kg/ha) indicating N stimulation of vegetative growth. At anthesis, number of fertile tillers was affected by N rate; the highest number was observed with the lower N application (40 kg N/ha). However, biomass increased similarly with both rates of N application compared to the control. At harvest, biomass increased similarly with both rates of N. A similar trend prevailed with the number of heads per ha. On the other hand, the 100-seed weight was not affected by the treatments, which indicates that number of heads and not weight of seeds was responsible for differences in yield. At tillering, the number of vetch plants per ha varied from 1,810,000 to 2,420,000. The fresh weight (biological yield) of vetch per ha was also increased significantly with the highest rate of N (80 kg/ha). A similar trend was observed with shoot dry matter. At anthesis and at harvest, the same trends were evident in terms of fresh and dry weights of shoot in response to N. Grain yield of vetch was not significantly different among treatments. However, grain yield tended to be lower without N applied, whereas the straw-yield response was just the opposite. Soil volumetric water content was much below the field capacity at all soil depths. Moreover, soil moisture was below the field capacity throughout the growing season, and growth was commensurately affected. On the other hand, fallowing did not conserve moisture in the upper soil layers. In the second season, barley was grown on all plots: after barley, or fallow or vetch. There were no clear effects from the previous crop/fallow on growth parameters or yield or even on soil-moisture status. However, barley responded positively to N application. Further and long-term research is needed to investigate the effects of cropping systems and N rates under rainfed agriculture where periodic drought events are common.

1. INTRODUCTION

Water and nitrogen (N) are the factors most likely to limit crop production in rainfed agriculture in most Mediterranean countries such as Jordan. Efficiency of use of both N and water are significantly influenced by agricultural practices, including crop rotation, tillage system and residue management.

It is well documented that continuously growing the same crop results in lower organic matter and lowers water-holding capacity of the soil. Moreover, crop rotation helps control diseases, insects and weeds and produces greater yields per unit area. Traditionally, farmers in Jordan use low inputs and rely on fallowing for increasing water storage in the root zone for the subsequent crop. Some farmers practice crop rotations according to the average annual rainfall. In addition, grazing of residues following grain harvest is common practice in rainfed areas of Jordan. Intensive grazing with animal traffic leaves the soil bare and compacted between growing seasons and exacerbates wind and water erosion. In addition, removal of crop residues and weedy fallow increase water losses through increased runoff and evapotranspiration, particularly during the winter rainy season. The yields of cereal crops (wheat/barley) in rainfed areas of Jordan are generally low, ranging from 200 to 1,000 kg/ha. Amount of residues associated with such yields are concommitantly low (300–1500 kg/ha), which may be insufficient to be effective for water conservation and erosion control. In addition, the residues may also be grazed, therefore, leaving only very small amounts available for the following rainy season.

Semi-arid environments are characterized by low, erratic and unevenly distributed rainfall. Therefore, it is difficult to determine the fertilizer N requirement to attain optimum yield. Variation in growing-season precipitation has a strong impact on yield and utilization of applied N, causing the potential for overfertilizing or underfertilizing with N. Higher precipitation produces higher yields which require more N. But when N is in excess of need, grain yield may be decreased substantially because of excessive vegetative growth and water use; soil-water reserves may be depleted more quickly, causing drought stress during grain-filling. Optimum N fertilization will improve productivity and produce more crop residue which, if left on the soil surface, will reduce evaporation, increase water infiltration and reduce wind erosion, thus sustaining the long-term productivity of the soil.

Fertilizer requirements of crops in various rotations in the rainfed area of Jordan are not well established. Legumes supply some N to subsequent crops, but, although highly recommended, their inclusion is not widely practiced. Concerns regarding agricultural sustainability, soil and environmental quality, and energy conservation have renewed interest in the inclusion of legumes. Their importance in crop rotations has received considerable attention in the past. Legumes provide substantial amounts of plant-available N to subsequent crops, and their presence may suppress weed populations, reduce the incidence of disease, and improve soil physical conditions [1, 2]. Most investigations on the utility of legumes have been carried out in conditions totally different from those in the Middle East region. In the Middle East, legume crops are harvested in an unusual way: the whole plant, including the roots is pulled up, leaving little residue. Therefore, the role of legumes in increasing soil N due to biologically fixed N is debatable [3–6]. Farmers in Jordan recognize that planting lentil is not beneficial for subsequent wheat, and is not commonly practiced. Green and Blackmer [7] suggested that differences in N-fertilizer requirement are better explained in terms of the amount of N immobilized during residue decomposition than by mineralization of biologically fixed N associated with legumes.

Managing crop residues has been a focus of study for many years because of their multiple potential roles in sustainable agriculture [8]. Including a small grain with a legume reduces the risk of erosion, but immobilization of N by the small-grain residue can reduce N availability to the following cereal crop [9]. Rate of residue decomposition depends on air temperature and soil moisture [10]. Kolberg et al. [11] found that precipitation in combination with air temperature and their interaction gave the best prediction of average daily N mineralization. Nitrogen fertilizer addition affects soil C and N dynamics after the crop takes up N [12]. Although the C/N ratio and N content have been used to describe residue decomposition, they are not always related to decomposition rate. Several models have been proposed to quantify residue weight loss under various environmental conditions [10].

Conservation of soil moisture in arid regions is of great interest and has received considerable attention. Leaving crop residues on the soil surface conserves soil moisture in addition to sustaining fertility. Therefore, conservation tillage is promoted because standing stubble and surface residues protect against wind and water erosion, improve moisture retention and reduce evaporation, thereby increasing soil-moisture content [13]. Agriculture reduces soil organic matter levels and contributes to atmospheric CO_2. Atmospheric CO_2 contains radioactive ^{14}C and stable ^{13}C isotopes suitable for tracer studies. Plant C-isotope ratios vary somewhat during the growing season and are affected by moisture [13, 14]. The C-isotope composition ($\delta^{13}C$) of crop residues and, consequently, the $\delta^{13}C$ of soil organic matter can be used to measure vegetation shifts, soil organic matter turnover and its residence in soil. Monitoring changes in $\delta^{13}C$ in plant residues may provide valuable insight into the physiological responses of crops to management-induced changes in soil-water availability and moisture deficits [13].

The objectives of this study were to determine the interacting effect of N rate, crop residue and crop rotation in rainfed agriculture of semi-arid regions in Jordan.

2. MATERIALS AND METHODS

Two field experiments were conducted at Maru Agricultural Research Station (1998–1999 and 1999–2000) and two at Jordan University of Science and Technology (JUST) Research Centre (2000–2001 and 2001–2002). The treatments investigated at each site are shown in the following table:

Treatments imposed at Maru and JUST

Growing season	Rotation	Crop residue (% coverage)	N rate (kg/ha)	Site
1998–1999	Wheat–wheat	100	0 (N0)	Maru
	(WW)	0	40 (N1)	
	Wheat–lentil (WL)	–	80 (N2)	
1999–2000	Wheat–fallow (WF)	100	0	Maru
	Wheat–wheat	0	40	
	(WW)	–	80	
	Wheat–lentil (WL)			
	Wheat–fallow (WF)			
2000–2001	Barley–barley (BB)	–	0	JUST
	Barley–vetch (BV)	–	40	
	Barley–fallow (BF)	–	80	
2001–2002	Barley–barley (BB)	–	0	JUST
	Barley–vetch (BV)	–	40	
	Barley–fallow (BF)	–	80	

2.1 Maru Agricultural Research Station

Two field experiments were carried out during the 1998–1999 and 1999–2000 growing seasons at the Agricultural Research Station at Maru, 100 km north of Amman. The soil (a very fine smectic, thermic Typic Chromoxerert) has a relatively high pH (~7.6) and 5.9% calcium carbonate. The climate is Mediterranean with a cool wet winter and hot dry summer. The site was planted in the 1997–1998 season with wheat and residues were left on the soil. In this study, the crop residue was removed from one half of the experimental site manually. The experiment had a split-split plot design, was run in four replications and had following treatments:

- three crop rotations (wheat–fallow), (wheat–lentil) and (wheat–wheat),
- two crop-residue management practices (0 or 100% of the residue incorporated, designated R0 and R100, respectively), and
- three N levels (0, 40 and 80 kg N/ha, designated N0, N1 and N2, respectively).

The rotations were in the main plots, residue management was in the sub-plots and the N levels were in the sub-sub plots. The area of each sub-sub plot was 3 × 9 m; 1.5 m was left between sub-sub-plots and 2 m were left between replications. Wheat (cv. Horani 27) and lentil (cv. Jordan) were planted using a seed drill at row spacing 17.5 cm and at 120 kg seeds/ha on November 26, 1998. The lentil had to be replanted on February 17, 1999, because of poor emergence.

Triple superphosphate was applied at 40 kg P_2O_5/ha to wheat and lentil, and N fertilizer as urea was applied at 0, 40, or 80 kg N/ha to wheat while lentil was treated with urea at 20 kg N/ha. Both fertilizers were broadcasted manually on March, 10, 1999. Nitrogen-15-urea (5% ^{15}N a.e) was added to an area of 2 m^2 of each plot of wheat and to three replicate plots of lentil. Aliquots of the proper amount were dissolved in fixed volumes of water and spread on the specified areas. Soil solution containing ^{15}N-labelled mineral solution was prepared and sent to the IAEA Seibersdorf laboratory for ^{15}N analysis [15]. Inorganic soil N was extracted in 2 *M* KCl [16].

Access tubes were installed in each of three replicate sub-sub-plots to a depth of 120 cm. Soil-moisture content was monitored at 20-cm increments during the growing season using a neutron moisture gauge. It was intended to take the moisture on a weekly basis and a day after each rainfall event. The goal was to calculate crop-water consumption in order to calculate water-use efficiency. Unfortunately, the assistant who was assigned to take the moisture measurements died suddenly and his replacement had problems with the gauge. Therefore, moisture measurements are not considered.

2.2. JUST Agricultural Research Centre

Field experiments were carried out in the 2000–2001 and 2001–2002 growing seasons at JUST's Agricultural Research Centre, located about 80 km northeast of Amman. An experiment with two replications was conducted on a farmer's field about 7 km northeast of the Research Centre. The soil at the research site is classified as a fine-loamy, mixed, thermic, calcic Paleargid. The parent material is alluvium derived from limestone. Soils of the area have a relatively high pH (7.8–8.0) and are calcareous with moderate calcium-carbonate content. These chemical characteristics of the soil limit the availability of P, N and micronutrients to the plant. The research site is located in a region that is classified as semi-arid with a Mediterranean type of climate with a cool relatively wet winter and a hot dry summer. The frequent land use in the region is a barley-based system, where the common cropping sequence is barley–fallow or continuous monocropping of barley. The low efficiency of the fallow in this region and the high demand on forage crops has encouraged farmers to include legumes in the rotation. In this study, three crop rotations were, therefore, investigated: barley–fallow; barley–barley and barley–vetch. The second factor was N rate, of which three were investigated: 0, 40 and 80 kg N/ha. The two factors each with three levels were investigated in a split-plot randomized complete block design with four replications for each combination of treatments. Crop rotation constituted the main plots and N levels were in the sub-plots. Each sub plot was 3 × 9 m. Barley (cv. Rum) and vetch (local cv. Balady) were planted manually at a row spacing 25 cm and a rate of 120 kg seeds/ha. Both crops were planted on December 10, 2000.

Due to cessation of rainfall for a long period after seeding, a limited amount of water was applied as supplemental drip irrigation which had been installed for this purpose. Irrigation water were applied at 250 m^3/ha in January, 200 m^3/ha in March and 200 m^3/ha in April, 2001.

Phosphorus was added to all plots as triple superphosphate at 40 kg P_2O_5/ha. Nitrogen fertilizer as urea was applied at seeding at 0, 40, and 80 kg N/ha. Fertilizers was broadcasted manually and incorporated in the top 10 cm of the soil. Within each sub-plot a micro-plot (1 × 2 m) was prepared for application of ^{15}N-labelled urea (5% ^{15}N a.e) at the appropriate rate. The measured amount of labelled fertilizer was dissolved in fixed volume of water and spread on the specified area. All ^{15}N analyses were performed at the IAEA Seibersdorf laboratory [15].

Soil moisture was monitored by neutron probe readings taken through access tubes inserted in three replications of each sub-sub-plot of to a depth of 75 cm. Soil moisture content was monitored at 15 cm increments during the growing season biweekly and a day after each rainfall event.

Plant samples were taken during the growing season and soil samples at the end of the experiment. At harvest, plant samples and soil samples were taken from the centre (sampling area 1 m^2) of each micro-plot for ^{15}N and ^{13}C analyses. For yield determination, the middle rows (from which no samples were taken previously) of the main plots were harvested manually. Shoot parameters and yield and yield components were determined with these specified samples.

3. RESULTS

3.1. Maru 1998–1999

3.1.1. Soil physical properties

The soil of the experimental site is characterized by having a clay texture to a depth of 120 cm (Table I). Based on the capacity of soil to retain moisture, available water was very low.

3.1.2. Soil chemical properties

Chemical analyses showed the soil is slightly basic with negligible dissolved salts along the whole soil profile (Table II). The content of $CaCO_3$ is relatively low and largely constant to a depth 120 cm. Available P was sufficient in the upper three soil layers due addition of P-fertilizer over a period of years. However, K content was moderate, while the inorganic N forms were low which might be explained in terms of loss by volatilization.

Table I. Some physical properties of the soil

Soil depth (cm)	Θ^a at 0.1 bar	Θ at 0.3 bar	Θ at 1.0 bar	Θ at 15 bar	Bulk density (g/cm^3)	Clay	Silt	Sand
	(%)					(%)		
0–15	46	40	37	34	1.00	50	49	1.1
15–30	52	46	42	39	1.26	53	46	1.2
30–60	53	45	40	38	1.22	52	47	0.9
60–90	52	47	41	38	1.25	53	46	1.2
90–120	54	47	41	39	1.26	52	47	1.0

[a] Volumetric water content.

Table II. Some chemical properties of the soil

Soil depth (cm)	PH	EC_e (dS/m)	$CaCO_3$ (%)	Avail. P	Avail. K	NH_4^+-N	NO_3^--N
				(ppm)			
0–15	7.6	0.27	5.9	15	352	6.1	5.2
15–30	7.4	0.25	4.6	10			
30–60	7.4	0.22	4.8	9			
60–90	7.5	0.24	5.7	2			
90–120	7.6	0.24	5.6	2			

3.1.3. Wheat

Rainfall during the growing season (1998–1999) was the least in four decades and the preceding summer had been extremely hot. Total rainfall during the season was about 185 mm, whereas the mean annual amount is about 350mm. The rainfall distribution (mm) was as follows: Oct ober 1.3, November 0.4, December 14.1, January 96.7, February 42.2, March 49.2 and April 8.4. Most came later of the season. These conditions resulted in germination failure in half of the lentil plots, and poor wheat growth of most of the plots. Accordingly, samples were taken from the 1-m rows of the micro-plots treated with ^{15}N to calculate biological and grain yields. Lentil plots did not produce grain. Nevertheless, samples of straw and grain were oven=dried at 68°C, ground and sub-samples were sent to the IAEA Seibersdorf laboratory for ^{15}N and ^{13}C analyses.

The biological and, in particular, the grain yields were very low (Table III), due mainly to limited rainfall but also to its delay and uneven distribution. The N contents of the straw and seeds were high, closer to normal values for legumes than for cereals. This is difficult to explain and care must be taken in the future. The results show that most plant N was derived from the soil; negligible amounts were from fertilizer. This trend is inconsistent with results reported elsewhere [6]. The small amount of N derived from fertilizer may be explained by volatilization of N. The δ^{13}C values were less negative in the grain than in the straw and more negative in the presence of residues.

Harvest index was very low (Table IV), from 0.08 for treatment R0N0 to 0.14 for R1N1. These low values show that seed growth was relatively poor. The same trend was found for N harvest index. The highest recover of N by wheat from fertilizer was only 2.3% in treatment R1N1. Therefore, great attention has to be given to management of fertilizer in the rainfed area.

Table III. Straw and grain yields, nitrogen uptake from soil and fertilizer, and δ^{13}C, wheat

Treat.	Plant part	Yield (kg/ha)	N (%)	Total N (kg/ha)	Ndff[a]		Ndfs[b] (kg/ha)	δ^{13}C (‰)
					(%)	(kg/ha)		
R0N0	Straw	1,170	1.6	27.4	0.0	0.0	27.4	–23.5
	Grain	156	3.8	5.96	0.0	0.0	5.96	–21.2
R0N1	Straw	2,045	1.3	26.8	2.4	0.65	26.1	–24.7
	Grain	203	3.4	6.91	2.5	0.18	6.73	–21.6
R0N2	Straw	2,478	1.6	40.4	3.0	1.2	39.2	–23.4
	Grain	268	4.1	10.9	2.8	0.30	10.6	–21.1
R1N0	Straw	2,009	1.3	26.3	0.0	0.00	26.3	–24.3
	Grain	293	3.5	10.2	0.0	0.00	10.2	–21.5
R1N1	Straw	2,064	1.4	27.9	2.5	0.69	27.2	–24.5
	Grain	333	3.5	11.8	2.1	0.25	11.5	–21.5
R1N2	Straw	2,611	1.4	37.3	3.7	1.4	36.0	–24.4
	Grain	259	3.5	8.73	2.8	0.24	8.5	–21.5

[a] Nitrogen derived from fertilizer. [b] Nitrogen derived from soil.

Table IV. Biological, grain and nitrogen yields and recovery, wheat

Treat.	Biol. yield	Grain yield	Harvest index	Total N (kg/ha)	N harvest index	N recovery (%)
	(kg/ha)					
R0N0	1,866	156	0.08	33.3	0.18	0.00
R0N1	2,248	203	0.09	33.7	0.21	2.05
R0N2	2,746	268	0.10	51.3	0.21	1.89
RIN0	2,302	293	0.13	36.5	0.28	0.00
R1N1	2,397	333	0.14	39.6	0.30	2.33
R1N2	2,870	259	0.09	46.1	0.19	2.03

Table V. Biological yield, %N, %^{15}N a.e, yield of nitrogen and %N derived from fertilizer, lentil

Treat.	Yield	N yield	N	^{15}N a.e	Ndff	δ^{13}C (‰)
	(kg/ha)		(%)			
R0N0[a]	76.0	1.92	2.5	0.046	0.081	–25.1
R0N0	324	8.43	2.6	0.062	0.011	–26.0
R0N0	404	10.1	2.5	0.077	0.013	–25.8
R1N0						
R1N0	230	5.33	2.3	0.083	0.015	–26.3
R1N0	166	3.54	2.1	0.090	0.016	–26.2

[a] 20 kg N/ha as urea added to all plots.

3.1.4. Lentil

Because lentil germination was poor, the plots were replanted on February, 17, 1999. However, more than half of the plots still did not germinate. Even with good growth there would have been insufficient time for significant biological N_2 fixation. The δ^{13}C values in the straw were more negative than for wheat, and this was even more pronounced in the presence of wheat residues (Table V).

3.1.5. Soil nitrogen: wheat

Tiny amounts of soil N were present in inorganic forms at all depths (Table VI). In addition, the quantities of N derived from the fertilizer were low and much less in the presence of crop residues. If the %^{15}N a.e values in the R0N0 and R1N0 treatments are considered as background, then the amounts of Ndff would be zero. The values for Ndff in the fallow plots have to be regarded as baseline since they had not been fertilized. Therefore, the amounts of Ndff in the other treatments were also zero.

3.1.6. Soil nitrogen: lentil

The determined values for N at all soil depths of the lentil plots were consistent with those obtained with wheat (Table VII). Only tiny amounts of N in the soil were derived from fertilizer.

Table VI. Soil nitrogen at various depths, wheat and fallow plots

Treat.	Soil depth (cm)	N	^{15}N a.e	Total N	Ndff	NH_4^+-N	NO_3^--N
		(%)		(kg/ha)			
R0N0	0–15	0.09	0.011	1,350	0.00	12.6	6.3
	15–30	0.07	0.006	1,260	0.00	10.8	6.8
	30–60	0.07	0.006	1,260	0.00	12.6	7.6
R0N1	0–15	0.10	0.005	1,500	1.31	14.7	6.3
	15–30	0.07	0.006	1,260	1.32	15.1	10.1
	30–60	0.08	0.007	1,440	1.76	15.1	0.0
R0N2	0–15	0.10	0.005	1,500	1.31	16.8	2.1
	15–30	0.09	0.004	1,620	1.13	10.1	7.5
	30–60	0.06	0.005	1,080	0.94	10.1	10.1
R1N0	0–15	0.08	0.004	1,200	0.00	6.3	8.4
	15–30	0.08	0.005	1,440	0.00	10.1	2.5
	30–60	0.06	0.004	1,080	0.00	0.0	8.4
R1N1	0–15	0.09	0.004	1,350	0.94	8.4	8.4
	15–30	0.08	0.004	1,440	1.01	2.5	15.1
	30–60	0.06	0.004	1,440	1.01	10.1	10.1
R1N2	0–15	0.09	0.002	1,350	0.47	16.8	2.1
	15–30	0.08	0.003	1,440	0.76	12.6	2.5
	30–60	0.05	–0.003	900	–0.47	10.1	7.5
Fallow	0–15	0.10	0.002	1,500	0.52	4.9	7.4
	15–30	0.10	0.001	1,800	0.31	8.4	7.1
	30–60	0.09	0.002	1,620	0.57	7.1	8.4

Table VII. Soil nitrogen at various depths, lentil plots

Treat.	Soil depth (cm)	N	^{15}N a.e	Total N	Ndff	NH_4^+-N	NO_3^--N
		(%)		(kg/ha)			
R0N0	0–15	0.12	0.039	1,800	12.3	2.1	4.2
	15–30	0.10	0.028	1,800	8.82	10.1	10.1
	30–60	0.08	0.010	1,440	2.52	2.5	12.6
R0N0	0–15	0.12	0.003	1,800	0.94	0.0	0.0
	15–30	0.08	0.002	1,440	0.50	4.2	10.5
	30–60	0.08	0.001	1,440	0.25	5.0	5.1
R0N0	0–15	0.10	–0.002	1,500	–0.52	6.3	0.0
	15–30	0.08	–0.001	1,440	–0.25	0.0	17.6
	30–60	0.08	–0.001	1,440	–0.25	7.6	12.6
R1N0	0–15	0.12	–0.001	1,800	–0.31	21.0	8.4
	15–30	0.11	0.000	1,980	0.00	27.7	2.5
	30–60	0.08	0.003	1,440	0.76	10.1	5.0
R1N0	0–15	0.10	0.012	1,500	3.15	16.8	2.1
	15–30	0.09	0.018	1,620	5.10	7.6	5.0
	30–60	0.08	0.011	1,440	2.77	15.1	7.6
R1N0	0–15	0.12	0.012	1,800	3.78	8.4	8.4
	15–30	0.11	0.013	1,980	4.50	12.6	7.6
	30–60	0.08	0.013	1,440	3.27	10.1	0.0

Table VIII. Probability level (P values) for each factor and interactions, 1999–2000

Stage	Variable	Factor			Interaction			
		A[a]	B[b]	C[c]	A×B	A×C	B×C	A×B×C
Tillering	Plant height	0.142	[d]	0.016				
	Plant #	0.082	0.296	0.008	0.299	0.235		0.047
	Tiller #			0.001				0.175
	Dry wt.		0.262	0.000[e]		0.336		
Anthesis	Pl ant height	0.120	0.258	0.000				
	Head #	0.055	0.068	0.000	0.155	0.061	0.008	0.025
	Plant #	0.188	0.061	0.002	0.362	0.043	0.213	0.027
	Tiller #	0.141	0.096	0.000	0.108		0.012	0.199
	Dry wt.			0.000	0.273		0.040	
Harvest	Yield	0.078		0.018		0.146		0.108
	100 seed		0.128	0.005		0.128	0.009	0.198
	Head wt.		0.068		0.001	0.117	0.001	
	Seed wt.		0.056	0.029	0.175	0.075	0.001	
	Shoot wt			0.001	0.183	0.021	0.014	
	Head #			0.000		0.029		0.098
	Dry wt.		0.145	0.001		0.051	0.023	
	Harvest index	0.123	0.149	0.001	0.004		0.002	

[a] Crop rotation.
[b] Residue management.
[c] Nitrogen rate.
[d] Blank = non-significant.
[e] Very highly significant.

3.2. Maru 1999–2000

3.2.1. Shoot parameters at tillering

Plant height at tillering was affected significantly only by N (Tables VIII and IX); increasing rates increased the height. Crop rotation and crop residue had no significant effect on plant height. The interaction was also non-significant. Number of plants per hectare was significantly affected by N rate, and by the interaction of the three treatments: number increased with N application and was the highest when the highest N rate was applied after fallow or after wheat. Number of tillers was increased with N application, whereas other treatments had no significant effect. Shoot dry matter was also increased with N application, but not affected by other treatments.

3.2.2. Shoot parameters at anthesis stage, wheat

Plant height at anthesis, as at tillering, was affected significantly only by N (Tables VIII and IX); increasing rates increased height. Crop rotation and crop residue had no significant effect on plant height. The interaction effect was also non-significant. The number of plants per hectare was significantly affected by N rate, by the interaction between crop rotation and N rate and by the interaction of the three treatments. The number increased with N application, but the interaction had no effect. Number of heads was influenced in the same pattern as the number of plants. Number of tillers was affected by N rate and the interaction among the three factors; the highest numbers were observed when N1 was applied with crop-residue incorporation and when wheat was planted after fallow or wheat. However, shoot dry matter was also increased with N application and affected by the interaction between the N-rate and the crop-residue treatments; within a level of N, R0 increased the dry weight more than did R1.

Table IX. Wheat shoot parameters at tillering, 1999–2000

Treatment	Previous crop	Plant height (cm)	Plant # (1,000/ha)	Tiller # (1,000/ha)	Dry wt. (kg/ha)
R0N0	Lentil	76.3	1,757	4,986	6,283
	Wheat	72.0	1,971	5,029	4,914
	Fallow	79.5	1,929	5,329	6,102
	Mean	75.9	1,886	5,114	5,766
R0N1	Lentil	78.8	1,671	6,286	7,156
	Wheat	82.0	2,257	6,300	7,469
	Fallow	81.8	2,571	7,486	8,299
	Mean	80.8	2,167	6,690	7,641
R0N2	Lentil	80.8	1,786	5,071	6,230
	Wheat	80.3	1,900	6,271	7,502
	Fallow	80.5	1,857	5,686	6,796
	Mean	80.5	1,848	5,676	6,843
R1N0	Lentil	80.0	1,571	5,686	6,654
	Wheat	74.5	1,557	4,871	5,120
	Fallow	79.0	1,943	5,757	6,637
	Mean	77.8	1,690	5,438	6,137
R1N1	Lentil	82.0	1,829	6,843	9,017
	Wheat	78.3	2,300	7,229	8,292
	Fallow	83.0	2,114	5,957	7,464
	Mean	81.1	2,081	6,676	8,258
R1N2	Lentil	79.0	1,614	5,314	6,621
	Wheat	78.8	1,500	4,600	6,702
	Fallow	79.5	2,486	6,486	7,866
	Mean	79.1	1,867	5,467	7,063

3.2.3. Shoot parameters and yield components at harvest, wheat

The 100-seed weight was affected significantly only by the interaction between crop residue and the N rate (Tables VIII and XI). The highest value was observed when the lowest N rate was applied; even when N was not applied, the 100-seed weight was higher in some cases, probably attributable to lower numbers of seeds. Surprisingly, the head weight was affected by the interaction between N rate and the crop residue, but not by N alone. All other parameters were affected significantly by N rate. Seed weight and shoot weight were also affected by the interaction between N and crop residue, while head number was affected, in addition to N alone, by the interaction between the N and crop rotation. Dry weight was influenced by N rate and by the N by crop-residue interaction. Dry weight tended to decrease with crop residue incorporation, but stayed high when N was applied. Finally the harvest index was affected by the N rate, by the interaction between N and rotation, and by the interaction between N and crop residue. Harvest index tended to decrease with the increase in N, and when crop residue was removed or not incorporated.

3.2.4. Yield of wheat

Final harvest yield was significantly affected only by N rate (Tables VIII and XI). The effects of rotation and the interaction among the three factors were significant only at the 0.07 and 0.1 probability levels, respectively. Yield tended to increase with increasing N rate regardless of the effects of other factors at the 0.05 probability level. However, at the 0.1 probability level, yield tended to increase when N was applied to wheat planted after wheat or after fallow.

Table X. Wheat shoot parameters at anthesis, 1999–2000

Treatment	Previous crop	Height (cm)	Head #	Plant #	Tiller #	Dry wt. (kg/ha)
			(1,000/ha)			
R0N0	Lentil	89.3	2,038	1,676	2,648	8,048
	Wheat	81.7	2,286	2,038	3,086	7,379
	Fallow	91.0	2,000	1,457	2,643	9,021
	Mean	87.3	2,108	1,724	2,792	8,150
R0N1	Lentil	90.0	3,333	2,514	4,857	12,371
	Wheat	91.3	4,220	3,676	5,886	12,541
	Fallow	96.8	2,686	1,786	3,529	9,894
	Mean	92.7	3,416	2,659	4,757	11,602
R0N2	Lentil	96.7	5,162	4,362	6,705	13,992
	Wheat	91.7	4,114	2,381	5,943	15,240
	Fallow	100	3,514	2,400	5,029	13,604
	Mean	96.3	4,263	3,048	5,892	14,279
R1N0	Lentil	91.0	1,957	1,686	2,986	7,804
	Wheat	86.3	2,243	2,186	3,229	8,407
	Fallow	90.8	2,043	1,343	2,943	9,483
	Mean	89.3	2,081	1,738	3,052	8,565
R1N1	Lentil	96.3	2,700	1,371	3,486	11,404
	Wheat	92.0	3,171	1,843	4,171	13,597
	Fallow	91.8	3,371	2,829	4,686	13,291
	Mean	93.3	3,081	2,014	4,114	12,764
R1N2	Lentil	99.8	3,014	2,243	4,243	11,196
	Wheat	98.5	3,800	2,286	4,657	12,489
	Fallow	98.0	2,586	2,157	4,157	10,549
	Mean	98.8	3,133	2,229	4,352	11,411

The expected positive effect of the legume as a previous crop was not observed in the on-farm experiment (data not shown). Again, increasing N rate increased yield. When N was not added, the yield of wheat after lentil was less then after wheat or fallow. However, when N was added the yield of wheat planted after lentil tended to increase, indicating that the lentil did not contribute significantly to the soil N, and N application was still necessary.

It should be noted that, in general, the yield and all parameters monitored were higher than those obtained in the previous season, obviously due to the more favourable weather conditions.

3.2.5. Nitrogen uptake and utilization by wheat and ^{13}C

The N content of the grain and shoot generally increased with increasing application of N (Table XII). There was no clear trend of effects of crop rotation or residue. The N derived from fertilizer by the grain and shoot increased with increasing N rate. Nitrogen-utilization efficiency tended either to remain approximately the same or increased with increasing N rate. The ^{13}C values tended to be more negative for shoot than for grain. No clear patterns of effect of crop rotation or crop residue were seen on N utilization or on ^{13}C value (data not shown).

Table XI. Wheat shoot parameters and yield components at harvest, 1999–2000, measured from 1-m row the samples

Treat.	Previous crop	100-seed weight (g)	Weight of heads	Seed weight	Shoot weight	Number of heads (1,000/ha)	Dry wt. (kg/ha)	Harvest index
			(kg/ha)					
R0N0	Lentil	4.16	4,288	3,162	1,126	2,762	10,850	0.28
	Wheat	3.50	3,424	2,468	956	3,086	8,875	0.27
	Fallow	4.08	3,799	2,693	1,106	2,429	10,898	0.24
	Mean	3.91	3,837	2,774	1,063	2,759	10,208	0.26
R0N1	Lentil	4.42	6,281	4,316	1,965	3,219	14,101	0.30
	Wheat	4.27	6,225	4,190	2,035	3,295	15,061	0.27
	Fallow	4.42	5,484	3,759	1,725	3,186	13,610	0.27
	Mean	4.37	5,997	4,088	1,909	3,233	14,257	0.28
R0N2	Lentil	3.90	5,445	3,502	1,943	3,333	14,906	0.23
	Wheat	3.83	5,503	3,350	2,153	3,276	14,666	0.22
	Fallow	3.74	4,403	2,451	1,952	2,629	12,512	0.19
	Mean	3.82	5,117	3,101	2,016	3,079	14,028	0.21
R1N0	Lentil	4.02	4,100	2,776	1,323	2,743	11,058	0.25
	Wheat	4.05	3,423	2,375	1,049	2,143	8,936	0.26
	Fallow	4.22	4,423	3,259	1,164	2,571	11,680	0.27
	Mean	4.10	3,982	2,803	1,179	2,486	10,558	0.26
R1N1	Lentil	3.68	4,315	2,622	1,693	2,943	11,727	0.22
	Wheat	3.76	3,988	2,420	1,568	2,557	10,731	0.22
	Fallow	3.76	4,183	2,722	1,461	3,752	11,483	0.23
	Mean	3.73	4,162	2,588	1,574	3,084	11,314	0.22
R1N2	Lentil	3.81	4,431	2,804	1,627	2,786	12,839	0.21
	Wheat	3.88	5,929	3,969	1,960	3,829	15,859	0.25
	Fallow	3.92	4,918	3,151	1,767	3,043	13,313	0.23
	Mean	3.87	5,093	3,308	1,785	3,219	14,004	0.23

3.2.6. Soil nitrogen at harvest

Nitrogen content was very low at all tested depths of the soil (Table XIII). Even with the zero-N treatment sometimes the values were about the same as with N applied. Values of ^{15}N, however, tended to increase with N rate, but all values remained low. The applied N, if not taken up by the crop, was lost by denitrification or volatilisation, which decreases the N-utilization efficiency in arid and semi-arid environments.

3.2.7. Conclusions

Wheat growth and yield at Maru in the 1999–2000 season were much better than in 1998–1999 due mainly to the more favourable weather conditions. Positive effects in 1999–2000 on plant growth and the yield were clear, indicating that N could be the second most limiting factor for crop production after rainfall. Crop rotation and crop residue had no effects. Wheat grown after lentil was relatively poorer than when grown after wheat or fallow. This should not be assumed to be a general trend as the opposite was expected. Further investigation to generate more data is needed to clarify the overall picture. In addition, values of the N-utilization efficiency were low, explainable by the high potential of N losses by denitrification and volatilization under arid and semi-arid conditions.

Table XII. Nitrogen uptake and utilization by wheat, 1999–2000

Treatment	Previous crop	Grain Ndff[a]	Shoot Ndff	Grain N	Grain Ndff	Shoot N	Shoot Ndff	Total Ndff	Fertil. utiliz'n.
		(%)		(kg/ha)					(%)
R0N1	Lentil	5.1	7.2	35.1	2.34	36.4	3.15	5.50	14
R0N1	Wheat	9.6	7.6	44.2	4.24	46.6	4.49	8.73	22
R0N1	Fallow	6.7	10	40.6	2.39	58.1	5.57	7.96	20
R0N2	Lentil	9.4	10	37.6	4.81	47.3	5.55	10.4	13
R0N2	Wheat	13	21	38.5	6.60	62.1	12.6	19.2	24
R0N2	Fallow	14	16	40.0	5.15	61.8	9.37	14.5	18
R1N1	Lentil	0.00	3.5	10.1	0.00	13.3	1.86	1.86	—
R1N1	Wheat	9.3	10	42.0	3.61	64.1	5.55	9.16	23
R1N1	Fallow	7.6	9.0	39.7	2.67	54.1	4.51	7.19	18
R1N2	Lentil	5.2	17	34.7	2.52	61.5	9.74	12.3	31
R1N2	Wheat	15	17	45.8	6.44	73.3	10.2	16.7	21
R1N2	Fallow	13	11	47.3	5.26	79.3	6.80	12.1	15

[a] N derived from fertilizer.

Table XIII. Soil N at the end of the experiment, 1999–2000

Soil depth (cm)	Treatment	N	^{15}N a.e.	Treatment	N	^{15}N a.e.	Treatment	N	^{15}N a.e.
		(%)			%N			(%)	
15	WWR0N0[a]	–	–	WLR0N0	0.12	0.012	WFR0N0	0.10	0.003
30		0.09	0.011		0.11	0.007		0.17	0.003
60		0.09	0.004		0.10	0.010		0.08	0.011
15	WWR0N1	0.10	0.118	WLR0N1	0.12	0.059	WFR0N1	0.10	0.075
30		0.09	0.057		0.11	0.036		0.10	0.059
60		0.08	0.063		0.10	0.019		0.07	0.020
15	WWR0N2	0.11	0.127	WLR0N2	–	–	WFR0N2	0.10	0.139
30		0.10	0.095		0.12	0.089		0.10	0.316
60		0.09	0.048		0.11	0.042		0.08	0.083
15	WWR1N0	0.09	0.004	WLR1N0	0.12	0.002	WFR1N0	0.10	0.004
30		0.08	0.005		0.10	0.003		0.10	0.004
60		0.09	0.004		0.07	0.005		0.09	0.004
15	WWR1N1	0.10	0.171	WLR1N1	0.13	0.031	WFR1N1	0.11	0.053
30		0.09	0.056		0.10	0.026		0.10	0.072
60		0.10	0.083		0.10	0.116		0.08	0.050
15	WWR1N2	0.07	0.032	WLR1N2	0.13	0.116	WFR1N2	0.11	0.142
30		0.11	0.135		0.11	0.071		0.11	0.064
60		0.08	0.038		0.10	0.075		0.08	0.033

[a] Wheat after wheat, after lentil and after fallow, respectively.

3.3. JUST Agricultural Research Centre, 2000–2001 first growing season

3.3.1. Parameters at tillering, barley

Barley-yield parameters at tillering are shown in Table XIV. Number of plants per hectare varied from 3,150,000 to 3,540,000, and difference between these values were not significantly associated with N rate. Number of tillers per plant were increased with N application. However, both N rates increased tiller number similarly. Fresh weight (biological yield) was increased significantly with the higher rate of N (80 kg /ha), but not significantly at the 0.05 level when the lower rate (40 kg N/ha) was applied. A similar trend was observed with dry weight. These responses indicate that addition of N stimulates vegetative growth and tillering when adequate soil moisture is available.

3.3.2. Parameters at anthesis, barley

Number of tillers per plant—considered at this stage as fertile tillers—was affected by N rate; the highest numbers were observed with the lower rate (40 kg N/ha) (Table XIV). The higher rate of N resulted in significantly fewer fertile tillers. This indicates that an excess of N in relation to soil moisture inhibits fertile tiller development. However, fresh and dry weights of shoots were increased similarly with both rates of N compared to the control.

3.3.3. Parameters at harvest, barley

Both fresh weight (biological yield) and dry weight of shoots were increased similarly with both rates of N application compared to the control treatment (Table XIV). Grain yield was increased with both rates of N; however, the higher rate did not significantly increase the yield compared to the lower rate. A similar trend was observed with the number of heads per hectare. On the other hand, 100-seed weight was not affected by the treatments, indicating that number of heads and not seed size was responsible for the treatment-differences in yield.

Table XIV. Yield, yield components, shoot parameters of barley at three growth stages, 2000–2001

Stage/yield aspect	N-rate (kg/ha)			$LSD_{0.05}$
	0	40	80	
Tillering				
Number (plants/ha)	3,540,000	3,150,000	3,460,000	NS
Tillers (per plant)	1.24	1.5	1.74	0.26
Fresh weight[a] (kg/ha)	11,280	14,018	17,652	1,103
Dry weight (kg/ha)	2,313	2,727	3,422	NS
Anthesis				
Fertile tillers (per plant)	0.66	0.80	0.68	0.09
Fresh weight (kg/ha)	18,000	23,340	24,530	4,933
Dry weight (kg/ha)	5,674	6,808	7,582	969
Harvest				
Fresh weight (kg/ha)	8,670	10,188	10,790	874
Dry weight (kg/ha)	7,600	9,013	9,610	775
Grain yield (kg/ha)	2,979	3,707	3,881	378
Straw yield (kg/ha)	5,691	6,481	6,909	NS
Heads (ha^{-1})	2,690,000	3,030,000	3,270,000	8476
100 seeds (g)	5.29	5.26	5.278	NS
Harvest index	34.5	36.4	36.19	NS
Height (cm)	75.1	74.0	81.2	3.62

[a] Biological yield.

Table XV. Yield, yield components and shoot parameters of vetch at three growth stages, 2000–2001

Stage/yield aspect	N-rate (kg/ha)			$LSD_{0.05}$
	0	40	80	
Tillering				
Number (plants/ha)	1,810,000	1,960,000	2,420,000	NS
Fresh wt. (kg/ha)	3,174	3,706	3,905	506
Dry wt. (kg/ha)	805	896	964	90.7
Anthesis				
Fresh weight (kg/ha)	7,853	11,811	11,987	1,916
Dry wt. (kg/ha)	2,953	3,980	4,043	400
Harvest				
Fresh wt. (kg/ha)	5,040	5,240	5,613	443
Dry wt. (kg/ha)	4,693	4,827	5,227	NS
Grain yield (kg/ha)	2,101	1,873	1,869	NS
Straw yield (kg/ha)	2,966	3,366	3,589	224
Heads (ha^{-1})	6,740,000	6,340,000	7,400,000	NS
100 seed (g)	7.23	6.74	7.25	0.35
Harvest index	0.42	0.36	0.32	0.32

3.3.4. Parameters, vetch

At tillering, the number of plants per hectare varied from 1,810,000 to 2,420,000 (Table XV). However, the differences were not associated with application of N. Fresh weight (biological yield) per hectare was increased significantly with the higher rate of N (80 kg/ha); the increase with the lower rate (40 kg N/ha) was not significant. A similar trend was observed with shoot dry matter.

At anthesis and at harvest, the same trends of response to N were obtained with the fresh and dry weights of shoots. Vetch grain yields were not significantly different across treatments. However, grain yield tended to be lower with N was applied, whereas the trend with straw yield was the reverse. This was reflected in the harvest index: it was highest for the control followed by the lower N rate.

3.3.5. Soil moisture

Soil volumetric water content (PV) values, as a function of soil depth, treatment and cropping system, are shown in Table XVI. The PV was below field capacity at all depths initially and throughout the season, which resulted in delayed germination and poor growth.

The fallow system did not conserve soil moisture in the rooting zone. However, in deeper layers slightly higher PV values were observed. It can be concluded that under such a harsh environment the utility of fallow for improving soil moisture storage for a subsequent crop is questionable. Most of the rain events were small, thus increasing evaporation and precluding moisture penetration of the soil profile.

The PV was not affected by N rate in any cropping system. Generally, PV decreases with time; at anthesis, soil moisture level was very low, inhibiting grain setting and compromising yields of both crops.

3.3.6. Nitrogen utilization, barley and vetch

Nitrogen content of barley was lowest where no N was added (N0 treatment, Table XVII). This more marked in grain than in shoot. In contrast, N content of vetch was not affected by N rate. Vetch contained much more N than barley due it its ability to fix atmospheric N_2, decreasing dependence on N fertilizer. Nitrogen utilization efficiency by barley was lower for the higher N rate but was low for all rates of N. Nitrogen utilization by vetch was lower than for barley with no significant effects of applied N.

3.3.7. Nitrogen fixation, vetch

Relatively little of the N assimilated by vetch came from fertilizer; more came from the soil and the bulk came from fixation (Table XVIII). The amounts fixed ranged from 98 to 173 kg N/ha.

Table XVI. Volumetric water content of the soil at five growth stages, 2000–2001

Treatment	Stage	Depth (cm)				
		0–15	15–30	30–45	45–60	60–75
		(%)				
	Initial	7.4	15	20	23	23
BN0	Emergence	15	27	28	27	25
	Tillering	15	27	28	27	25
	Anthesis	11	21	22	25	24
	Harvest	10	19	20	23	25
BN1	Emergence	14	27	28	27	25
	Tillering	14	27	28	27	26
	Anthesis	12	21	22	24	25
	Harvest	9.5	19	20	24	25
BN2	Emergence	14	27	27	27	25
	Tillering	14	28	27	27	25
	Anthesis	12	22	22	24	24
	Harvest	10	18	19	23	24
Fallow	Emergence	15	27	29	28	26
	Tillering	15	28	28	28	26
	Anthesis	10	21	24	25	24
	Harvest	8.6	19	20	24	25
VN0	Emergence	15	28	28	27	26
	Tillering	15	28	28	27	25
	Anthesis	11	22	23	25	24
	Harvest	8.6	18	20	23	25
VN1	Emergence	15	27	27	27	25
	Tillering	15	27	27	27	25
	Anthesis	10	22	23	25	24
	Harvest	9.4	19	21	24	25
VN2	Emergence	14	26	27	27	25
	Tillering	14	27	28	27	25
	Anthesis	11	22	24	25	25
	Harvest	8.5	19	21	23	25

Table XVII. Nitrogen utilization by barley and vetch, 2000–2001

Trt.	Grain N	Grain ^{15}N	Shoot N	Shoot ^{15}N	Grain Ndff	Shoot Ndff	Grain DW	Grain N	Grain Ndff	Shoot DW.	Shoot N	Shoot Ndff	Total Ndff	Fert. util.
	(%)						(kg/ha)							(%)
BN0	2.0	0.01	0.65	0.00			2,979	59.4		5,691	36.9			
BN1	2.1	0.48	0.59	0.59	9.2	11	3,707	76.1	6.88	6,481	38.7	4.36	11.3	14
BN2	2.3	0.66	0.71	0.81	13	15	3,881	90.0	11.2	6,909	48.2	7.59	18.8	12
VN0	5.4	0.00	1.2	0.00			2,102	113		2,966	34.7			
VN1	5.1	0.05	1.3	0.13	0.99	2.6	1,873	95.7	0.94	3,366	43.1	1.11	2.1	5.1
VN2	5.2	0.05	1.3	0.11	1.0	2.0	1,869	97.9	0.96	3,598	45.3	0.90	1.9	4.7

Table XVIII. Nitrogen uptake and derived from fertilizer, soil and biological N_2 fixation, vetch, 2000–2001

Trt.	Grain N	Grain ^{15}N	Shoot N	Shoot ^{15}N	Grain Ndff[a]	Shoot Ndff	Grain Ndfs	Shoot Ndfs	Grain Ndfa	Shoot Ndfa	Grain N	Shoot N	Fixed N
	(%)										(kg/ha)		
VN0	4.9	.00	0.86	0.0							102	22.7	
	5.5	.00	1.2	0.0							89.0	30.6	
	6.1	.00	1.0	0.0							153	36.2	
	5.0	.00	1.7	0.0							109	49.5	
Mean	5.4	.00	1.2	0.0							113	34.7	
VN1	5.3	.07	1.3	0.14	1.4	2.7	17	19	81	78	95.7	41.1	110
	4.8	.07	1.00	0.14	1.3	2.8	16	28	83	69	91.1	31.9	97.8
	5.0	.03	1.4	0.16	0.65	3.1	4.6	19	95	78	96.5	54.9	134
	5.3	.03	1.3	0.09	0.61	1.7	6.2	15	93	83	99.5	44.6	130
Mean	5.1	.05	1.2	0.13	0.99	2.6	11	20	88	77	95.7	43.1	118
VN2	5.3	.07	1.1	0.14	1.3	2.7	7.3	12	91	86	82.8	38.5	109
	5.0	.09	1.3	0.13	1.8	2.5	9.2	12	89	85	89.1	46.3	119
	5.3	.03	1.1	0.09	0.55	1.8	5.2	10	94	88	142	44.3	173
	5.4	.02	1.5	0.06	0.47	1.1	4.9	9.4	95	89	77.4	52.1	120
Mean	5.2	.05	1.3	0.11	1.0	2.0	6.6	11	92	87	97.9	45.3	130

[a] Nitrogen derived from fertilizer, soil and fixation, respectively.

3.3.8. Soil nitrogen at the end of the experiment

The N content of the soil was very low at all depths (Table XIX). The ^{15}N values showed very little residual fertilizer, indicating that, since little was assimilated by the crops, most of the added N must have been lost by volatilization and denitrification.

3.4. JUST Agricultural Research Centre, 2001–2002 second season

Applied N had significant effects on all shoot parameters at tillering and anthesis (Table XX). On the other hand, the previous crop had no significant effect. Addition of N significantly increased final grain yields (Table XXI). Barley yields were lowest when grown after barley.

Table XIX. Nitrogen at different soil depths under different cropping systems, 2000–2001

Treatment	Soil depth/ replicate (cm)	N	^{15}N a.e.	Ndff remaining in soil
			(%)	
BN0	15-1	0.09	0.002	0.000
	15-2	0.06	0.002	0.000
	15-3	0.05	0.003	0.001
BN1	30	0.09	0.056	0.011
		0.07	0.026	0.005
		0.04	0.012	0.002
BN2	45	0.09	0.040	0.008
		0.07	0.013	0.003
		0.05	0.010	0.002
VN0	15	0.11	0.001	0.000
		0.08	0.002	0.000
		0.05	0.003	0.001
VN1	30	0.09	0.041	0.008
		0.07	0.015	0.003
		0.05	0.009	0.002
VN2	45	0.10	0.026	0.005
	45	0.09	0.013	0.002
	45	0.05	0.006	0.001
Fallow	15	0.10	0.001	0.000
	30	0.07	0.002	0.000
	45	0.05	0.002	0.000
Averages				
BN0	15	0.07	0.00	0.00
BN1	30	0.07	0.03	0.01
BN2	45	0.07	0.02	0.00
VN0	15	0.08	0.00	0.00
VN1	30	0.07	0.02	0.00
VN2	45	0.08	0.01	0.00
Fallow	15	0.10	0.10	0.10
	30	0.07	0.07	0.07
	45	0.05	0.05	0.05

No clear trend has been observed for any of the factors investigated in terms of volumetric water content of the soil (Tables XXII and XXIII). Long-term research is needed to further evaluate these factors for their effects on water utilization.

Nitrogen utilization was decreased with the higher N rate, but was not significantly affected by the previous crop (Table XXIV). The residual N in the soil was very low and did not differ significantly among treatments (Table XXV). The low residual N indicated that most non-utilized N was subjected to losses by volatilization and/or denitrification. Carbon-isotope composition was not significantly affected by the treatments (XXVI).

Table XX. Shoot parameters of barley at tillering and anthesis, 2001–2002

Previous crop	N-rate (kg N/ha)	Tillering				Anthesis		
		Plants	Tillers	Fresh wt.	Dry wt.	Fertile tillers	Fresh wt.	Dry wt.
		(1,000/ha)	(plant^{-1})	(kg ha^{-1})		(plant^{-1})	(kg/ha)	
Barley	0	318	1.77	8,130	2616	1.17	10,910	4,630
	40	299	2.33	12,790	3170	1.35	12,820	5,500
	80	323	255	10,930	3426	1.40	14,530	5,840
Fallow	0	288	1.91	7,860	2558	1.18	13,610	5,460
	40	327	2.31	10,500	3219	1.36	15,220	6,250
	80	284	2.65	10,650	3399	1.42	15,800	6,280
Vetch	0	303	1.74	7,850	2548	1.17	13,460	5,550
	40	320	2.19	9,640	3020	1.35	15,110	6,150
	80	282	2.64	10,540	3378	1.46	16,770	6,770
LSD$_{0.05}$		NS	NS	NS	NS	NS	NS	NS
Effect of N-rate								
	0	303	1.81	7,947	2574	1.17	12,660	5,213
	40	315	2.27	10,977	3136	1.35	14,383	5,967
	80	296	2.61	10,707	3401	1.43	15,700	6,297
LSD$_{0.05}$		NS	0.133	1,721	196	0.09	1,335	580
Effect of previous crop								
Barley		313	2.21	10,617	3071	1.31	12,753	5,323
Fallow		299	2.29	9,670	3059	1.32	14,876	5,997
Vetch		301	2.19	9,343	2982	1.33	15,113	6,157
LSD$_{0.05}$		NS	NS	NS	NS	NS	NS	NS

3.5. Conclusions

Due to the dry conditions and frequency of drought events, supplemental irrigation should be recommended to avoid complete failure of crops and to minimize negative impacts on yield. With supplemental irrigation, the addition of N was justified and resulted in increased yield. The addition of the lower rate of N (40 kg/ha) was enough to support the highest yield. The positive effect of supplemental irrigation on response to N application suggests that soil moisture is the chief constraint to crop growth and N may be the second most-limiting factor in this semi–arid region. The fallow system was not efficient in conserving and improving the moisture storage capacity of the soil; therefore, other types of crop rotation should be evaluated. This can be done adequately only with long-term investigations to evaluate possible cumulative effects. The relatively low values for N-utilization efficiency are to be expected under such dry condition with very low rainfall and high atmospheric temperature that enhance N losses by denitrification and volatilization. Under the relatively better weather condition in the second season, the barley responded positively to N fertilization.

Table XXI. Yield and yield components of barley at harvest, 2001–2002

Previous crop	N-rate	Biol. yield	Grain yield	Straw yield	Dry wt.	Heads (1,000/ha)	1,000-grain wt. (g)	Harvest index (%)
	(kg N/ha)							
Barley	0	6,150	1,814	4,336	4,966	341	43.5	30
	40	7,700	2,041	5,659	6,061	356	41.9	27
	80	7,500	1,978	5,356	5,985	376	35.8	27
Fallow	0	7,220	1,935	5,285	5,692	349	39.7	27
	40	9,100	2,508	6,592	7,208	418	37.3	28
	80	9,870	2,652	7,218	7,740	422	36.2	27
Vetch	0	7,520	2,116	5,405	5,983	383	41.5	28
	40	9,730	2,505	7,225	7,729	455	38.3	26
	80	10,230	2,613	7,618	8,091	445	36.2	26
LSD$_{0.05}$		NS	NS	NS	NS	NS	NS	NS
Effect of N-rate								
	0	6,963	1,955	5,009	5,547	358	41.6	28
	40	8,843	2,351	6,492	6,999	410	39.2	27
	80	9,200	2,414	6,731	7,272	414	36.0	26
LSD$_{0.05}$		868	217	737	644	496	1.97	NS
Main effect of previous crop								
Barley		7,117	1,945	5,117	5,671	3,577	40.4	28
Fallow		8,730	2,365	6,365	6,880	3,963	37.7	27
Vetch		9,160	2,411	6,749	7,268	4,277	38.7	27
LSD$_{0.05}$		1,386	328	1,249	1,065	NS	NS	NS

Table XXII. Volumetric water content of soil under barley after barley, fallow or vetch, 2001–2002

Treatment	Growth stage	Soil depth (cm) 0–15	15–30	30–45	45–60	60–75
		(%)				
BBN0	Initial	7.7	14	19	23	24
	Emergence	12	21	24	26	27
	Tillering	9.6	19	23	25	25
	Anthesis	14	25	28	26	26
	Harvest	8.3	17	21	23	25
BBN1	Initial	7.5	13	19	22	25
	Emergence	13	22	24	25	25
	Tillering	8.5	17	21	22	24
	Anthesis	12	22	22	23	25
	Harvest	8.0	15	20	22	24
BBN2	Initial	6.9	13	19	22	24
	Emergence	12	19	20	23	25
	Tillering	8.4	15	20	23	24
	Anthesis	12	24	24	23	24
	Harvest	7.8	15	20	22	23
BFN0	Initial	7.1	12	19	22	24
	Emergence	11	19	20	23	25
	Tillering	8.1	16	20	22	24
	Anthesis	12	23	22	22	24
	Harvest	8.0	15	19	22	24
BFN1	Initial	7.3	13	20	23	25
	Emergence	13	22	24	25	17
	Tillering	9.8	17	22	23	24
	Anthesis	15	23	24	24	25
	Harvest	8.9	17	21	21	24
BFN2	Initial	7.8	14	19	23	25
	Emergence	14	21	24	26	26
	Tillering	8.9	17	21	24	25
	Anthesis	15	24	24	24	25
	Harvest	8.2	15	20	22	25
BVN0	Initial	7.5	13	19	22	25
	Emergence	11	19	21	22	24
	Tillering	8.6	17	20	22	21
	Anthesis	14	23	25	25	25
	Harvest	8.5	15	21	23	25
BVN1	Initial	7.3	14	19	22	25
	Emergence	11	18	20	22	23
	Tillering	8.5	15	19	22	24
	Anthesis	13	22	23	24	24
	Harvest	7.8	14	19	22	24
BVN2	Initial	7.5	14	19	23	25
	Emergence	11	19	21	23	24
	Tillering	8.9	16	20	23	24
	Anthesis	12	22	24	24	24
	Harvest	8.2	15	20	22	24

Table XXIII. Volumetric water content at different growth stages of barley grown after barley, fallow or vetch, 2001–2002

Treatment	Stage	Soil depth (cm) 0–15	15–30	30–45	45–60	60–75
		(%)				
BB		9.8	18	22	23	25
BF		10	18	21	23	2
BV		9.6	17	21	23	24
BBN0		10	19	23	25	26
BBN1		9.8	18	21	23	24
BBN2		9.4	17	21	22	24
BFN0		9.4	17	20	22	24
BFN1		11	18	22	23	23
BFN2		11	18	22	24	25
BVN0		10	17	21	23	24
BVN1		9.8	17	20	22	24
BVN2		10	18	21	23	24
BB	Initial	7.3	13	19	22	25
	Emergence	12	21	23	25	26
	Tillering	8.8	17	21	23	24
	Anthesis	13	24	25	24	25
	Harvest	8.0	16	21	23	24
BF	Initial	7.4	13	19	23	25
	Emergence	13	21	23	25	23
	Tillering	8.96	17	21	23	24
	Anthesis	14	23	23	23	25
	Harvest	8.4	16	20	22	24
BV	Initial	7.4	14	19	23	25
	Emergence	11	19	20	22	24
	Tillering	8.6	16	20	22	23
	Anthesis	13	22	24	24	25
	Harvest	8.2	15	20	23	24

Table XXIV. Nitrogen uptake and utilization by barley grown after barley, vetch or fallow

Trt.	Grain N	Grain ^{15}N	Shoot N	Shoot ^{15}N	Grain Ndff	Shoot Ndff	Grain wt.	Grain N	Grain Ndff	Shoot dwt	Shoot N	Shoot Ndff	Total Ndff	Fert. util. (%)
	%						(kg/ha)							
BBN0	1.8	0.039	0.49	0.046			1,814			4,336				
BBN1	1.8	1.0	0.63	1.3	20	25	2,040	36.5	7.46	5,659	35.7	8.43	15.9	40
BBN2	2.0	1.4	0.76	1.2	267	24	1,978	38.5	10.2	5,356	40.3	9.62	19.8	25
BVN0	1.7	0.005	0.54	0.025	0.10	0.49	2,115	35.8	0.03	5,404	29.3	0.14	0.20	
BVN1	1.8	1.2	0.57	1.2	23	23	2,504	46.2	10.4	7,225	41.3	9.43	19.9	50
BVN2	1.8	1.3	0.65	1.3	25	26	2,612	46.1	11.5	7,618	49.3	12.9	24.5	31
BFN0	1.7	0.008	0.64	0.019	0.08	0.38	1,934	17.0	0.03	5,285	33.3	0.12	0.20	
BFN1	2.0	0.90	0.76	0.90	18	18	2,507	50.1	8.89	6,592	49.5	8.79	17.7	44
BFN2	2.1	0.96	0.71	1.15	19	23	2,652	56.7	10.8	7,218	52.1	12.0	22.8	29

Table XXV. Soil nitrogen at three soil depths at the end of the experiment

Treat.	Depth (cm)	N	^{15}N a.e.	Treat.	N	^{15}N a.e.	Treat.	N	^{15}N a.e.
		(%)			(%)			(%)	
BBN0	0–15	0.09	0.003	BVN0	0.09	0.002	BFN0	0.09	0.003
	15–30	0.09	0.003		0.08	0.003		0.08	0.003
	30–60	0.07	0.003		0.06	0.004		0.06	0.004
BBN1	0–15	0.10	0.081	BVN1	0.09	0.041	BFN1	0.10	0.046
	15–30	0.09	0.046		0.08	0.019		0.09	0.016
	30–60	0.07	0.026		0.06	0.014		0.06	0.018
BBN2	0–15	0.10	0.108	BVN2	0.09	0.047	BFN2	0.10	0.062
	15–30	0.07	0.030		0.05	0.029		0.08	0.012
	30–60	0.10	0.047		0.10	0.006		0.07	0.010

Table XXVI. Carbon isotope composition of grain and shoot

Treatment	δ^{13}C Grain	Shoot
	(‰)	
BBN0	–23.6	–25.9
BBN1	–22.8	–25.5
BBN2	–22.7	–25.7
BVN0	–22.8	–26.0
BVN1	–22.6	–26.1
BVN2	–22.8	–26.3
BFN0	–22.0	–25.9
BFN1	–22.5	–25.7
BFN2	–22.9	–26.3

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USE OF NUCLEAR TECHNIQUES TO INCREASE FERTILIZER NITROGEN- AND PHOSPHORUS-USE EFFICIENCIES IN MUSTARD AND WHEAT IN RAINFED CONDITIONS

M.S. SACHDEV
Indian Agricultural Research Institute,
New Delhi, India

Abstract

Field experiments were conducted for three years from 1998–1999 to 2001–2002 at the Indian Agricultural Research Institute farm with mustard (*Brassica juncea* 'T-59') and wheat (*Triticum aestivum* 'WH-147') during the winter season under rainfed conditions and with cowpea (*Vigna unguiculata* 'V 890') during the monsoon season. Three levels of N and P were applied (0, 30 and 60 kg N ha^{-1} and 0, 15 and 30 kg P_2O_5 ha^{-1} for mustard; 0, 40 and 80 kg N ha^{-1} and 0, 20 and 40 kg P_2O_5 ha^{-1} for wheat). In treatments N_1 and N_2, ^{15}N-urea was applied to micro-plots. Also in treatments P_1 and P_2, ^{32}P-labelled single superphosphate was applied to micro-plots. During the monsoon season in the same layouts cowpea was grown with 20 kg N ha^{-1} and maize as the reference crop for measuring biological N_2 fixation using the ^{15}N-dilution technique. Wide variation amongst replicates in germination and dry matter yield was recorded at the Z30 stage in wheat. Nitrogen and P contents were higher in N- and P-fertilized plots during the first two years. However, during the third and fourth years these differences were very much less as the wheat was sown without tillage to conserve moisture. The highest wheat-grain yield of 1.89 Mg ha^{-1} was obtained with 80 kg N ha^{-1} and 40 kg P_2O_5 ha^{-1} in the third year (2000–2001); this treatment gave only 1.21 Mg ha^{-1} in the second year (1999–2000). The highest mustard-seed yield of 1.59 Mg ha^{-1} was obtained with the highest applications of N and P in the third year (2000–2001). Both in mustard and in wheat, increases in yields were more pronounced with N application than with P. Fertilizer-N use efficiency in mustard during the four years ranged from 31 to 72%. Wheat utilized fertilizer N less efficiently. In both mustard and wheat, nearly 90% of the applied fertilizer N could be recovered in either the crop or soil. Fertilizer-P recovery in mustard was nearly twice that in wheat. Mustard extracted more water from the soil than did wheat. The δ^{13}C data in wheat grain and straw showed no relationship with other parameters. However, the δ^{13}C values in mustard stover at harvest showed a positive linear relationship with consumptive water-use efficiency, seed yield and total N uptake. There was no effect of the previous cropping of mustard or wheat on grain yield or N accumulation by cowpea. During the two years, it removed nearly 130 kg N ha^{-1} in grain and straw, of which some two-thirds was derived from biological N_2 fixation. The data showed a negative N balance for the cowpea-mustard cropping system, even with an application of 60 kg N ha^{-1} to mustard, and for cowpea-wheat with 40 kg N ha^{-1} applied to wheat, as observed in the first two years with conventional tillage. With the cowpea residues left on the soil during the winter season and crops sown with minimum tillage (mulch-minimum-tillage), the N-balance became positive. Recommendations are difficult due to high seasonal variability; a critical examination using models is needed. The primary factor for increasing production in such rainfed conditions is better water management with more attention paid to nutrient management.

1. INTRODUCTION

Sustainable food security is needed for the arid and semi-arid regions of the tropical, sub-tropical and warm temperate climate zones. In these regions, supplies of locally grown food are unreliable because much of it is produced from non-irrigated crops grown 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 those with plentiful water resources. High-yielding varieties produced in the Green Revolution express their full potential with large inputs of agrochemicals including fertilizers. In arid and semi-arid regions, crop responses to inputs such as fertilizers are generally low and unprofitable to the farmer. Understandably, the level of inputs has remained low and yields are not increasing. The problem of increasing crop productivity in these regions is widely recognized as difficult.

1.1. Rainfed Agriculture in India

Of 142 million ha of agricultural land used in India, over 90 million ha is unirrigated. Nearly 67 million ha of this rainfed area have a mean annual precipitation with the 500 to 1,500 mm range. Productivity and production stability in rainfed areas is low. Consequently, although rainfed agriculture occupies about 63% of the total cropped area, it contributes only 45% of the country's agricultural production. Even when the full irrigation potential of the country becomes operative, 50% of the sown area will remain rainfed. Rainfed agriculture supports 40% of India's one billion population, and within the rainfed belt, cultivation of 91% pulses, 80% oilseeds and 65% cotton occurs. Demands for food will continue to rise, necessitating increases in productivity from rainfed regions to 2 t ha^{-1} from the present level of 0.9 t ha^{-1}. This is associated with serious degradation in the natural resource base in the country over the past 5 decades. The problem is compounded further if we consider four other main features of these areas: moisture and nutrient loss, vulnerability to drought, diverse agricultural practices and overall low productivity.

Major rainfed crops grown in India comprise coarse grains, particularly pearl millet and sorghum, pulses, oilseeds and cotton. Not only are yields of these crops low, but the technology-transfer gap is also wide. The region is characterized by erratic and often low rainfall, degraded and poorly fertile soils and harsh temperature regimes. Frequently, these areas are inhabited by resource-poor farmers whose risk-taking ability is low, hence use of monetary inputs is restricted.

Many farmers depend on livestock as an alternative source of income. Nearly two out of every three of the cattle population (458 million head) are in rainfed regions. With substantial increases in use of diesel and electricity in Indian agriculture over the past three decades, animal power has decreased except in the eastern states (Assam, Bihar, Orissa) where it has shown an increase. Livestock is the source of most organic manure. It is estimated that by 2025, India will apply 40 Mt of plant nutrients, out of which 10 Mt will still come from organic sources.

Against this background, it is imperative to devise ways to improve and sustain overall productivity (crop, soil, livestock). Some estimates reveal that nutrient removal in harvested crops is far in excess of nutrient addition through fertilizers, resulting in a negative balance of 5.5 million tonnes of NPK. An approach involving chemical fertilizers, organic manures, crop residues and biofertilizers is the only viable means of bridging the gap between nutrient demand and supply to boost agricultural production; optimizing socio-economic factors that affect farmers will also be an essential component. Thus, integrated nutrient management (INM) can help provide a better livelihood for resource-poor farmers in rainfed areas if the various components and gains from this system are considered. A review of research on INM reveals that two major aspects have not received attention: (i) location-specific technology, and (ii) profitable technology compared to the existing farm practices. The review also makes it clear that the INM practices being advocated in these areas are often not based on the indigenous technological knowledge of the farmers and do not take into account the basic needs of farm family, farm size, or social groups and their perceptions. Rainfed agriculture development is resource-centred and a holistic approach is required, which entails:

- development of strategies to utilize the resources as per capacity so that resource quality is maintained if not enhanced;
- development of strategies for conservation and efficient use of resources through interventions such as land treatments (tillage practices to maximize in situ rainwater harvesting, and to minimize postliminary losses of soil stored water), use of restorer inputs (chemical fertilizers, organic manures, crop residues, soil amendments, etc.) and introduction of appropriate plant species and management of dominant constraints;
- assessment of the relevance of introduced technologies vis-à-vis farmers' perceptions of, and interactions with, indigenous as well as modern practices and the local environment;
- undertaking system-based research and technology development seeking to maximize crop production in synergy with livestock, tree, fodder and fuel components of the system and ensure development of appropriate technologies for wider diffusion.

Keeping these aspects in mind, we conducted field trials for four years with mustard and wheat as test crops grown during the winter season under rainfed conditions with conventional tillage in the first two years and with conservation tillage and utilizing monsoon-season-grown cowpea residues as soil mulch. The parameters studied were fertilizer-N and -P effects on economic yield, total and applied nutrient (N and P) utilization using ^{15}N and ^{32}P and in-situ water monitoring using a neutron moisture probe. Also, attempts were made to generate carbon-isotope discrimination ($\delta^{13}C$) values and other plant parameters.

2. EXPERIMENTAL DETAILS

A field experiment was conducted for four years in the Todapur Block of the Indian Agricultural Research Institute farm with mustard (*Brassica juncea* L.) and wheat (*Triticum aestivum* L.). The soil at the experimental site is alluvial loam belonging to the Mehrauli series and has been classified as coarse loamy non-acid hypothermic typic Ustochrept. The soil profile description is described in Table I.

The experimental treatments were three levels of N and three levels of P with four replications. Nitrogen and P levels for mustard and wheat crop were as follows:

Fertilizer	Designation	Mustard	Wheat
		(kg ha^{-1})	
Nitrogen	N_0	0	0
	N_1	30	40
	N_2	60	80
Phosphorus	P_0	0	0
	P_1	15	20
	P_2	30	40

Table I. Some physico-chemical and moisture-profile characteristics of the soil

Depth (cm)	Sand	Silt	Clay	PH	EC (dS/m)	$CaCO_3$	Organic C	CEC [cMol(p$^+$) kg^{-1}]	Total N (%)
	(%)					(%)			
0–21	50	36	13	8.1	0.30	0	0.47	7.5	0.047
21–52	55	31	12	8.3	0.25	0	0.18	7.8	0.035
52–93	54	30	13	8.4	0.35	0	0.15	9.0	0.031
93–117	57	30	11	8.1	0.30	0	0.13	10.5	0.027
117–138	50	32	16	8.1	0.30	0	0.13	—	0.025
138–173	46	36	18	8.0	0.25	0	—	—	0.024

Depth (cm)	Bulk density (g/cc)	LLW	ULD	ULS	Available water (%)	Available moisture to 60-cm depth	Available moisture to 100-cm depth
						(cm)	
0–21	1.41	0.110	0.297	0.437	13	7.12	11.7
21–52	1.41	0.095	0.251	0.371	11		
52–93	1.41	0.094	0.254	0.359	11		
93–117	1.47	0.091	0.268	0.422	12		
117–138	1.52	0.151	0.362	0.449	14		
138–173	1.50	0.156	0.389	0.481	16		

Table II. Initial soil ammonium- and nitrate contents and moisture status

Season	Soil depth (cm)	Ammonium-N (mg kg^{-1})	Nitrate-N (mg kg^{-1})	Soil moisture (cm^3 cm^{-3})
1998–1999	0–15	2.67±0.37	2.71±0.49	0.212±0.012
	15–30	2.60±0.48	1.94±0.13	0.275±0.001
	30–60	2.03±0.30	1.79±0.16	0.286±0.006
	60–90	2.08±0.32	1.63±0.13	0.275±0.004
	90–120	1.69±0.24	1.51±0.05	0.274±0.001
	120–150	1.77±0.32	1.55±0.20	0.280±0.006
1999–2000	0–15	2.15±0.15	2.54±0.31	0.216±0.004
	15–30	2.22±0.17	1.88±0.14	0.275±0.002
	30–60	1.93±0.19	1.66±0.16	0.279±0.005
	60–90	1.95±0.17	1.50±0.13	0.276±0.003
	90–120	1.70±0.11	1.58±0.19	0.271±0.005
	120–150	1.58±0.15	1.55±0.18	0.271±0.004
2000–2001	0–15	3.24±0.26	1.65±0.20	0.235±0.004
	15–30	2.57±0.21	1.32±0.18	0.281±0.003
	30–60	1.85±0.17	1.25±0.11	0.278±0.003
	60–90	1.68±0.20	1.10±0.14	0.278±0.003
	90–120	1.50±0.16	1.15±0.15	0.277±0.002
	120–150	1.45±0.18	1.30±0.19	0.279±0.002
2001–2002	0–15	2.61±0.21	1.78±0.31	0.228±0.005
	15–30	2.16±0.52	2.29±0.48	0.275±0.004
	30–60	1.85±0.38	1.78±0.31	0.276±0.003
	60–90	1.59±0.38	1.53±0.48	0.276±0.004
	90–120	1.97±0.45	2.10±0.63	0.275±0.004
	120–150	1.72±0.33	1.65±0.55	0.275±0.001

The initial soil-moisture and mineral-N contents before the sowing of winter-season mustard and wheat for the four years of experimentation are given in Table II. The mineral-N contents were generally low, but moisture was good for sowing winter crops.

The experiment had a randomized block design. The main plot size for mustard was 6.0 × 3.0 m and for wheat 5.0 × 3.0 m. In each N_1 and N_2 plot, a micro-plot of size 1.0 × 1.0 m was made for ^{15}N-urea application. Also in P_1 and P_2 plots, a separate micro-plot of 1.0 × 1.0 m was made for application of ^{32}P-labelled single superphosphate (approximately 0.5 mCi ^{32}P/g P_2O_5). Nitrogen was applied as urea and P as single superphosphate (16% P_2O_5) in the main plots. Basal doses of muriate of potash were applied at 30 kg K_2O/ha to mustard and 40 kg K_2O/ha to wheat. Nitrogen was applied in two splits and P was applied in a single dose as a basal broadcast and incorporated. For mustard, half the N was broadcast at sowing and incorporated and the remainder was top-dressed at pre-flowering. For wheat, a third of the N was broadcast at sowing and incorporated and the remainder was top-dressed at Z30.

In both crops, four aluminium access tubes were installed to a depth of 180 cm in N_2P_2-treatment plots for recording soil moisture status during crop growth using a Troxler model 4300A neutron moisture probe. The total winter rainfall during the first cropping season was 130 mm—with a maximum of 71.9 mm in January 1999—nearly double the long-term average. During the 1999–2000, 2000–2001 and 2001–2002 seasons, rainfall was 44.5, 37.8 and 36.3 mm, respectively. The growing season summary of the experiments for the four years is presented in Table III.

Table III. Growing-season summary for duration of the experiment, under rainfed conditions

Season		1998–1999	1999–2000	2000–2001	2001–2002
Kharif (monsoon)	Preceding crop	Fallow	Cowpea	Cowpea	Cowpea
	Cultivar	–	V 890	V 890	V 890
	Planted	–	17 Jul ’99	13 July ’00	05 July ’01
	Fertilizer N (kg Nha^{-1})	–	20	20	20
	Fertilizer P (kg P_2O_5 ha^{-1})	–	30	30	30
	Harvested	–	21 Oct ’99	12 Oct ’00	03 Oct ’01
Rabi (winter)	Crop	Mustard/ wheat	Mustard/ wheat	Mustard/ Wheat	Mustard/ wheat
	Mustard variety	T-59	T-59	T-59	T-59
	Wheat variety	WH-147	WH-147	WH-147	WH-147
	Planted	16 Oct ’98	26 Oct ’99	19 Oct ’00	10 Oct ’01
	N treatments, mustard (kg N ha^{-1})	0, 30 & 60	0, 30 & 60	0, 30 & 60	0, 30 & 60
	P treatments, mustard (kg P_2O_5 ha^{-1})	0, 15 & 30	0, 15 & 30	0, 15 & 30	0, 15 & 30
	N treatments, wheat (kg N ha^{-1})	0, 40 & 80	0, 40 & 80	0, 40 & 80	0, 40 & 80
	P treatments, wheat (kg P_2O_5 ha^{-1})	0, 20 & 40	0, 20 & 40	0, 20 & 40	0, 20 & 40
	Rainfall (mm)	130	44.5	37.8	36.3
	Mustard harvested	15 Mar ’99	21 Mar ’00	22 Mar ’01	23 Mar ’02
	Wheat harvested	07 Apr ’99	10 Apr ’00	05 Apr ’01	04 Apr ’02

Wheat samples were collected from the main plots at Z30, flag-leaf, 1 week after 50% anthesis, physiological maturity and final harvest. Mustard samples were collected at the flowering and maturity stages only. The samples were dried at 70°C and dry-matter yields recorded. Sub-samples were then analysed for total N. The micro-plots were harvested at physiological maturity and analyzed for total N and P as well as for ^{15}N and ^{32}P for grain and straw in wheat, and for seed, stover and pod-husk in the case of mustard. After the crop harvests, soil samples were collected from ^{15}N micro-plots to a depth of 60 cm in 15-cm intervals and analysed for total N, ammonium- and nitrate-N and ^{15}N in each.

During the summer season (April to June) the plots were left undisturbed and after the onset of monsoon, in the same layout all seventy-two plots (thirty-six each of wheat and mustard) were planted to cowpea in July each year; the cowpea crops were harvested in October after picking the pods. To measure biological N_2 fixation by cowpea by the ^{15}N-dilution technique (‘A’ value method), four plots from each previous crop of wheat and mustard were selected and a micro-plots of 1 m^2 (1.0 × 1.0 m) was made in each. The reference crop was maize, planted in an adjacent site in four plots with a micro-plot in each for ^{15}N application. Nitrogen was applied to the cowpea at 20 kg N ha^{-1} and to the maize crop at 120 kg N ha^{-1}. Urea labelled with ^{15}N was applied to the micro-plots.

After harvest of the cowpea crop, the land was prepared and the second-year experiment with mustard and wheat was initiated. In the third and fourth years the mustard and wheat crops were sown with minimum tillage and a mulch of cowpea residue. Basal fertilizers were applied by opening a furrow to a depth of 8 to 10 cm and seeds were sown above it at about 3 to 4 cm depth. All other operations were similar as in the first and second years. In the third year, termites attracted by the mulch were controlled by application of chlorpyriphos to the soil.

In the fourth year (2001–2002), a parallel experiment was conducted to differentiate the effects of minimum tillage and cowpea-residue mulch on the performance of mustard and wheat grown on residual moisture in the winter season under rainfed conditions. In this side experiment, after picking the cowpea pods the stover was harvested and removed and the mustard and wheat crops were sown with minimum tillage only (no mulch). All other operations and treatments were identical to those in the main experiment, but with no application of ^{15}N- and ^{32}P-labelled fertilizers in micro-plots.

3. METHODS

Total N contents of soil, plant and grain samples were determined using standard Kjeldahl procedures. The ammonium and nitrate contents of soil were determined by steam distillation after extraction with 2 *N* KCl. The ^{15}N in different components was determined by Duma's procedure using an ^{15}N emission analyser (JASCO model N-150) according to Fiedler and Proksch [1]. Phosphorus in digested plant samples was determined colorimetrically [2]. The ^{32}P-activity measurements were made with a liquid scintillation counter following the Cerenkov procedure. Oil content in mustard seeds was measured non-destructively by pulsed NMR (Bruker, model Mini-spec 20) [3]. Nitrogen-15 in soil samples and $\delta^{13}C$ measurements for wheat grain, mustard seed and wheat/mustard straw were made at IAEA's Seibersdorf Laboratory by mass spectrometry.

4. RESULTS:

4.1. Cowpea

The cowpea crops were grown during the monsoon season in the same layout as in the previous winter season mustard and wheat crops. There was no effect of previous crop or treatment on the grain yield of cowpea in any year. However, in the third year (2000–2001) the straw yield of cowpea was significantly higher with the higher amounts of N applied to the previous mustard and wheat crops (Tables IV–VI). Also, both grain and straw yields of cowpea were nearly 10% higher in the third year compared to other two years; consequently, the total N accumulation by the cowpea was also higher. Determinations of biological N_2 fixed by cowpea are given in Table VII. Percent N derived from fertilizer (%Ndff) in cowpea was in the range of 3.9 to 4.5, that from soil (%Ndfs) 32 to 36, and fixation accounted for 60 to 65%. During 1999, the fixed N uptake was about 80 kg ha^{-1}, during 2000 it was 90 kg ha^{-1} and in the last year (2001), it was about 75 kg ha^{-1}.

Table IV. Yield, nitrogen content and uptake by cowpea (1999) grain and straw as influenced by nitrogen and phosphorus treatments to previous crops of mustard or wheat

Treatment	Previous crop											
	Mustard		Wheat		Mustard		Wheat		Mustard		Wheat	
	Yield				N content				N uptake			
	Grn	Strw	Grn	Strw	Grn	Str	Grn	Str	Grn	Str	Grn	Str
	(Mg ha^{-1})				(%)				(kg ha^{-1})			
N_0P_0	1.17	3.67	1.15	3.71	4.2	2.0	4.2	2.0	49.4	72.2	47.8	73.6
N_0P_1	1.21	3.63	1.18	3.67	4.4	1.9	4.2	2.0	53.4	70.2	49.2	72.6
N_0P_2	1.21	3.69	1.19	3.72	4.3	2.0	4.2	2.0	51.6	72.3	49.7	72.5
N_1P_0	1.20	3.69	1.18	3.73	4.2	2.0	4.3	2.0	51.0	71.8	50.0	74.2
N_1P_1	1.20	3.69	1.18	3.73	4.2	2.0	4.0	2.0	50.3	72.4	47.5	73.1
N_1P_2	1.23	3.71	1.20	3.74	4.2	2.0	4.2	1.9	51.4	74.0	50.4	72.5
N_2P_0	1.24	3.65	1.21	3.69	4.2	2.0	4.2	2.0	52.6	71.5	51.3	72.6
N_2P_1	1.24	3.70	1.22	3.73	4.3	2.0	4.2	2.0	53.6	73.6	51.0	74.4
N_2P_2	1.25	3.78	1.22	3.81	4.2	2.0	4.1	2.0	52.7	75.3	50.4	75.4
	C.D. at 5%											
N	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
P	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
N × P	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Table V. Yield, nitrogen content and uptake by cowpea (2000) grain and straw as influenced by nitrogen and phosphorus treatments to previous crops of mustard and wheat

Treatment	Previous crop											
	Mustard		Wheat		Mustard		Wheat		Mustard		Wheat	
	Yield				N content				N uptake			
	Grn	Str	Grn	Str	Grn	Str	Grn	Str	Grn	Str	Grn	Str
	(Mg ha^{-1})				(%)				(kg ha^{-1})			
N_0P_0	1.35	3.96	1.27	4.01	4.4	2.0	4.3	2.1	59.0	79.7	54.5	82.1
N_0P_1	1.33	3.92	1.32	4.02	4.6	2.0	4.3	2.0	61.3	77.8	56.7	82.0
N_0P_2	1.32	4.03	1.38	4.05	4.4	2.0	4.4	2.0	57.9	81.5	59.8	81.5
N_1P_0	1.34	4.04	1.38	4.07	4.4	2.00	4.4	2.1	58.6	80.8	60.9	83.6
N_1P_1	1.29	4.02	1.35	4.03	4.3	2.0	4.2	2.0	55.9	81.1	56.5	81.7
N_1P_2	1.29	4.06	1.42	4.03	4.3	2.1	4.3	2.0	56.0	83.9	61.5	80.8
N_2P_0	1.35	4.12	1.43	4.04	4.4	2.0	4.4	2.0	59.3	82.7	62.7	83.3
N_2P_1	1.31	4.18	1.26	4.12	4.5	2.1	4.3	2.1	58.5	85.7	54.7	84.8
N_2P_2	1.29	4.25	1.38	4.20	4.4	2.1	4.3	2.0	56.6	87.7	59.1	85.7
C.D. at 5%												
N	NS	0.08	NS	0.07	NS	NS	NS	NS	NS	2.39	NS	1.73
P	NS	NS	NS	NS	NS	0.03	NS	NS	NS	2.39	NS	NS
N × P	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Table VI. Yield, nitrogen content and uptake by cowpea (2001) grain and straw as influenced by nitrogen and phosphorus treatments to previous crops of mustard and wheat

Treatment	Previous crop											
	Mustard		Wheat		Mustard		Wheat		Mustard		Wheat	
	Yield				N content				N uptake			
	Grn	Str	Grn	Str	Grn	Str	Grn	Str	Grn	Str	Grn	Str
	(Mg ha^{-1})				(%)				(kg ha^{-1})			
N_0P_0	1.11	3.52	1.16	3.53	4.6	1.9	4.5	2.0	50.4	67.9	51.6	69.0
N_0P_1	1.16	3.29	1.20	3.44	4.6	2.0	4.6	2.1	52.8	65.9	54.7	72.1
N_0P_2	1.20	3.48	1.23	3.40	4.6	1.9	4.5	1.9	55.0	67.4	55.1	66.0
N_1P_0	1.18	3.52	1.17	3.50	4.5	2.0	4.5	2.1	53.3	69.2	52.4	71.9
N_1P_1	1.21	3.56	1.17	3.40	4.6	2.1	4.5	2.0	55.1	72.1	52.9	67.2
N_1P_2	1.21	3.39	1.14	3.33	4.5	2.0	4.5	1.9	54.8	67.8	51.0	64.5
N_2P_0	1.18	3.57	1.14	3.51	4.5	2.0	4.6	2.0	53.3	71.7	52.2	69.8
N_2P_1	1.16	3.45	1.18	3.55	4.6	2.0	4.5	2.0	53.1	68.2	53.0	69.8
N_2P_2	1.21	3.35	1.16	3.56	4.5	2.1	4.6	2.0	54.4	69.6	53.2	72.6
C.D. at 5%												
N	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
P	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
N × P	NS	NS	NS	NS	NS	NS	NS	0.10	NS	NS	NS	4.56

Table VII. Sources of nitrogen for cowpea

Parameter/ Source	1999				2000				2001			
	Previous crop											
	Mustard		Wheat		Mustard		Wheat		Mustard		Wheat	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
%Ndff[a]	4.5	0.24	4.5	0.07	4.4	0.18	4.7	0.09	3.9	0.11	3.9	0.03
%Ndfs	32	0.73	31	1.4	31	2.8	33	2.1	36	2.0	36	1.1
%Ndfa	64	0.74	64	1.4	65	3.0	63	2.1	60	2.0	60	1.1
Total N (kg ha^{-1})	125	2.17	123	1.31	140	2.91	142	2.98	127	7.18	120	3.54
Fert. N (kg ha^{-1})	5.63	0.21	5.51	0.06	6.15	0.22	6.65	0.15	5.02	0.34	4.72	0.11
Soil N (kg ha^{-1})	39.4	0.82	38.7	1.96	43.3	3.60	46.7	2.85	45.5	4.14	42.8	2.00
Fixed N (kg ha^{-1})	80.3	2.24	78.7	0.83	90.4	5.49	89.0	3.98	76.6	4.20	72.6	2.28

[a] %N derived from fertilizer, soil and fixation (air), respectively.

Table VIII. Effects of applied nitrogen and phosphorus on wheat grain yield

Season	P treat.	N treatment			Mean	Factor	SEM (±)	C.D. at 5%
		N_0	N_{40}	N_{80}				
		(q ha^{-1})						
1998–1999	P_0	5.45	10.7	14.4	10.2	*N*	0.14	0.40
	P_{20}	7.32	11.9	16.1	11.8	*P*	0.14	0.40
	P_{40}	8.19	13.7	17.8	13.2	$N \times P$	0.24	NS
	Mean	6.98	12.1	16.1				
1999–2000	P_0	5.33	7.04	10.7	7.70	*N*	0.09	0.25
	P_{20}	5.81	7.33	11.5	8.21	*P*	0.09	0.25
	P_{40}	5.86	10.3	12.1	9.41	$N \times P$	0.15	0.44
	Mean	5.67	8.22	11.4				
2000–2001	P_0	5.26	10.5	14.2	9.98	*N*	0.16	0.46
	P_{20}	6.86	12.3	16.9	12.0	*P*	0.16	0.46
	P_{40}	8.74	14.2	18.9	13.9	$N \times P$	0.28	0.80
	Mean	6.95	12.3	16.6				
2001–2002	P_0	4.41	9.03	10.5	7.98	*N*	0.12	0.35
	P_{20}	5.61	9.88	13.1	9.53	*P*	0.12	0.35
	P_{40}	6.33	11.1	13.8	10.4	$N \times P$	0.21	0.61
	Mean	5.45	10.0	12.5				

4.2. Wheat and mustard

4.2.1. Wheat

There was wide variation in germination percentage and dry-matter yields at Z30 amongst replications. Nitrogen and P contents were higher in the N- and P-fertilized treatments during the first two years. However, during the third and fourth years these differences were very much less as the wheat was sown without tillage operation and cowpea-stover residues were retained to conserve moisture. Grain yield was significantly influenced by N and P applications (Table VIII). Grain-N content also showed an increasing trend with N and P applications, but straw N content increased only at the higher level of N. During the second year, the grain yield was much lower than in the first year, mainly because of less winter rainfall: only 42.5 mm compared to 130 mm in 1998–1999.

In the third and fourth years, winter rains were much less than the seasonal average of 75 mm as in the second year (1999–2000). However, even then, both crops showed good growth and production especially with application of both N and P (Tables VIII and XIV). The highest wheat grain yield of 1.89 Mg ha^{-1} was obtained with 80 kg N ha^{-1} and 40 kg P_2O_5 ha^{-1}. Moisture retention in the soil profile also was much higher compared to the previous two years, as a result of minimum tillage and mulching. Neutron-probe data indicated very little loss of water, consistent with visual observations from mid-December to end of January: the stover mulch was wet, particularly as a result of conservation of overnight dew.

Tables IX to XII show trends in increasing total-N, total-P, uptake of fertilizer N and P as well as use efficiency of fertilizer N and fertilizer P similar to those observed with wheat grain yields in response to applications of increasing levels of N and P.

Total N and fertilizer N uptake by wheat grain (from 9.10 to 24.7 kg ha^{-1}) and in wheat straw (from 4.10 to 10.6 kg ha^{-1}) were significantly increased by N and P application. The fertilizer-N recovery ranged from 14 to 26% (Table X), and was higher with the lower level of N application. The application of P significantly increased the fertilizer-N recovery. The fertilizer-N-use efficiency in the second year was nearly half that of the first year mainly due to less favourable soil-moisture conditions, resulting in significant declines in grain and total dry matter yields. However, in the third and fourth years due to soil-moisture conservation from mulching and minimum tillage, there were significant increases in wheat grain yields and, consequently, in N and P uptake; use efficiencies of fertilizer N and P were also increased.

Residual fertilizer N in the soil after wheat harvest was between 65% and 75% and it is presumed that the remaining 9.4 to 11% was lost by ammonia volatilization; no ^{15}N could be traced below a depth of 15 cm, except in the first year when some fertilizer N was leached to 15 to 30 cm as a result of higher rainfall.

Table IX. Effects of applied nitrogen and phosphorus on total nitrogen uptake by wheat

Season	P treat.	N treatment			Mean	Factor	SEM (±)	C.D. at 5%
		N_0	N_{40}	N_{80}				
		(kg N ha^{-1})						
1998–1999	P_0	13.7	28.4	39.8	27.3	*N*	0.77	2.24
	P_{20}	18.9	33.7	49.0	33.9	*P*	0.77	2.24
	P_{40}	21.5	38.1	53.4	37.7	*N × P*	1.34	NS
	Mean	18.0	33.4	47.4				
1999–2000	P_0	13.2	19.7	29.6	20.8	*N*	0.34	0.99
	P_{20}	15.1	20.9	33.0	23.0	*P*	0.34	0.99
	P_{40}	16.0	27.2	35.2	26.1	*N × P*	0.59	1.71
	Mean	14.8	22.6	32.6				
2000–2001	P_0	12.6	26.2	37.5	25.4	*N*	0.42	1.20
	P_{20}	17.2	30.1	43.8	30.4	*P*	0.42	1.20
	P_{40}	21.0	36.6	50.3	36.0	*N × P*	0.72	NS
	Mean	16.9	31.0	43.9				
2001–2002	P_0	12.0	23.5	30.8	22.1	*N*	0.30	0.87
	P_{20}	14.9	25.5	36.6	25.7	*P*	0.30	0.87
	P_{40}	17.1	29.7	39.4	28.7	*N × P*	0.52	1.50
	Mean	14.7	26.3	35.6				

Table X. Effects of applied nitrogen and phosphorus on fertilizer-nitrogen recovery by wheat

Season	P treat.	N treatment			Mean	Factor	SEM (±)	C.D. at 5%
		N_0	N_{40}	N_{80}				
		(%)						
1998–1999	P_0	–	31	24	28	N	0.72	2.13
	P_{20}	–	38	30	34	P	0.88	2.61
	P_{40}	–	44	34	39	$N \times P$	1.24	NS
	Mean	–	38	29				
1999–2000	P_0	–	18	14	16	N	0.29	0.85
	P_{20}	–	19	16	18	P	0.35	1.04
	P_{40}	–	26	18	22	$N \times P$	0.50	1.48
	Mean	–	21	16				
2000–2001	P_0	–	29	22	26	N	0.43	1.27
	P_{20}	–	33	26	30	P	0.52	1.56
	P_{40}	–	42	31	36	$N \times P$	0.74	2.20
	Mean	–	35	26				
2001–2002	P_0	–	24	17	20	N	0.36	1.08
	P_{20}	–	26	20	23	P	0.44	1.32
	P_{40}	–	32	23	27	$N \times P$	0.63	NS
	Mean	–	27	20				

Table XI. Effects of applied nitrogen and phosphorus on total phosphorus uptake by wheat

Season	P treat	N treatment			Mean	Factor	SEM (±)	C.D. at 5%
		N_0	N_{40}	N_{80}				
		(kg P_2O_5 ha^{-1})						
1998–1999	P_0	4.71	9.16	12.3	8.73	N	0.26	0.74
	P_{20}	7.79	12.6	19.6	13.3	P	0.26	0.74
	P_{40}	9.37	15.2	22.1	15.6	$N \times P$	0.44	1.29
	Mean	7.29	12.3	18.0				
1999–2000	P_0	4.91	7.18	9.89	7.33	N	0.15	0.44
	P_{20}	6.62	9.17	14.2	9.98	P	0.15	0.44
	P_{40}	7.40	12.1	15.5	11.7	$N \times P$	0.26	0.76
	Mean	6.31	9.48	13.2				
2000–2001	P_0	5.63	11.4	15.3	10.8	N	0.27	0.77
	P_{20}	9.03	15.5	23.2	15.9	P	0.27	0.77
	P_{40}	11.5	19.1	27.0	19.2	$N \times P$	0.46	1.33
	Mean	8.73	15.3	21.9				
2001–2001	P_0	5.21	10.1	12.9	9.41	N	0.15	0.43
	P_{20}	7.41	13.2	18.7	13.1	P	0.15	0.43
	P_{40}	9.53	14.6	21.6	15.2	$N \times P$	0.26	0.74
	Mean	7.38	12.7	17.7				

The P contents of wheat grain and straw were influenced by N and P application and increased with increasing levels of each (Tables X and XI). The interaction of N and P application on P content of wheat grain was positive. Total P uptake by wheat ranged from 4.70 to 22.1 kg P_2O_5 ha^{-1} and from 0.37 to 1.23 kg P ha^{-1} came from fertilizer. Fertilizer-P recovery by wheat ranged from 3.0 to 22% and increased significantly with increasing levels of applied N. Fertilizer P recovery was between 7.2 and 14% at 20 kg P_2O_5 ha^{-1} and between 5.1 to 12% at 40 kg P_2O_5 ha^{-1}. Fertilizer-P recovery by wheat was significantly influenced by an N × P interaction. However, during the second year, like all other parameters, fertilizer P recovery was low. In the third and fourth years, there were significant increases in the fertilizer-P-use efficiency, with rainfall more or less similar to that of the second year, mainly because of the water-conservation effects of the cowpea stover mulch and minimum tillage. Consumptive water-use efficiencies in the third and fourth years were some 50 to 100% greater than that observed in the second year (Table XIII).

Table XII. Fertilizer-phosphorus recovery by wheat

Season	P treatment	N treatment			Mean	Factor	SEM (±)	C.D. at 5%
		N_0	N_{40}	N_{80}				
		(%)						
1989–1999	P_{20}	5.5	9.96	16	10.6	N	0.25	0.73
	P_{40}	4.2	7.00	10	7.14	P	0.20	0.60
	Mean	4.8	8.48	13		$N \times P$	0.35	1.03
1999–2000	P_{20}	4.2	6.42	11	7.17	N	0.13	0.40
	P_{40}	3.0	5.18	7.0	5.08	P	0.11	0.32
	Mean	3.6	5.80	8.9		$N \times P$	0.19	0.56
2000–2001	P_{20}	6.2	12	22	13.5	N	0.45	1.33
	P_{40}	5.4	11	18	11.3	P	0.37	1.09
	Mean	5.8	12	20		$N \times P$	0.64	1.89
2001–2002	P_{20}	5.7	12	18	11.9	N	0.18	0.53
	P_{40}	4.8	8.9	15	9.48	P	0.14	0.43
	Mean	5.2	11	16		$N \times P$	0.25	0.74

Table XIII. Effects of applied nitrogen and phosphorus on water-use efficiency of wheat

Season	P treat	N treatment			Mean	Factor	SEM (±)	C.D. at 5%
		N_0	N_{30}	N_{60}				
		(kg/ha-mm)						
1998–1999	P_0	2.39	4.70	6.33	4.47	N	0.06	0.18
	P_{20}	3.21	5.23	7.08	5.17	P	0.06	0.18
	P_{40}	3.59	6.00	7.79	5.79	$N \times P$	0.10	NS
	Mean	3.06	5.31	7.06				
1999–2000	P_0	2.57	3.39	5.16	3.70	N	0.04	0.12
	P_{20}	2.79	3.53	5.53	3.95	P	0.04	0.12
	P_{40}	2.82	4.94	5.82	4.53	$N \times P$	0.07	0.21
	Mean	2.73	3.95	5.50				
2000–2001	P_0	2.64	5.29	7.22	5.05	N	0.08	0.24
	P_{20}	3.44	6.20	8.50	6.04	P	0.08	0.24
	P_{40}	4.40	7.17	9.53	7.03	$N \times P$	0.15	NS
	Mean	3.50	6.22	8.41				
2001–2002	P_0	2.50	4.93	6.55	4.86	N	0.07	0.21
	P_{20}	3.24	5.73	7.82	5.60	P	0.07	0.21
	P_{40}	4.09	6.60	8.69	6.46	$N \times P$	0.13	NS
	Mean	3.28	5.75	7.68				

Table XIV. Effects of applied nitrogen and phosphorus on seed yield of mustard

Season	P treat.	N treatment			Mean	Factor	SEM (±)	C.D. at 5%
		N_0	N_{30}	N_{60}				
		(q ha^{-1})						
1998–1999	P_0	4.15	7.63	10.8	7.53	N	0.13	0.36
	P_{15}	4.57	12.0	14.3	10.3	P	0.13	0.36
	P_{30}	4.56	13.2	14.00	10.6	$N \times P$	0.22	0.63
	Mean	4.43	11.0	13.0				
1999–2000	P_0	3.86	6.36	9.07	6.43	N	0.11	0.30
	P_{15}	4.08	9.88	11.3	8.41	P	0.11	0.30
	P_{30}	4.20	11.0	11.1	8.76	$N \times P$	0.18	0.53
	Mean	4.05	9.06	10.5				
2000–2001	P_0	4.53	8.25	11.9	8.23	N	0.13	0.39
	P_{15}	4.90	12.4	15.1	10.8	P	0.13	0.39
	P_{30}	5.12	13.8	15.9	11.6	$N \times P$	0.23	0.67
	Mean	4.85	11.5	14.3				
2001–2002	P_0	4.64	7.69	10.9	7.75	N	0.11	0.31
	P_{15}	5.04	11.7	13.7	10.2	P	0.11	0.31
	P_{30}	5.36	13.0	14.8	11.0	$N \times P$	0.19	0.54
	Mean	5.01	10.8	13.1				

4.2.2. Mustard

Mustard seed yields ranged from 3.90 to 15.9 q ha^{-1} and were significantly increased by application of both N and P (Table XIV). The mean effect of application of only 30 kg N ha^{-1} was an increase of more than 100% seed yield and with application at 60 kg N ha^{-1} it increased by nearly 200%. Seed yield also increased with P application and a positive N × P interaction affected seed yield. Stover yield was significantly influenced by N application only. Similar to wheat, mustard showed much better growth during the third and fourth years even though winter rains were less compared to those of the second year and were only about 50% of the long-term average. Seed yields were also higher than in the first year when winter rains were much higher than the average. Nitrogen and P applications significantly increased N contents in seed, stover and pod-husk (data not presented). Phosphorus contents in all parts of mustard were significantly increased by N or P application; however, only stover P content was significantly increased with both N and P applied.

There were significant increases in total N and P uptake with both N and P applications and their interaction was also statistically significant (Tables XV and XVII). The %Ndff values in various components of the mustard crop ranged from 33 to 42, and greater with the higher level of N (60 kg N ha^{-1}) (data not presented). Fertilizer-N uptake by mustard seeds ranged from 7.80 to 14.9 kg ha^{-1} at 30 kg N ha^{-1} and from 14.7 to 18.7 kg ha^{-1} at 60 kg N ha^{-1}; it was increased significantly by both N and P application (data not presented). Fertilizer-N recovery by mustard was 34 to 64% in the first year, 31 to 61% per cent in the second year, and during the third and fourth years very significant increases in the fertilizer-N-use efficiency were obtained, ranging between 37 to 76% a result of water conservation (Table XVI). Application of P significantly increased fertilizer-N recovery by the crop. This was primarily as a result of better exploitation of soil water even from deeper soil layers and consequently much higher uptake of nutrients—a similar trend prevailed in uptake of P.

The %Pdff values ranged from 18 to 32 and were higher in seed than in stover or pod-husk portions. The total fertilizer P recovered in the mustard was 6.00 to 31.9 kg ha^{-1} at 15 kg P_2O_5 ha^{-1} and 6.57 to 29.8 kg ha^{-1} at 30 kg P_2O_5 ha^{-1} (Table XVII). Nitrogen application showed a highly significant effect on percent recovery of fertilizer P, from as low as 5.2 in the second year with application of 30 kg P_2O_5 ha^{-1} at zero N to 32% at 15 kg P_2O_5 ha^{-1} with 60 kg N ha^{-1} application (Table XVIII).

Table XV. Effects of applied nitrogen and phosphorus on nitrogen uptake by mustard

Season	P treat	N treatment N_0	 N_{30}	 N_{60}	Mean	Factor	SEM (±)	C.D. at 5%
		(kg ha^{-1})						
1998–1999	P_0	19.2	34.8	52.2	35.4	*N*	0.96	2.79
	P_{15}	22.2	52.1	61.8	45.4	*P*	0.96	2.79
	P_{30}	21.3	56.3	60.4	46.0	*N* × *P*	1.66	4.83
	Mean	20.9	47.7	58.1				
1999–2000	P_0	17.6	31.1	45.4	31.4	*N*	0.53	1.53
	P_{15}	19.7	46.1	54.6	40.1	*P*	0.53	1.53
	P_{30}	20.4	50.9	55.5	42.3	*N* × *P*	0.92	2.66
	Mean	19.3	42.7	51.8				
2000–2001	P_0	22.2	39.0	59.2	40.1	*N*	0.60	1.74
	P_{15}	24.1	57.1	72.6	51.3	*P*	0.60	1.74
	P_{30}	25.4	63.1	75.3	54.7	*N* × *P*	1.04	3.01
	Mean	23.9	53.1	69.0				
2001–2002	P_0	21.4	35.2	53.5	36.7	*N*	0.55	1.59
	P_{15}	23.7	53.0	64.6	47.1	*P*	0.55	1.59
	P_{30}	26.3	59.1	70.7	52.1	*N* × *P*	0.95	2.75
	Mean	23.8	49.1	63.0				

Table XVI. Effects of applied nitrogen and phosphorus on fertilizer-nitrogen recovery by mustard

Season	P treat.	N treatment N_0	 N_{30}	 N_{60}	Mean	Factor	SEM (±)	C.D. at 5%
		(%)						
1998–1999	P_0	–	34	34	34	*N*	1.20	3.58
	P_{15}	–	55	42	48	*P*	1.47	4.38
	P_{30}	–	64	42	53	*N* × *P*	2.08	6.19
	Mean	–	51	39				
1999–2000	P_0	–	34	31	33	*N*	0.64	1.91
	P_{15}	–	54	38	46	*P*	0.79	2.34
	P_{30}	–	61	39	50	*N* × *P*	1.11	3.31
	Mean	–	49	36				
2000–2001	P_0	–	52	43	48	*N*	0.77	2.29
	P_{15}	–	70	54	62	*P*	0.95	2.81
	P_{30}	–	76	55	66	*N* × *P*	1.34	3.97
	Mean	–	66	50				
2001–2002	P_0	–	44	37	40	*N*	0.52	1.55
	P_{15}	–	62	45	54	*P*	0.64	1.90
	P_{30}	–	72	51	62	*N* × *P*	0.91	2.69
	Mean	–	59	44				

There was no influence of N and P application or the season on seed-oil content (Table XIX). However, total oil yield was significantly increased by graded increased N and P application and their interaction was also significant (Table XX). The application of 30 kg N ha^{-1} and 15 kg P_2O_5 ha^{-1} increased the oil yield by nearly 140%. Thus showing that even under adverse rainfed conditions, fertilizer application to mustard can have higher economic returns.

The balance-sheet of fertilizer N showed that less than 10% of the applied N could not be accounted for; 90% was accounted for either as taken up by the crop or residual in the soil (data not presented).

Table XVII. Effects of applied nitrogen and phosphorus on fertilizer-phosphorus uptake by mustard

Season	P treat.	N treatment			Mean	Factor	SEM (±)	C.D. at 5%
		N_0	N_{30}	N_{60}				
		(kg ha^{-1})						
1998–1999	P_0	5.08	8.08	13.0	8.73	N	0.31	0.89
	P_{15}	6.59	14.5	18.2	13.1	P	0.31	0.89
	P_{30}	6.86	16.5	18.9	14.1	$N \times P$	0.53	1.55
	Mean	6.18	13.1	16.7				
1999–2000	P_0	4.52	7.70	10.4	7.5	N	0.18	0.51
	P_{15}	6.00	12.4	15.3	11.2	P	0.18	0.51
	P_{30}	6.57	14.4	16.1	12.4	$N \times P$	0.31	0.89
	Mean	5.70	11.5	13.9				
2000–2001	P_0	11.1	15.4	22.1	16.2	N	0.65	1.90
	P_{15}	14.8	22.3	31.9	23.0	P	0.65	1.90
	P_{30}	16.3	26.3	29.8	24.1	$N \times P$	1.13	3.29
	Mean	14.1	21.3	27.9				
2001–2002	P_0	8.68	13.0	19.2	13.6	N	0.49	1.41
	P_{15}	13.2	19.9	26.5	19.9	P	0.49	1.41
	P_{30}	16.1	25.5	28.3	23.3	$N \times P$	0.84	2.45
	Mean	12.7	21.3	24.7				

Table XVIII. Effects of applied nitrogen and phosphorus on fertilizer-phosphorus recovery by mustard

Season	P treat.	N treatment			Mean	Factor	SEM (±)	C.D. at 5%
		N_0	N_{30}	N_{60}				
		(%)						
1998–1999	P_{15}	7.9	22	30	20	N	0.41	1.23
	P_{30}	5.8	15	19	13	P	0.34	1.01
	Mean	6.8	19	25		$N \times P$	0.59	1.74
1999–2000	P_{15}	6.8	18	24	16	N	0.38	1.14
	P_{30}	5.2	13	15	11	P	0.31	0.93
	Mean	6.0	15	19		$N \times P$	0.54	1.61
2000–2001	P_{15}	9.7	24	32	22	N	0.52	1.54
	P_{30}	7.4	19	23	16	P	0.42	1.26
	Mean	8.6	21	27		$N \times P$	0.74	2.18
2001–2002	P_{15}	7.6	19	25	17	N	0.19	0.56
	P_{30}	6.4	15	18	13	P	0.16	0.46
	Mean	7.1	17	225		$N \times P$	0.27	0.80

Table XIX. Effects of applied nitrogen and phosphorus on oil content of mustard seeds

Season	P treat.	N treatment			Mean	Factor	SEM (±)	C.D. at 5%
		N_0	N_{30}	N_{60}				
		(%)						
1998–1999	P_0	41	40	41	41	*N*	0.20	NS
	P_{15}	40	40	41	40	*P*	0.20	NS
	P_{30}	40	41	40	40	*N* × *P*	0.35	NS
	Mean	40	40	40				
1999–2000	P_0	41	40	41	41	*N*	0.20	NS
	P_{15}	40	40	41	40	*P*	0.20	NS
	P_{30}	40	41	40	40	*N* × *P*	0.35	NS
	Mean	40	40	40				
2000–2001	P_0	41	41	41	41	*N*	0.16	NS
	P_{15}	40	41	41	41	*P*	0.16	NS
	P_{30}	41	41	41	41	*N* × *P*	0.27	NS
	Mean	41	41	41				
2001–2002	P_0	41	41	41	41	*N*	0.08	NS
	P_{15}	41	41	41	41	*P*	0.08	NS
	P_{30}	41	41	41	41	*N* × *P*	0.15	NS
	Mean	41	41	41				

Table XX. Effects of applied nitrogen and phosphorus on yield of mustard oil

Season	P treat.	N treatment			Mean	Factor	SEM (±)	C.D. at 5%
		N_0	N_{30}	N_{60}				
		(kg ha^{-1})						
1998–1999	P_0	169	308	437	305	*N*	5.1	14.8
	P_{15}	181	486	580	416	*P*	5.1	14.8
	P_{30}	183	534	563	427	*N* × *P*	8.8	25.6
	Mean	178	443	527				
1999–2000	P_0	157	256	367	260	*N*	4.4	12.9
	P_{15}	162	399	457	339	*P*	4.4	12.9
	P_{30}	169	444	448	353	*N* × *P*	7.7	22.3
	Mean	163	366	424				
2000–2001	P_0	183	335	483	334	*N*	5.6	16.1
	P_{15}	198	509	612	439	*P*	5.6	16.1
	P_{30}	208	564	642	472	*N* × *P*	9.6	27.9
	Mean	197	469	579				
2001–2002	P_0	190	315	447	317	*N*	4.35	12.6
	P_{15}	206	482	565	418	*P*	4.35	12.6
	P_{30}	219	534	603	452	*N* × *P*	7.54	21.9
	Mean	205	443	538				

Table XXI. Effects of applied nitrogen and phosphorus on water-use efficiency by mustard

Season	P treat.	N treatment			Mean	Factor	SEM (±)	C.D. at 5%
		N_0	N_{30}	N_{60}				
		(kg grain/ha-mm water)						
1998–1999	P_0	2.01	3.70	5.24	3.65	*N*	0.06	0.18
	P_{15}	2.22	5.83	6.95	5.00	*P*	0.06	0.18
	P_{30}	2.21	6.39	6.79	5.13	*N* × *P*	0.11	0.31
	Mean	2.15	5.31	6.33				
1999–2000	P_0	2.83	4.66	6.66	4.72	*N*	0.08	0.22
	P_{15}	3.00	7.25	8.27	6.17	*P*	0.08	0.22
	P_{30}	3.08	8.03	8.17	6.43	*N* × *P*	0.13	0.39
	Mean	2.97	6.5	7.70				
2000–2001	P_0	3.57	6.44	9.56	6.52	*N*	0.16	0.46
	P_{15}	3.82	9.59	11.8	8.40	*P*	0.16	0.46
	P_{30}	3.96	10.8	12.4	9.05	*N* × *P*	0.27	0.79
	Mean	3.79	8.93	11.3				
2001–2002	P_0	3.15	5.21	7.46	5.27	*N*	0.09	0.25
	P_{15}	3.41	7.94	9.38	6.91	*P*	0.09	0.25
	P_{30}	3.61	8.87	10.0	7.50	*N* × *P*	0.15	0.43
	Mean	3.39	7.34	8.95				

4.2.3. Water-use efficiency

Water-use efficiency by mustard (Table XXI) was higher than by wheat (Table XIII). The neutron-probe data showed more soil-moisture depletion in the surface 30 cm under mustard than under wheat. Mustard also extracted much more water from deeper soil layers . Water use efficiency in mustard was 2.01 to 12.4 kg grain/ha-mm of water (Table XXI) compared to 2.39 to 9.53 kg grain/ha-mm of water in wheat (Table XIII).

Application of cowpea straw mulch and minimum tillage had very positive effects in conserving soil water (data not presented).

In mustard, positive correlations were obtained between $\delta^{13}C$ values in stover and water use efficiency, total and seed yield and total N uptake in the third and fourth years (data not presented). No such correlations were observed in wheat.

5. CONCLUSIONS

The increased production of winter-season crops under rainfed conditions solely on conserved moisture can be accomplished by employing appropriate management practices directed primarily towards soil-moisture retention and nutrient mobilization. The results of four years of experimentation revealed that the performance of both wheat and mustard in the first year (1998–1999) was good primarily due to higher and timely winter rainfall. In the second year (1999–2000), winter rainfall was much lower than average and occurred mainly towards the end of season; consequently, crops suffered. Although in the third and fourth years (2000–2001 and 2001–2002) the winter rainfall was even less than in the second year, due to application of straw mulch and minimum tillage, the soil retained moister longer and, although winter rains were poor they were timely, which helped establishment of good wheat and mustard crops, thus stronger responses to applied N and P were observed.

A critical appraisal of N input and output data reveals that mustard is much better adapted to utilize soil moisture and nutrients, particularly N, than is wheat. Nevertheless, negative N balances resulted even when the biological fixed of N by cowpea was taken into account. However, this negative balance was made positive by leaving the cowpea straw on the soil, which also resulted in better regulation of soil moisture and, probably, temperature.

The important point emerging from these four years of investigations was that nuclear techniques—to deduce applicable recommendations—need to be employed judiciously. High seasonal variability in crop growth suggested the need to employ computer-simulation models to arrive at recommendations. The primary factor for increasing the production in rainfed situations is better water management, and more attention needs to be directed at nutrient management.

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OPTIMIZATION OF WATER AND NUTRIENT USE BY MAIZE AND PEANUT IN ROTATION BASED ON ORGANIC AND ROCK PHOSPHATE SOIL AMENDMENTS

M. SENE
Centre National de Recherches Agricoles de Bambey,
Bambey, Senegal

A.N. BADIANE
Institut Sénégalais de Recherches Agricoles,
Dakar, Senegal

Abstract

A four-year nationwide project was initiated in 1997 to boost food and cash-crop production. Phosphorus and calcium from local mines were applied as mineral amendments and/or organic matter applications were made as strategies to optimize nutrient and water use by staple crops. The objective was to determine optimal balances between soil nutrients and water dynamics in degraded semi arid soil. A long-term experiment was installed at Nioro du Rip Research Station in 1997 within a corn–peanut cropping system in the Senegal peanut basin. The four treatments under comparison were: control with no P or Ca added, phosphogypsum and phosphate rock (PG-PR) at 1,000 kg/ha, manure at 5,000 kg/ha every two years, and PG-PR mix combined with manure. Data collected during the subsequent rainy seasons consisted of soil-fertility change, maize and peanut water balance, nitrogen (N)-use efficiency, $\Delta^{13}C$ values and yield components. Water-balance components (infiltration, evapotranspiration, storage and drainage) were obtained through weekly monitoring with a neutron probe to a depth of 4.3 m and tensiometers installed at depth ranges of 1.4 to 1.6 m. Nitrogen-15-labeled fertilizer was applied in 1999 and 2001 to determine fertilizer-N-use efficiency by maize. Moisture data indicated a rapid downward movement of the wetting front for all treatments. In dry soil conditions, volumetric water-content values increased from 0.1 m^3m^{-3} in the top horizon layer (0–10 cm) to 0.25 m^3m^{-3} at the depth of 1.0 m. In 2000, the water content below 1.0 m depth was high, with values at the bottom of the access tubes reaching 18% of the total rainfall. This trend was attributed to increasing clay content with profile depth coupled with less evaporative loss. Findings from this study indicate that water losses through evapotranspiration (approximately 50% of the effective annual rainfall) did not limit maize productivity in 1999 and 2001, or that of peanut in 2000. The current practice of applying PG-PR for soil-fertility maintenance did not appear to have a positive effect on maize and peanut yields over time; however, positive effects on soil chemical properties such as exchangeable Ca were noted, though of short duration due to leaching related to drainage water losses. Increased exchangeable Ca content and base saturation values in the soil profile were obtained as a result of the PR + PG mix, specifically in the top 30 cm from an initial mean value of 65% to a base saturation value of 90% in 1997 and 78% in 1999. This report provides a synthesis of pertinent results obtained during project implementation and serves to illustrate methodology in assessing soil-water dynamics, crop-water-use efficiency and soil-nutrient trends in the peanut basin for sustainable food productivity while protecting these vulnerable sandy soils.

1. INTRODUCTION

The challenge for agriculture over the next decades will be to meet the world's ever-increasing demand for food in a sustainable way. As noted in earlier studies, scarce water resources and declining soil fertility coupled with mismanagement of plant nutrients have made this task more difficult, especially in semi-arid ecosystems [1–3]. In the Senegal peanut basin, fallow practices have almost disappeared from farmers' land-use systems. This situation results from the introduction of peanut as a cash crop and also from increased demands for food crops by an increasing population. The enormously high pressure on these fragile soils — with extremely low inherent fertility combined with drought-associated problems observed over the past thirty years — is detrimental both to annual and to perennial vegetation cover. Degradation of these Sahelian soils results from erosion and continuously decreasing soil fertility closely tied to nutrient leaching, unreplenished nutrients removed in crop harvests and irrational soil-water-use strategies [4]. Similarly, Crosson [5] observed that in most farmers' fields, soil-water characteristics indicate deep percolation beyond crop-rooting depth, even under moderate rainfall conditions, which increases risk of nutrient leaching risks. Alarmingly, recent work by Henao and Baanante [6] suggested that nutrient mining may be accelerating [7]. Soil organic-matter losses and severe acidification due to continuous cropping and/or grazing are compromising the resilience of the food-production system.

The major constraints in this rain-fed cropping system can be characterized as two-fold:

- high frequency of crop-water stress due to spells of drought coupled with frequent temporary waterlogging,
- immense loss of soil fertility—organic matter decrease and acidification—caused by leaching and farmers' practices such as complete removal of crop residues.

The optimization of water and nutrient uptake is, therefore, a major task to achieve sustainable increases in crop production and, hence, realize food security. The underpinning task of this work was to achieve this objective. Based on the use of the available natural resources to restore soil fertility, one strategy implemented in this study was the utilization of locally available rock phosphate and organic matter (manure) as possible alternatives to chemical fertilizers to correct P and Ca deficiencies. However, there is a substantial knowledge vacuum regarding the agronomic potential of these by-products.

1.1. General objective

The general objective was to re-enforce the basis for sustainable increases in food-crop productivity for two main cropping systems within the peanut basin by optimizing crop-water and nutrient use, based on improved natural resource management.

The specific objectives were to:

- improve soil fertility by identifying and evaluating the most efficient methods of natural resource management based on a combination of organic and inorganic applications and soil tillage,
- evaluate crop water and nutrient use efficiencies,
- ascertain the long-term impact of imposed treatments on crop yield and soil fertility.

2. MATERIALS AND METHODS

2.1. Site location

The trial was initiated in 1997 at Nioro Agricultural Research Station (13°45.274' N, 15°47.203' W), Senegal. The soil at the experimental site is classified as an Alfisol (USDA taxonomy) with slope averaging 1% and pH values less than 5.4 in the top 30 cm.

2.2. Climate

The site is situated in a semi-arid zone with low unimodal rainfall-distribution characteristics, an annual precipitation average of about 650 to 700 mm, and a class-A pan evaporation of approximately 1,800 mm y^{-1}. The rainy season lasts from June to October. The mean maximum air temperature varies from 23°C to 42°C between January and May with a mean minimum temperature variation from 15°C to 28°C. Rainfall statistics for the past five years at Nioro station (Table I) confer two groups of rainfall conditions with the first two years as relatively dry with 650 mm in fifty-two events as opposed to the last three wet years with mean annual rainfall of 920 mm in sixty-four events. Ten rainfall events, each of over 30 mm have been recorded for each of the last three cropping seasons of the project duration.

Annual water balances were determined using neutron probes (Troxler 3222 and Troxler 4301). Aluminium access tubes were installed in this sandy clay soil to a depth of 4.3 m. Soil-water-profile monitoring was performed on a weekly basis from sowing to harvest and data were analyzed for three rainy seasons. Three replicates out of the four were equipped with access tubes for each of the four treatments, hence giving a total number of twelve tubes. Initial soil-water-profile values were obtained from mid-May readings under dry soil conditions. Tensiometers were installed at two depths (1.4 and 1.6 m) to estimate drainage water losses if the wetting front would go below 4.3 m, the maximum depth of access-tube installation.

2.3. Treatments

Continuous mineral fertilizer applications, with regular high rates of urea were applied once every two years to maize as a cereal crop with plot sizes of 15 × 6 m. Treatments and crop sequences are presented in Tables II and III, respectively. Phosphorus and Ca amendments were applied once every four years with hindsight to avoid over application [8,9]. The rate of 700 kg/ha of PG-PR in T2 and T4, applied in 1997, was increased to 1,000 kg/ha in 2000 to compensate for the small amount of P contained in PG. Manure was applied at 5,000 kg/ha once every two years to maize. Immediately after amendment applications, every two years, the soil was ploughed to a depth of 20 cm to enhance incorporation.

In the 1999 rainy season, $^{15}N^{1}$-urea (5.4% a.e.) was applied to maize at a rate of 212 kg N/ha. In the 2001 rainy season, N-use efficiency (NUE) was evaluated for maize by application of ^{15}N-urea (1% a.e.) applied on July 23 and August 24, 2001, in equal amounts.

The maize/peanut rotation was set out in a completely randomized block design. Details of fertilizer applications are elucidated in Table IV. NPK applications were made at sowing then 7 to 10 days after sowing for peanut, and at the weeding and thinning stages for maize.

Table I. Rainfall at Nioro Agricultural Research Station, 1997–2001

Detail	1997	1998	1999	2000	2001
Annual rainfall (mm)	617	682	979	978	814
Number of rainfall events	59	46	75	56	60
Beginning of rainy season	June 5	July 21	June 27	June 13	June 8
End of rainy season	Oct 12	Oct 12	Oct 17	Oct 18	Oct 11

Table II. Treatments

Designation	Description
T1	Plowing (P) + Fertilizer N and K applied at recommended rate for crops (P + NK)
T2	P + NK + 50% phosphogypsum (PG) and 50% Taïba phosphate rock (PR) mix at 1,000 kg/ha: (P + NK + PG-PR)
T3	P + NK + manure at the rate of 5 t/ha added once every two years, in 1997 and in 1999 (P + NK + M)
T4	P + NK + PG-PR + M

Table III. The maize/peanut rotation

Year	Crop sequence	Variety/Cycle duration (days)
1997	Ma-P-Ma-P-Ma	Maize: 'Synthetic C' (90) in1997; 'Pool' (86–90) in 1999 and 2001 Peanut: '73-33' (110)

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[1] Provided by the project for cereal crops (5.4 % a.e.).

Table IV. Fertilizer applications

Crop	N	P_2O_5	K_2O	First ^{15}N-urea application	Second ^{15}N-urea application
	(kg/ha)				
Maize[a]	18	30	15	100	100
Peanut	9	30	15	—	—

[a] In 1999, urea was applied to maize at 212 kg N/ha.

3. RESULTS AND DISCUSSION

3.1. Changes in soil-profile water content: the wetting front

The 1999 rainy season was characterized by a large amount of early, evenly distributed rainfall. Consequently, field operations like ox ploughing and fertilizer and organic matter applications, as well as maize sowing, were conducted under optimum conditions. On the sowing date, July 7, 7 days after the first rainfall event (Table I), a total rainfall of 189 mm was recorded. Soil-water monitoring, using a neutron probe and tensiometers, indicated a rapid downward movement of the wetting front regardless of treatment (Fig. 1) The wetting front was located at 1.30 m on the sowing date yet the estimated maximum maize rooting depth where drainage losses were expected to occur was at 1.5 m. In late September, the wetting front had gone below 4.3 m, the depth of access-tube installation. This resulted in important drainage implications that are later accounted for in the soil-water-balance components.

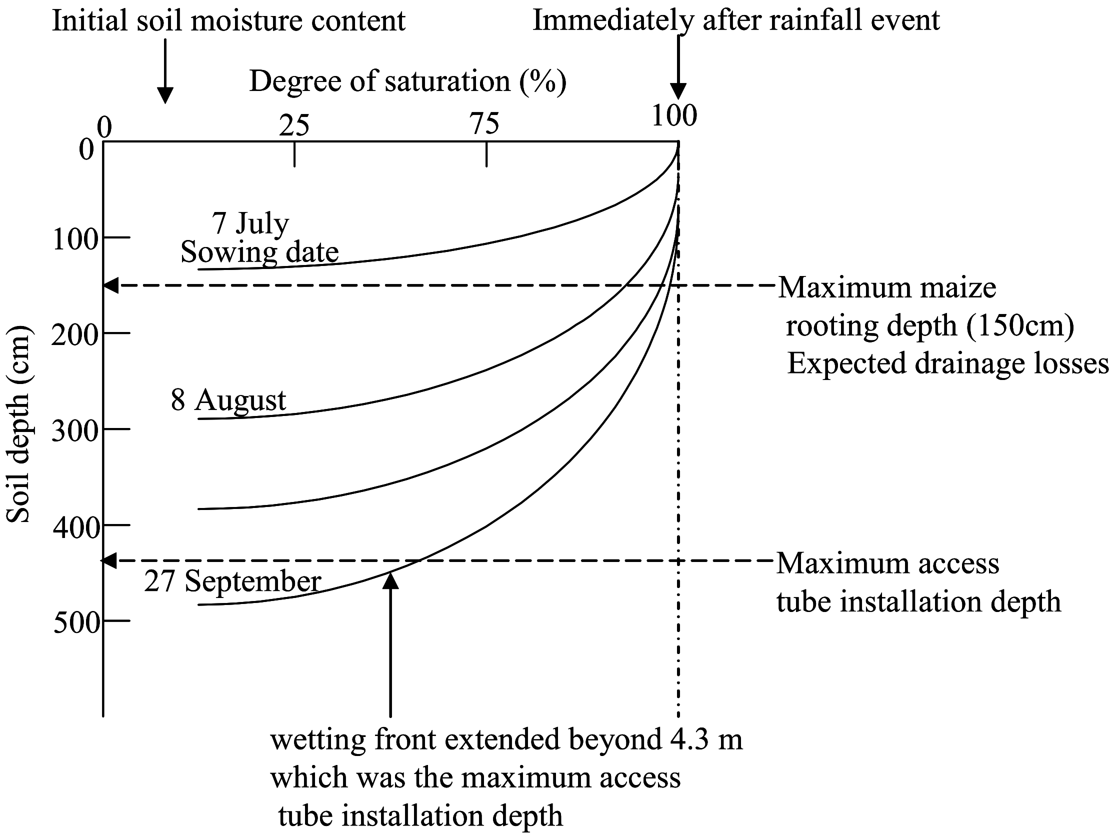

FIG. 1. Variation of the wetting front in the maize trial, 1999.

In 2000, peanut was sown in mid-July when the wetting front for all treatments was located between 0.5 and 0.7 m. For most plots, maximum peanut rooting depth (i.e. 1.5 m) was reached between August 8 and August 14. Deep percolation increased and reached the tube base (4.3 m depth) as early as mid-September. In fact, for all twelve access tubes, drainage water was observed on September 27. Consequently, drainage water was determined by use of the mass-conservation equation for the time period when the wetting front dropped below 1.5 m, i.e. from August 8 to September 27.

In the 2001 cropping season, maize was sown on June 26 when the wetting front was located between 0.6 and 0.7 m, regardless of treatment, which corresponded to a total rainfall of 792 mm. The maximum maize rooting depth of 1.5 m had already been reached on July 23 when the recorded rainfall totalled 682 mm. For all treatments, the wetting front was between 3.5 and 4.0 m on August 28 and went below 4.3 m 1 week later. In summary, there is evidence of drainage-water losses in the past three years on this on-station experimental site, which need to be taken into account.

In dry soil conditions, water-content values increased from 2% on the top layer to 9 to 10% at a depth of 1.0 m. In 2000, the water content below 1.0 m was high, with values reaching 18% at the bottom of the access tubes. This trend followed the clay content in the profile. Changes in water-content were closely related to rainfall distribution and crop development. The largest water content variation was observed within the 0- to 0.50-m top layer which had a maximum value of 22% in mid-July of 1999, 23% in mid-September, 2000, and 18% in mid-July of 2001. In deeper horizons (>1.5 m), water content ranged between 15% and 20% in 1999, between 17% and 25 % in 2000, and between 15% and 22% in 2001. This confirmed the high amount of infiltrated water in the soil profile. It must be emphasized that no treatment effects were noted in 1999 or in 2000. Results from the daily tensiometer measurements at 1.4 m and 1.6 m depth depicted total hydraulic head changes with gradient values that indicated a downward water movement (data not shown).

3.2. Soil-water components

These components included rainfall (R), water storage (S) for which the variation (ΔS) at 1.5 m depth between two subsequent dates of neutron-probe readings was computed, drainage water (D), and evapotranspiration water (ETR). For maize in 1999–2001 and for peanut in 2000, mean values for soil-water balance were determined for the four treatments at maturity (Table V, Fig. 2).

In 1999, drainage started early in the maize growing season, thirty days after sowing (DAS). Drainage water represented approximately 15% of the total rainfall. This fraction increased to 45% for T1, T2 and T3 and to 36 % for T4. Maize water use was higher for the high input treatment (T4). However, water requirements for all treatments were met during the respective phenological phases**.**

Table V Water-balance components at maturity for maize and peanut

Component	Treatment	Maize in 1999	Peanut in 2000	Maize in 2001
		(mm)		
Annual R		711	821	792
Drainage	Control	300	356	166
	PG-PR	347	352	208
	Manure (M)	324	331	158
	M + PG-PR	254	328	150
ETR	Control	397	403	417
	PG-PR	348	393	378
	Manure (M)	377	421	438
	M + PG-PR	435	413	431

For peanut planted in 2000, unlike maize planted in 1999, no drainage water was observed for any treatment at 10 DAS (Fig. 2). At 24 DAS, after 167 mm of rainfall, drainage was observed on all treatments, but with little in the high-input treatment (only 3.3 mm compared to a mean value of 20 mm for the control). In other words, the combination of PG-PR mix and manure had a positive effect on drainage control early in the growing season. But this effect tended to disappear later in the season. At mid-cycle (data not shown), total drainage water represented 34%, 32%, 30% and 28% of total rainfall recorded for control, PG-PR mix, manure and manure plus PG-PR mix, respectively.

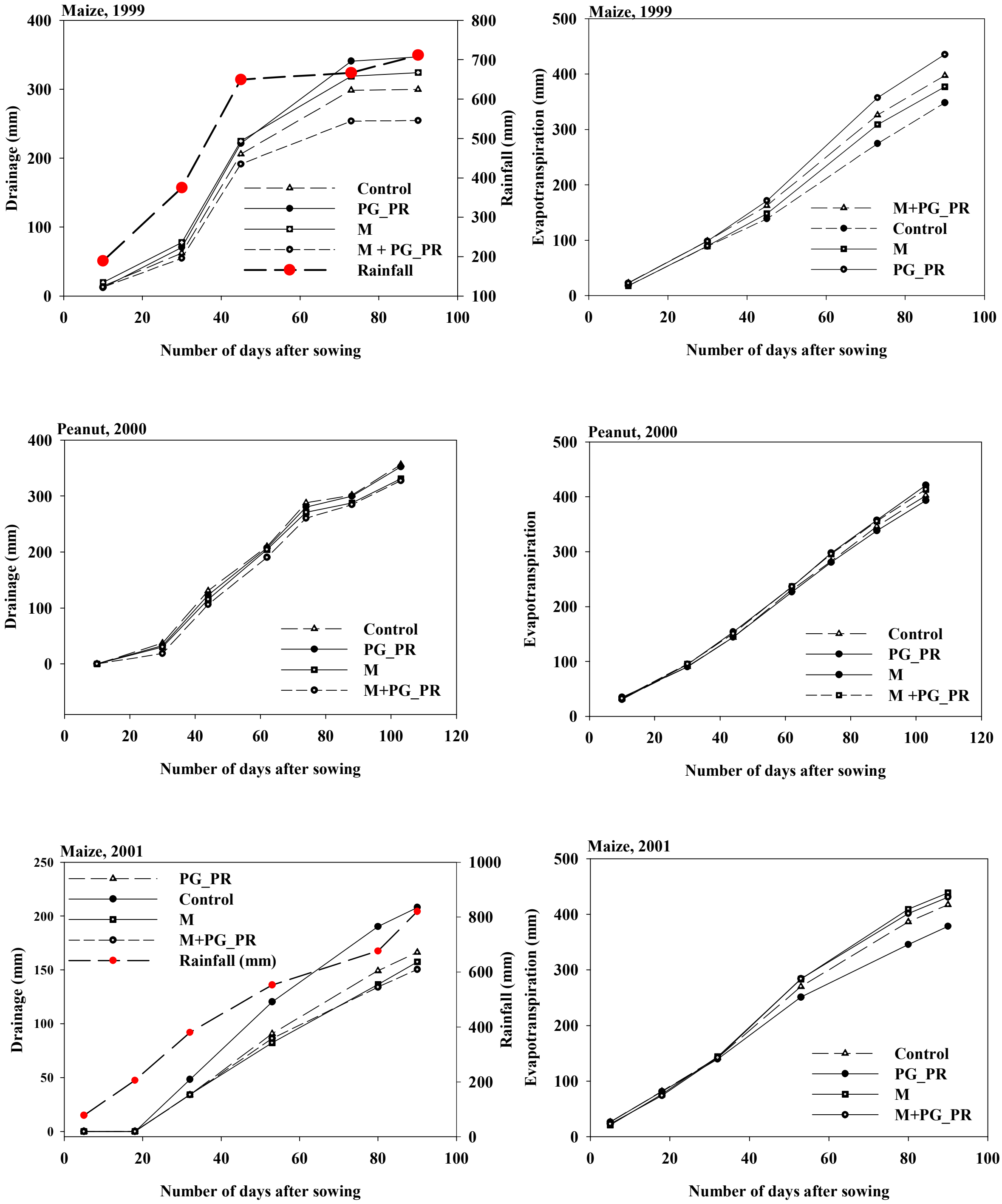

FIG. 2. Drainage and evapotranspiration water losses at harvest for maize in 1999 and 2001 and peanut in 2000.

At harvest, drainage values were similar and accounted for about 40% of annual rainfall. No treatment effect was found on ETR during the cropping season, except for the period between 24 and 30 DAS, when mean daily ETR dropped to 2.8 mm/d due to little rainfall input (only 37 mm were recorded). Peanut water needs were met for all treatments throughout the cropping season. At harvest, annual ETR went from a minimum mean value of 393 mm for PG-PR to a maximum mean value of 421 mm for the manure treatment. The mean ETR value represented about 49% of total rainfall. For maize in 2000, no drainage water loss was observed up to 20 DAS. After 30 DAS, drainage water losses occurred for all treatments and were higher for PG-PR than for the other three treatments including the control. ETR for the PG-PR treatment was lower towards maize maturity. At harvest, ETR for PG-PR was 12% lower than for the manure treatment.

3.3. Water uptake

Drainage losses and crop evapotranspiration variations from sowing to harvest at plant maturity as related to soil amendments for maize in 1999 and 2001, and peanut in 2000, are shown in Fig. 2. For maize in 1999, combining manure, rock phosphate and phosphogypsum mitigated such losses, and, correspondingly, maize evapotranspiration from around 45 DAS up to harvest, as compared to the control or the other treatments. For maize in 2000, no treatment effects were observed on these two water-loss components, whereas maize in 2001 showed a trend similar to that observed in 1999. For both crop years, rain water was less efficiently used when phosphogypsum was applied.

3.4 Dynamics of soil chemical characteristics three years after amendment applications

Soil-analyses results obtained from samples collected immediately after maize harvest in 1997 and 1999 are presented in Table VI. There was no observed treatment effect on measured pH values; severe soil acidity problems still prevailed. However, due to an increase in exchangeable Ca in the soil profile as a result of the PR and PG mix, there were increases in the base-saturation values, especially for the upper layer of the profile. From the initial mean value of 65%, the base-saturation value increased up to 90% in 1997 and to 78% in 1999. Despite the second manure application in 1999, no effect on soil organic matter was observed.

Table VI. Soil chemical analyses after maize harvest in 1997 and 1999

Treatment	Depth (cm)	pH$_{(water)}$		pH$_{(KCl)}$		Exch. Ca (mg/kg)		Base saturation (%)	
		1997	1999	1997	1999	1997	1999	1997	1999
Control	0–10	5.0	5.4	4.4	4.5	0.5	0.2	73	69
	10–20	5.2	5.4	4.3	4.4	0.5	0.3	77	63
	20–40	5.0	5.5	4.2	4.5	0.7	0.5	78	72
PG-PR	0–10	5.2	—	4.6	—	0.7	—	90	—
	10–20	4.9	—	4.3	—	0.6	—	85	—
	20–40	4.9	—	4.2	—	0.8	—	83	—
Manure	0–10	5.7	—	5.0	—	0.6	—	94	—
	10–20	5.3	—	4.3	—	0.5	—	77	—
	20–40	5.0	—	4.2	—	0.7	—	67	—
PG-PR + manure	0–10	5.3	5.5	4.9	4.6	0.8	0.3	84	76
	10–20	5.1	5.5	4.5	4.5	0.6	0.4	74	80
	20–40	5.0	5.2	4.3	4.3	0.8	0.6	73	75

3.5 Effect of P and Ca amendments on yields

The effects of P and Ca amendments on maize yields in 1997, 1999 and 2001, as well as on peanut in 1998 and 2000, are presented in Table VII. There was wide variation among plots within treatments as indicated by the large coefficients of variation (CVs). Low maize-yield values obtained in 1997 and 1999 are indicative of the low soil fertility; they were not linked to water-related problems since the annual rainfall (Table I) suggests that the profile was not water-limited. Treatment effects were significant on crop yield in 1999, but not in 1997 of 1998. In 1999, the PG-PR mix at 1,000 kg/ha did not significantly improve stover or grain yield over the control.

A positive effect on maize yield was associated only with the application of manure. Similar findings have been highlighted in numerous studies on soil organic matter [10, 11]. On a more positive note, maize yields have also been reported to rise from 1.0 to 1.7 metric tons [7]. In our study, manure alone or associated with PG-PR mix gave a 100% yield increase. Gerner and Baanante [12] have reported analogous effects in their work on phosphate rock application in West African agriculture.

In 2000, the PG-PR mix had no positively significant effect on pod or hay yields. Compared to the control, this treatment tended to have negative effects. Manure alone or combined with PR and PR mix significantly increased pod and hay yields. Compared to PG-PR, manure gave a 100% increase in pod yield. The lowest hay yield was observed with the PG-PR mix. These results indicate the poor performance of the residual effect of PG-PR on peanut yield. The PG-PR mix did not improve soil fertility (Table VII). As mentioned above, soil pH remained fairly low even with application of PG-PR. Aluminium toxicity, which was exacerbated by Ca leaching with time, could be implicated in the poor yields of hay and pods. In 2001, PG-PR mix had significant effects on grain and straw yields. Significant yield increases were obtained only with manure alone or in combination with PG-PR mix (Table VII).

3.6. Water-use efficiency

With water and soil resources being finite, the only option for increasing biomass production in rainfed semi-arid agricultural systems is to increase the water productivity [7], i.e. the water-use efficiency (WUE), by producing more biomass per unit of water. This is clearly illustrated by using Gregory's [13] definition of WUE [Eq (1)], based on the actual rainwater supplied (yield per unit of water supplied), which takes into account all the water flows of the hydrological cycle involved in biomass production. This expression of WUE is motivated by the large water losses in semi-arid ecosystems due to the erratic and unpredictable rains combined with physically fragile, crust-prone soils, which result in large water "losses" in the form of surface runoff and deep percolation.

$$WUE = \frac{Y/T}{1 + (E + S + D)/T} \tag{1}$$

where

Y is yield (kg/ha),
S is surface runoff (mm),
T is transpiration (mm),
D deep percolation (mm),
E is evaporation (mm).

Based on estimated maize water use and yield values, mean WUE values were determined for 1999 and 2001 for each of the treatments, as well as WUE for peanut in 2000 (Table VIII). In 1999, differences in maize WUE values between treatments were similar to those obtained for maize yield (Table VII). Compared to the control treatment, manure application at the rate of 5 t/ha every two years, alone or combined with PG-PR mix application at a rate of 1 t/ha once every four years increased grain or straw yields by two fold. WUE values for the control were 2 kg/ha/mm and 2.15 kg/ha/mm for grain and straw, respectively, as compared to a value of 4 kg/ha/mm/ when manure was applied.

For peanut in 2000, WUE was much lower for pods than for hay; for each treatment, hay WUE values were at least twice those of pods. Regarding pod and hay yield values, the PG-PR application had a negative effect as reflected in the exceptionally low WUE values of 1.97 and 4.4. Compared with mineral-fertilizer applications (control and PG-PR treatments), manure application, alone or in combination with PG-PR, improved pod WUE significantly. For hay, the application of PG-PR resulted in a significant decrease in WUE as compared to the control; the effect was similar to that of manure. Maize WUE values in 2001 were low compared to those determined in 1999. This was partly due to the low yields obtained for all treatments except PG-PR + manure.

Table VII. Soil amendment effects on maize and peanut yields

Treatment	Maize 1997		Peanut 1998		Maize 1999		Peanut 2000		Maize 2001	
	Grain	Straw	Pod	Hay	Grain	Straw	Pod	Hay	Grain	Straw
	(kg/ha)									
Control	712	1,800	1,420	4,000	806a	857a	936a	2,950b	442a	377a
PG-PR	1,740	3,030	1,640	3,750	1,042ab	986a	773a	1,750a	591a	636ab
Manure (M)	1,820	3,460	1,810	4,590	1,698b	1,588b	1,550b	2,600b	1,591b	966bc
PG-PR + M	1,540	3,140	1,940	4,480	1,829b	1,665b	1,450b	3,134b	1,610b	1,202c
Mean	1,540	2,860	1,700	4,210	1,344	1,274	1,780	2,600	1,039	795
F test	NS[a]	NS	NS	NS	S[b]	HS[c]	S	S	HS	HS
CV (%)	45	35	9	18	32	25	14	15	24	27

[a] No significant effect.

[b,c] Significant at the 1% or 5% level, respectively.

Table VIII. Water-use efficiency values for maize in 1999 and 2001, and peanut in 2000

Treatment	Maize 1999		Peanut 2000		Maize 2001	
	Grain	Straw	Pod	Hay	Grain	Straw
	(kg/ha/mm)					
Control	2.03a	2.15a	2.33a	7.33b	1.06	0.9
PG-PR	3.09ab	2.93a	1.97a	4.45a	1.56	1.68
Manure (M)	4.50b	4.21b	3.68b	6.18b	3.63	2.20
PG-PR + M	4.20b	3.83b	3.51b	7.58b	3.74	2.79

Table IX. Nitrogen-use efficiency and Δ^{13}C values for grain and total above-ground biomass of maize in 1999 and 2001 as affected by soil amendment

Year	Component	Parameter	Control	PG-PR	Manure (M)	PG-PR + M
1999	Grain	NUE (%)	9.4±4.6	12.2±5.7	18.5±5.7	18.4±7.6
		Δ^{13}C (‰)	−10.7±0.10	−10.8±0.11	−10.5±0.25	−10.5±0.11
	Total	NUE (%)	16.9±7.0	21.2±9.1	30.3±4.7	29.8±11.6
		Δ^{13}C (‰)	−11.1±0.08	−11.2±0.14	−11.0±0.18	−11.0±0.04
2001	Grain	NUE (%)	8.2±4.5	10.0±3.1	9.9±2.4	13.3±8.4
		Δ^{13}C (‰)	−10.3±0.14	−10.1±0.15	−10.1±0.14	−10.1±0.12
	Total	NUE (%)	10.4±6.0	12.1±3.0	11.6±2.9	15.8±9.3
		Δ^{13}C (‰)	−10.4±0.14	−10.4±0.06	−10.4±0.28	−10.4±0.19

3.7 Nitrogen-use efficiency

Efficient use of N amendments in cereal production has been widely implicated in maximizing farmers' economic returns and maintaining soil and water quality [1,14]. In this study, maize NUE values estimated for grain and total biomass were improved by soil amendments (Table IX). In 1999, grain or total biomass NUE values were increased by 30% with the PR-PG treatment, and by 100% for manure and manure + PR-PG. In 2001, a lower increase (~40%) was obtained. For $\Delta^{13}C$ in 1999 and 2001 (Table IX), a very small variation in values was observed for grain and total maize biomass. Therefore, soil amendments did not affect maize $\Delta^{13}C$. These values were more negative in 1999 (–10.6 and –11.1‰ for grain and total biomass, respectively) than in 2001 (–10.2 and –10.4‰, respectively).

4. CONCLUSION

To combat continuous degradation in soil fertility, soil amendments with locally available mineral and organic fertilizers were sought to provide sustainable yield increases through optimization of crop-soil water and nutrient use. We focused on analysis of effects of several P- and Ca-source fertilizers on two principal crops, maize and peanut, cultivated as in the prevailing crop rotation. Two major conclusions can be drawn from the crop-water balance terms obtained from the regular moisture measurements:

- The ETR mean values for any of the compared treatments represented at least 50% of effective annual rainfall. Water losses through ETR were not a limiting factor for maize in 1999 or 2001; neither were they limiting for peanut in 2000.
- There was substantial water loss through drainage, implying non-negligible nutrient losses within the profile.

For the corn/peanut rotation system in the Senegal peanut basin, the current practice of applying phosphogypsum and phosphate rock for soil fertility maintenance was shown to have no positive effect on corn or peanut yields over time. However, it had a positive effect on soil chemical properties such as exchangeable Ca; but this improvement was of short duration due to leaching related to drainage water losses. In that regard, PR and PG mix at the applied rate was not as efficient as PR alone in correcting deficiencies in P and Ca. Therefore, relying on this product without further studies to clarify some vital aspects such as optimal application rate could lead to failure of research efforts geared towards this product. This was similarly reported in previous comparisons of mixtures of phosphogypsum and rock-phosphate [15, 16].

Manure alone or in combination with PG-PR effectively increased maize-grain and straw yields in 1999 and 2001, and peanut-pod and hay yields in 2000. These yield increases reflected observed increases in efficiency of use of N as well as of water. As for the long-term experiment concerning the study analysis of phosphogypsum efficiency in correcting soil P deficiency and/or soil acidity as compared to phosphate rock and lime, soil P and Ca amendments—particularly the 50% PG and 50%PR and lime treatments at recommended rates—indicated that phosphogypsum did not noticeably improve soil fertility status over the control treatment, except for increased Ca content. As a result, low corn yields were obtained in 1997, 1999 and 2001. Significant treatment effects were observed on peanut pod yield in 1998, indicating a positive effect of Ca uptake. In 1999 and 2001, maize NUE values were low and were not positively affected by P or Ca amendments. The NUE mean value for the 50% PG and 50%PR treatment for total dry matter was particularly low (17%). More striking was the mean NUE value for the lime treatment, which was lowest (only 11%). It is suspected that the P and Ca source amendments could have been added at a lower rate.

Practices that entail inappropriate land use, poor soil-water and nutrient management and lack of inputs have led to drastic declines in productivity that can result in soil erosion, salinization and consequent loss of vegetation. Sub-Saharan soils are widely at risk. This vulnerable resource is undergoing severe degradation since traditional methods used by indigenous farmers (shifting cultivation and nomadic grazing) no longer supply the increasing needs of the ever-expanding human and livestock populations. This work highlights practices that would be beneficial in halting and reversing arable-land degradation. It is hoped that this will be achievable by improving and sustaining soil-moisture conditions and finding viable economic solutions to fertility depletion. A holistic approach to soil water is necessary, requiring the integration of both physical information and social factors if versatile sustainable solutions are to be found. The core of the solution lies in producing more food from existing water and land resources. The current challenge is to identify and integrate the physical and social dimensions of present and future global-change research, both of which have key roles to play in addressing this urgent challenge.

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OPTIMIZATION OF WATER AND NUTRIENT USE IN RAIN-FED SEMI-ARID FARMING THROUGH INTEGRATED SOIL-, WATER- AND NUTRIENT-MANAGEMENT PRACTICES

I.V. SIJALI, P.T. KAMONI
Kenya Agricultural Research Institute,
Nairobi, Kenya

Abstract

Increased food production can be attributed largely to high-input farming, involving appropriate crop varieties grown on fertile soils and well supplied with adequate moisture, fertilizer and pesticides, as happened during the Green Revolution. In contrast, there is some evidence in semi-arid regions that crop yields can be increased and yield variation decreased with a combination of careful management and low inputs of nutrients. Trials were conducted in Machakos District, in a semi-arid location, during the long rains (March to June) of 1999, 2000 and 2001. Using nuclear techniques, the effects of fertilizer-N inputs and cultivation practices on nitrogen and water-uptake efficiencies in maize were evaluated. Expected benefits of ridging over flat cultivation did not always occur. Rain-fed production of maize grain weakly favoured the split application of N followed by single application at plant emergence in terms of water- and fertilizer-use efficiencies.

1. INTRODUCTION

Families are occupying arid and semi-arid lands (ASALs) in Kenya in increasing numbers. This is hardly surprising for the ASALs represent about 80% of Kenya's landmass [1]. Of the arable lands, about 20% are highly populated. Often the rainfall barely supports crops, yet people in these areas continue to depend on rain-fed agriculture for survival.

The aim of this study was to contribute to the knowledge on the soil-nutrient-water interaction in rainfed conditions for improved development of the arid and semi-arid lands. Use of nuclear technologies assisted in gaining better understanding of the interacting factors. The trials were conducted in Machakos District, a semi-arid area characterized by erratic rainfall, especially during the long rains, March to June [2]. Maize (*Zea Mays* L.) is the most important source of both income and subsistence for most Kenyan farmers. A dryland maize variety, 'Katumani Composite B' (KCB), developed and popularized during late 1960s and early 1970s is the recommended variety for the area [3]. For this reason KCB maize was used as the test crop in this work.

2. MATERIALS AND METHODS

The soils have been classified as chromic luvisols [4]. They are developed on quartzo-feldsphatic gneisses, and are well drained, deep to very deep, dark red to reddish brown clay with soil texture ranging from friable clay to sandy clay loam. Soil depth varied within short distances in the same plot, from 50 cm to more than 120 cm. In general, soil chemical data indicated that organic matter and N were in low supply. Other major nutrients — P, K, Ca and Mg — were in adequate supply.

A split-plot randomized block design was used with two soil- and water-management treatments, ridging (SWM_1) and flat cultivation (SWM_2), and input treatments (Table I) that included mode and time of application of N fertilizer. Mode of application included single application or in equal splits. The times of application were at emergence (time 1, T_1) and application at knee-high (time 2, T_2).

Experimental site selection included preliminary evaluations based on soil sampling and location. The plots were split into a main plot for harvest of grain yield and a micro-plot for fertilizer-N evaluation using ^{15}N [5]. The micro-plots received labelled calcium ammonium nitrate (CAN) (2.3 to 2.5% atom excess) at 25 and 50 kg N ha^{-1}, at emergence or when the plants were at knee height, in a single or split application. The NIL plots did not receive any N fertilizer input. The main plots received ordinary CAN at the same rates and time of application as the micro-plots. Fertilizer N was applied to the surface along the plant rows.

Table I. Input treatments

Treatment	1999	2000	2001	2002
NIL	1	1	1	1
50 kg N ha^{-1} at T_1	2	2	2	2
I[b] + 50 kg Nha^{-1} at T_1	N/A[c]	N/A	3	N/A
FYM[d] + 50 kg Nha^{-1} at T_1	N/A	3	N/A	N/A
50 kg N ha^{-1} at T_2	4	4	4	4
25 kg N ha^{-1} at T_1 and T_2	4	5	5	4

[a] Numbers within the body of the table represent treatment numbers.

[b] Irrigation.

[c] Not applied.

[d] Farmyard manure.

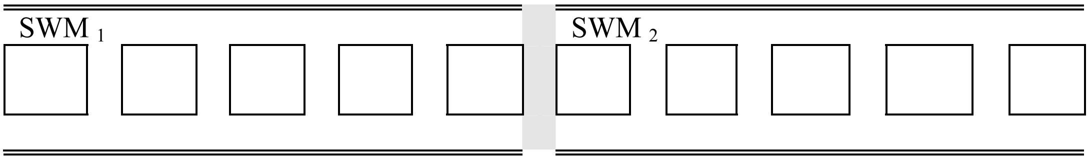

FIG. 1. Experimental layout of plots per farmer.

Table II. Sowing, N-application and harvesting dates

Operation	1999	2000	2001
Date planted (sowing date)	19/3/99	31/3/00	29/3/01
Date of first N application	7/4/99	15/4/00	13/4/01
Date of second N application	4/5/99	N/A[a]	11/5/01
Date of harvesting of micro-plots	26/6/99	27/5/00	5/7/01
Date of final harvest (grain yield)	30/7/99	N/A	4/8/01

[a] Not applicable

The general layout of the treatments in the fields is shown in Fig. 1. Replications were made in the on-station experiment. The treatments were not replicated in the on-farm experiments; four farms were selected.

2.1. Nitrogen treatments

The experimental plots were split into a main plot for harvest of grain yield and a micro-plot for fertilizer-N evaluation using ^{15}N. The micro-plots received labelled CAN (2.3 to 2.5% a.e.) at 25 and 50 kg N ha^{-1} (Table II) at plant emergence or when the plants were knee high, in single or split application. The NIL plots did not receive any N fertilizer. The main plots received ordinary CAN at the same rates and times of application as the micro-plots. Fertilizer N was applied to the soil surface along the plant rows.

2.2. Crop-growth parameters

In 2000, final plant heights were measured at harvest, whereas in 2001, four plants per plot were tagged and monitored for crop height, leaf length and width, and leaf count on a weekly basis. Leaf area index (LAI) values were calculated from four plants per plot using the leaf-length and -width data. Final plant heights were compared among treatments.

2.3. Harvesting

The micro-plots were harvested at early dough stage. The plants were cut at ground level. Cobs and stalk were separated and fresh weight was obtained for each component. Fresh sub-samples were taken to the laboratory, oven-dried at 70°C for 3 days and then weighed. After grinding, samples were sent to the FAO/IAEA laboratory in Seibersdorf for analyses of N, ^{15}N and δ^{13}C. Soil samples were also taken from the micro-plots, oven-dried between 40 and 45°C for 2 days, ground finely, sieved and sent to Seibersdorf for analysis.

The main harvest plots were harvested when the maize plants had senesced. After shelling, the grain weight for each plot was recorded. Moisture content of the grain at harvest was recorded and the final grain weight normalized to a moisture content of 12.5%.

2.4. Fertilizer-use efficiency

The results of ^{15}N analysis of plant material and stock solution were used to partition the N [Eq (1)].

$$\%Ndff = \frac{(atom\ \%^{15}N\ excess)_{plant\ sample}}{(atom\ \%^{15}N\ excess)_{fertilizer}} \times 100 \qquad (1)$$

where

Ndff is the plant N derived from fertilizer.

Fertilizer-use efficiency (FUE) was calculated from the partitioning between the N fertilizer taken up by the plant in relation to the rate applied [Eq (2)].

$$\%FUE = \frac{Fertilizer\ N\ yield}{Fertilizer\ N\ applied} \times 100 \qquad (2)$$

where

fertilizer N yield is calculated by multiplying the total N yield by the %Ndff.

2.5. Water-use efficiency

Seasonal water use in each treatment was calculated from a modified version [Eq (3)] of the soil-water-balance equation. Change in moisture storage in the soil profile (ΔS + D) was calculated from in-situ measurements by neutron probe [4]. Rainfall amount was obtained by summing the daily rainfalls over the season. Runoff and deep percolation were assumed to be negligible.

$$P + I - ET = \Delta S + D \qquad (3)$$

where

P	is rainfall (mm),
I	is irrigation (mm),
ET	is crop evapotranspiration (mm),
ΔS	is change in soil water storage in the root zone (mm),
D	is deep percolation (mm).

Water-use efficiency was computed in kg of harvested component per m^3 of water for grain production [Eq (4)], which is the marketable produce, and aboveground dry matter (total dry matter) [Eq (5)].

$$WUE = \frac{grain\ yield(kg)}{ET(mm) \times harvest\ area(m^2)} \qquad (4)$$

$$WUE_{TDM} = \frac{TDM\ \ yield(kg)}{ET(mm) \times harvest\ area(m^2)} \qquad (5)$$

2.6. Carbon discrimination

The ratio of ^{13}C to ^{12}C of the plant material was measured as carbon discrimination, δ^{13}C, and compared to water-use efficiency data [6].

3. RESULTS AND DISCUSSION

3.1. Rainfall

Seasonal rainfall totals were 239, 144, 222 and 172 mm in 1999, 2000, 2001 and 2002, respectively. The rains were erratic with 167 (67%), 84 (52%) and 128 mm (60%) of the seasonal totals, respectively, falling from sowing date to plant maturity in 1999, 2000 and 2001, respectively. In 2002, rainfall was low and erratic. After early sowing, only 18 mm were received in 3 weeks, leading to poor germination and unfavourable soil-moisture conditions for topdressing with N fertilizer.

3.2. Crop-growth parameters

In 2000, average plant heights at harvest were 47.1, 40.9 and 35.4 cm for the single application of N at emergence, FYM plus single application and split application treatments, respectively. In 2001, LAI (Fig. 2) trends were highest for the single N application at emergence and the split N application. The combination of single application at emergence with irrigation had a lower but prolonged LAI trend.

3.3. Soil- and water-management options

Maize yields (Table III) did not show a consistent trend. However, in 1999 when rainfall was higher, grain yields were 30% more under ridging compared to flat cultivation. On the other hand, in 2000 under the driest conditions, dry matter yields were 28% less under ridging compared to flat cultivation. This suggests that the rainfall characteristics play a roll in determining benefits of land-management practice.

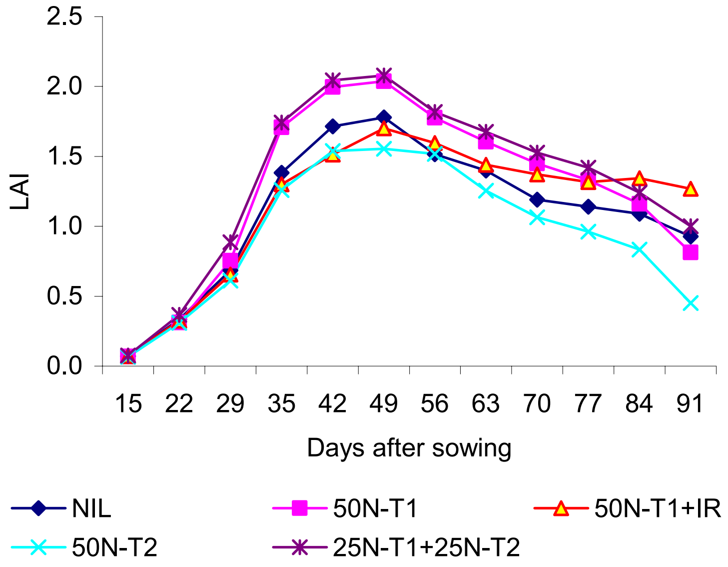

FIG. 2. Trends in leaf-area index values, 2001.

Table III. Effects of soil- and water-management options on grain and total dry-matter yields

Soil & water management	Grain yield			TDMY		
	1999	2000[a]	2001	1999	2000	2001
	(kg ha^{-1})					
Ridging	901		1,184	4,548	691	3,927
Flat cultivation	682		1,035	4,109	958	3,904

[a] The crop dried before reaching maturity.

Table IV. Effects of soil- and water-management options on fertilizer-use efficiency

Soil & water management	FUE		
	1999	2000	2001
	(%)		
Ridging	23	2.1	9.4
Flat cultivation	21	3.7	9.2

Table V. Effects of soil- and water-management options on water-use efficiency

Soil & water management	WUE					
	Grain			Total dry matter		
	1999	2000[a]	2001	1999	2000	2001
	(kg m^{-3})					
Ridging	0.45		0.70	2.34	0.66	2.45
Flat cultivation	0.37		0.56	2.14	0.95	2.45

[a] The crop dried before reaching maturity.

Table VI. Effects of soil- and water-management options on carbon-isotope composition

Soil & water management	$\delta^{13}C$		
	1999	2000	2001
	(‰)		
Ridging	–12.46	–12.35	–11.84
Flat cultivation	–12.36	–12.25	–11.71

Fertilizer-use efficiency (Table IV) did not show a significant difference between the two water-management options.

Water use efficiency (Table V) did not vary much between the soil and water-management treatments although, overall, it was higher under ridging in 1999 and 2001.

Mean $\delta^{13}C$ values (Table VI) were more negative under ridging compared to flat cultivation.

Table VII. Treatment effects on yields

Treatment	Grain yield			TDM		
	1999	2000[a]	2001	1999	2000	2001
	(kg ha^{-1})					
NIL	736		859	4,595	851	3,720
50 kg N ha^{-1} at T_1	784		702	4,307	1151	3,291
I[b] +50 kg N ha^{-1} at T_1	N/A[c]		2,306	N/A	N/A	5,374
FYM[d] + 50 kg N ha^{-1} at T_1	N/A		N/A	N/A	734	N/A
50 kg N ha^{-1} at T_2	861		684	4,168	N/A	3,049
25 kg N ha^{-1} split at T_1 and T_2	936		995	4,244	561	4,143

[a] The crop dried before reaching maturity.

[b] Irrigation.

[c] Not assessed.

[d] Farmyard manure.

Table VIII. Treatment effects on fertilizer-use efficiency

Treatment	FUE		
	1999	2000	2001
	(%)		
50 kg N ha^{-1} at T_1	37	3.2	18
I +50 kg N ha^{-1} at T_1	N/A[a]	N/A	13
FYM + 50 kg N ha^{-1} at T_1	N/A	4.0	N/A
50 kg N ha^{-1} at T_2	2.8	N/A	0.40
25 kg N ha^{-1} at T_1 and T_2	27	1.6	15

[a] Not assessed.

3.4. Input treatments

Rainfed production of maize grain was weakly favoured by the split application of N (Table VII). Low rainfall, as in 2000, did not allow the T_2 treatments to be applied; the crop had already wilted. Irrigation, introduced in 2001, significantly increased maize yields compared to rainfed production.

The FUE results (Table VIII) show that rain-fed production of maize grain weakly favoured the split application of N. Strong N-treatment effects were found on total N uptake and FUE. Higher FUE values (37% in 1999, 3.2% in 2000 and 18% in 2001) were found with the single application of N at plant emergence; however, the split application produced superior FUE values (27% in 1999, 1.6% in 2000 and 15% in 2000) when the crop was at knee height than with the single application (2.8% in 1999 and 0.4% in 2001). The knee-height application did not apply in 2000 because of the dry conditions. During 2002, the soil was not wet enough for the early N topdressing and most plants dried before reaching knee height.

Water-use efficiencies for grain production were highest with the split application, at 0.48 and 0.73 kg m^{-3} in 1999 and 2001, respectively (Table IX). Even more-efficient utilization of water, in terms of total biomass production, was found in the NIL treatment in 1999 (2.37 kg m^{-3}) and 2000 (1.02 kg m^{-3}) but was highest in the split application in 2001(3.03 kg m^{-3}).

Table IX. Treatment effects on water-use efficiency

Treatment	WUE					
	Grain			Total dry matter		
	1999	2000[a]	2001	1999	2000	2001
	(kg m^{-3})					
NIL	0.38		0.63	2.37	1.02	2.71
50 kg N ha^{-1} at T$_1$	0.33		0.51	2.22	0.99	2.41
I[b] +50 kg N ha^{-1} at T$_1$	N/A[c]		0.79	N/A	N/A	1.83
FYM[d] + 50 kg N ha^{-1} at T$_1$	N/A		N/A	N/A	070	N/A
50 kg N ha^{-1} at T$_2$	0.45		0.51	2.16	N/A	2.26
25 kg N ha^{-1} at T$_1$ and T$_2$	0.48		0.73	2.22	0.50	3.03

[a] The crop dried before reaching maturity.

[b] Irrigation.

[c] Not assessed.

[d] Farmyard manure.

Table X. Treatment effects on carbon-isotope composition

Treatment	$\delta^{13}C$		
	1999	2000	2001
	(‰)		
NIL	–12.4	N/A	–11.8
50 kg N ha^{-1} at T$_1$	–12.6	–12.2	–11.9
I[a] +50 kg N ha^{-1} at T$_1$	N/A[b]	N/A	–11.6
FYM[c] + 50 kg N ha^{-1} at T$_1$	N/A	–12.3	N/A
50 kg N ha^{-1} at T$_2$	–12.4	N/A	–11.7
25 kg N ha^{-1} at T1 and T$_2$	–12.2	–12.4	–11.8

[a] Irrigation.

[b] Not assessed.

[c] Farmyard manure.

In Table X, average $\delta^{13}C$ values are presented. Regression of $\delta^{13}C$ and WUE on plant biomass production showed a good correlation in 2000 (R^2 = 0.869), but was weak in 1999 (R^2 =0.021) and in 2001 (R^2 = 0.233). No trend could be attributed to these values.

4. CONCLUSIONS

Improvements in water- and fertilizer-use efficiencies were attributed to input management in terms of early application of the fertilizer or split application. To use moisture most efficiently for grain production, split application of N fertilizer was preferable. To use the fertilizer efficiently, the early single application of N was superior to the other options. Fertilizer use efficiency was highly dependent on the rainfall during the growing period. With the data currently available, positive trends in supplementing N through inorganic fertilizer application with earlier application of N fertilizer, single or split, are beneficial. The key is to combine nutrient inputs with crop-management practices to increase the supply of water to the crop without depleting soil organic matter and nutrients.

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LIST OF PARTICIPANTS

Asseng, S.
CSIRO Division of Plant Industry
Private Bag PO
Wembley, WA 6014, Australia
Tel.: +61 8 93336615
Fax: +61 8 93878991
Email: s.asseng@ccmar.csiro.au

Bationo, A.
Tropical Soil Biology and Fertility Institute of CIAT (TSBF-CIAT)
c/o ICRAF, Gigiri
PO Box 30677
Nairobi, Kenya
Tel: +254 2 524755 International: +1 415 8336645
Fax: +254 2 524763 +254 2 524764
Email: A.Bationo@cgiar.org

Cai, G.
Institute of Soil Science
Academia Sinica
Department of Soil-Plant Nutrition
PO Box 821, 71 Beijing Road East
Nanjing, Jiangsu Province 210008
People's Republic of China
Tel.: +86 25 6881065
Fax: +86 25 6881000
Email: gxcai@issas.ac.cn or caiguixin@hotmail.com

El Mejahed, K.
Institut National de la Recherche Agronomique
Centre Aridoculture
BP 589
Settat, Morocco
Tel.: +212 23403210/18 or +212 63680640
Fax: +212 23403209/23402626
Email: elmejahed@hotmail.com or arido@iam.net.ma (attn: El Mejahed)

Heng, L.K.
Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture
Soil and Water Management & Crop Nutrition Section
Wagramer Strasse 5
PO Box 100
A-1400 Vienna, Austria
Tel.: +43 1 2600 28263
Fax: +43 1 2600 28222
Email: L.K.Heng@iaea.org

Keerthisinghe, G.
Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture
Soil and Water Management & Crop Nutrition Section
Wagramer Strasse 5
PO Box 100
A-1400 Vienna, Austria
Fax: +43 1 26007
Email: G.Keerthisinghe@iaea.org
Gamini.Keerthisinghe@fao.org

Mahaman, I. (Report not submitted)
Institut National de Recherche Agronomique du Niger (INRAN)
BP 429
Niamey, Niger
Tel.: +227 72 3434
Fax: +227 72 2144
Email: sareli@intnet.ne

Maraux, F. (Report not submitted)
CIRAD Visiting scientist in FAO
AGLW Section
Viale delle Terme di Caracalla
00100 Rome, Italy
Tel: +39 0657053931
Fax: +39 0657056275
Email: Florent.Maraux@fao.org

Mohammad, W.
Nuclear Institute for Food and Agriculture (NIFA)
Nuclear Agriculture Division
PO Box 446, Tarnab
Peshawar 25000, Pakistan
Tel.: +92 91 2964058
Fax: +92 91 2964059
Email: nifa@psh.paknet.com.pk

Moutonnet, P.
Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture
Soil and Water Management & Crop Nutrition Section
Wagramer Strasse 5
PO Box 100
A-1400 Vienna, Austria
Fax: +43 1 26007
Email: p.moutonnet@wanadoo.fr

Myers, R.
31 Woonalee Street
Kenmore
Queensland 4069, Australia
Tel.: +61 7 3878 5024
Email: rjkmyers@bigpond.net.au

Prieto, D. (Report submitted late)
Estación Experimental Agropecuaria
Santiago del Estero, Argentina
Tel.: +54 385 4224430/4730
Fax: +54 385 4224596
Email: dprieto@correo.inta.gov.ar

Ramana, M.V.
Regional Agricultural Research Station
Palem, Mahabubnagar District
Andhra Pradesh 509 215, India
Tel.: +91 08540 28646 or 91 08 540 28441
Fax: +91 08540 28646
Email: Maparlavr@yahoo.com

Mohammad Rusan, M.J.
Jordan University of Science and Technology (JUST)
Agriculture Centre for Research and Production
Faculty of Agriculture
Dept. of Natural Resources and the Environment
PO Box 3030
Irbid, Jordan
Tel.: +962 7201000
Fax: +962 7095069
Email: mrusan@just.edu.jo

Ryan, J. (Report not submitted)
Natural Resources Management Programme
International Centre for Agricultural Research in Dry Areas (ICARDA)
PO Box 5466
Aleppo, Syrian Arab Republic
Tel: +963 21 2213433
Fax: +963 21 2213490 or 5744622
Email: J.Ryan@cgiar.org

Singh Sachdev, M.
Nuclear Research Laboratory, Indian Agricultural Research Institute
New Delhi – 110 012, India
Tel/Fax: +91 11 25842902
Fax: +91 11 25842454 / 25846420
Email: mssachdev@excite.com or mssachdev@iari.res.in

Sene, M.
Institut Sénégalais de Recherches Agricoles (ISRA)
Route des Hydrocarbures
Bel-Air, BP 3120
Dakar, Senegal
Tel.: +221 9514993
Fax: +221 9514995
Email: modousen@refer.sn or msene@isra.sn

Sijali, I.V.
Kenya Agricultural Research Institute
National Agricultural Research Laboratories
Soil and Water Management – Irrigation and Drainage Programme
PO Box 14733 – 00800
Nairobi, Kenya
Tel.: +254 20 4444250/4444144
Fax: +254 20 4443926
Email: irrigation@iconnect.co.ke

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