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Optimizing nitrogen fertilizer application to irrigated wheat

Results of a co-ordinated research project organized by the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture 1994–1998

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FOREWORD

Irrigation is available for about 40% of wheat produced in developing countries, and efficiency of nutrient use under irrigated conditions is thought to be low by international standards. Nitrogen (N), which accounts for about two-thirds of all the fertilizers used in developing countries, is a major economic input. According to FAO and World Bank reports, there has been a dramatic increase in N fertilizer use for irrigated wheat production. The many benefits of applying N to irrigated crops are well known to growers around the world. Examples from developed countries clearly illustrate that zeal for higher yields can lead to inefficient use of inputs (water, nutrients, and pesticides). Poor management of one or more of these inputs is likely to reduce the effectiveness of the others. Techniques and management systems must be developed to improve N-uptake efficiency by crops, which will help to protect the environment.

Irrigated wheat is an obvious target for increased production to satisfy demand, because yields are relatively high at 3 to 8 t ha^{-1}. Past research by the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture and other groups has shown how much nitrogen and other nutrients are typically required to produce a given yield of wheat on soils of medium to low fertility. These data are critical because they provide a reference with which current N management practices can be compared. This type of simple comparison helps to identify opportunities for improvement of N management practices. Unfortunately, much remains to be done to integrate and assemble pertinent concepts and principles into management packages and simulation models that can effectively address production problems in developing countries. In the case of wheat production, the growth simulation model Ceres-Wheat has been developed to help evaluate and compare management options. A certain minimum data set is required, but once that need is met, the model can quickly be used to evaluate specific management practices that would otherwise require several years of costly field research.

This TECDOC summarizes the results of a Co-ordinated Research Project (CRP) on The Use of Nuclear Techniques for Optimizing Fertilizer Application under Irrigated Wheat to Increase the Efficient Use of Nitrogen Fertilizer and Consequently Reduce Environmental Pollution. The project was carried out between 1994 and 1998 through the technical co-ordination of the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture. Fourteen Member States of the IAEA and FAO carried out a series of field experiments aimed at improving irrigation water and fertilizer-N uptake efficiencies through integrated management of the complex interactions involving inputs, soils, climate, and wheat cultivars. Its goals were:

- to investigate various aspects of fertilizer N uptake efficiency of wheat crops under irrigation through an interregional research network involving countries growing large areas of irrigated wheat,
- to use ^{15}N and the soil-moisture neutron probe to determine the fate of applied N, to follow water and nitrate movement in the soil, and to determine water balance and water-use efficiency in irrigated wheat cropping systems,
- to use the data generated to further develop and refine various relationships in the Ceres-Wheat computer simulation model,
- to use the knowledge generated to produce a N-rate-recommendation package to refine specific management strategies with respect to fertilizer applications and expected yields.

The CRP was organized according to recommendations from a consultants meeting in 1993. Four research co-ordination meetings were convened in 1994, 1996, 1997 and 1998, the venue for the first, third and the fourth of which was Vienna, Austria. The second meeting was held at CIMMYT, Mexico City, Mexico. During the first meeting, research methods and field-experimental layout were discussed and elaborated by the principal investigators. During the later meetings, experimental results and their implications were reviewed; additional field experiments, if needed, were suggested and discussed. The principal investigators were trained twice in the use of the Ceres-Wheat simulation model as proposed by DSSAT, version 3.0. The FAO/IAEA Agriculture and Biotechnology Laboratory in Seibersdorf, Austria, assisted in the project through analytical services and training.

The IAEA would like to express its appreciation to the CRP investigators for their commitment, without which the project would not have reached a successful conclusion. This IAEA officers responsible for publication were P. Moutonnet, L.K. Heng and P.M. Chalk of the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture. The final reports were reviewed and compilied by A. Eaglesham, Ithaca, NY, USA.

EDITORIAL NOTE

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SUMMARY

Introduction

Nitrogen (N) and water are the most common limiting factors in agricultural systems throughout the world. Wheat crops need sufficient available water and N to achieve optimum yields and adequate grain-protein content. Lower economical benefits for farmers often arise from the use of sub-optimal rates of N fertilizers. On the other hand, excessive N fertilizer use may result in environmental problems such as nitrate contamination of groundwater and emission of N_2O and NO. In spite of the economical and environmental importance of good N fertilizer management, the development of optimum fertilizer recommendations is still a major challenge in most agricultural systems in developing countries. Efficient use of fertilizer requires comprehensive knowledge of soil, plant, fertilizer and the environment. The chemical and physical characteristics of the soil, the amount of water applied by irrigation or natural precipitation, and the amount, timing and sources of nitrogen applied are important factors to consider.
Approximately 20% of all cultivated land in the world is under irrigation, providing between 35–40% of all crop production. Many countries such as Egypt, India, Israel and Pakistan depend mostly on irrigation to meet their agricultural production. In the developing countries, about 70–80% of the fresh water resources are used for irrigation. However, irrigation scheduling is often inappropriate; either crop water requirements are miscalculated, or means for water distribution are outdated and inefficient. As a result, farmers still tend to over-irrigate, and therefore many irrigation projects do not provide their full measure of anticipated benefits owing to the development of shallow water tables, salinization, over- or under-irrigation, inefficient N fertilizer use, etc.

Approach
In 1993, the Joint FAO/IAEA Division implemented an international research project on the use of nuclear techniques for optimising fertilizer application under irrigated wheat, to increase the efficient use of nitrogen fertilizers and consequently reduce environmental pollution. The co-ordinated research project (CRP) aimed to investigate various aspects of nitrogen use efficiency of the wheat crop under irrigation through an interregional research network of experimental sites in countries with large cultivated areas of irrigated wheat. The effects of timing of irrigation application, type of fertilizer, genotypes and rotation effects were also studied.

Two nuclear techniques, the soil moisture neutron probe and ^{15}N-labelled fertilizers, were employed in the CRP. Field studies were conducted under different irrigated and environmental conditions in countries represented by the scientific co-operators. Several devices were installed for collecting soil solution samples and measuring soil water fluxes: tensionics, suction cups, tensiometers, gypsum blocks, small lysimeters, in addition to the neutron probe soil water measurement, so that water uptake and the amount of N leached could be calculated. ^{15}N-labelled fertilizer was applied to micro-plots to determine fertilizer-N uptake by plants and the amounts retained in the soil and leached. The contributions of fertilizer and soil to total N in grain and straw were also calculated from ^{15}N-enrichment data.

The preparation of solutions for determination of $^{15}N/^{14}N$ isotope ratios, with special reference to dilute samples, was improved: the micro-diffusion method was simplified to be more suitable for rapid isotope-ratio determination in soil solutions collected through porous ceramic cups. The SPAD chlorophyll-meter was used for generating readings from leaves of irrigated wheat at particular growth stages and different rates of N fertilizer.

Another objective of the CRP was to build up a database for the Ceres-Wheat growth simulation model of DSSAT (Decision Support System for Agrotechnology Transfer). DSSAT can assist in the decision making process of defining optimal N fertilizer strategies based on existing knowledge of crop responses to N.

Results

Grain yield and fertilizer N uptake

The amount of nitrogen uptake by plants varied from country to country. In many countries, it was observed that increasing the amount of fertilizer application did not result in increasing yield. In Austria, where three N fertilizer rates were applied by either fertigation or broadcasting, only 27% was taken up by winter wheat when 240 kg N ha^{-1} was applied, and 44% when the fertilizer rates were between 120 and 180 kg N ha^{-1}.

In Bangladesh, wheat grain yields and yield-contributing components increased with the amount of fertilizer N (0, 60, 120 and 180 kg N ha^{-1}, respectively). Fertilizer-N uptake was highest with 180 kg N ha^{-1} and varied from 16 to 50% of that applied. Grain yields ranged from 1.22 to 5.25 t ha^{-1}, with no significant difference between the 120 and 180 kg N ha^{-1} treatments. Application of 120 kg N ha^{-1} may therefore be recommended for economic yield for wheat cultivation in the area. Nitrogen applied to wheat had a positive residual effect on a subsequent rice crop in comparison with the zero-N controls.

In Brazil, a two-year study showed that maximum grain productivity was obtained with 90 kg N ha^{-1}. Urea-N uptake ranged from 52% for application at sowing, to 85% when applied at tillering. The residual N after harvest of grain represented around 40% of that applied, with 21% in soil, 3% in roots and 16% in the wheat straw. Soybean recovered less than 2% of the N applied to the wheat.

In Chile, the effects of timing, type of fertilizer, irrigation and sulfur interaction, genotypes and rotation effects were studied on volcanic ash soils, fertilized at 0, 75, 150 and 225 kg N ha^{-1}. The results indicated that residue incorporation in the rotation, optimum irrigation (>170 mm), three split applications of N and nutritional problem correction (acidification and sulfur deficiency), promoted wheat yields and fertilizer-N efficiency. Applied-N recoveries were only about 50% and significant loss can occur in these soils. However, grain yields of 6 to 8 t ha^{-1} were achieved when the soil was managed appropriately.

In China, N-application rates significantly affected wheat grain yields and straw dry matter. Grain yields were higher with 150 than with 225 kg N ha^{-1}, whereas the highest fractional recoveries of N from ammonium bicarbonate occurred with 75 kg N ha^{-1}, with 38.5% in 1994–95 and 33.5% in 1996–1997. On the basis of grain yield, N recovery and soil-N balance, ammonium bicarbonate at 150 kg N ha^{-1} was the optimum rate when applied basally and as a top dressing to wheat.

In Egypt, field experiments were conducted on three main soil types: old irrigated clay soil of the Nile Valley, newly reclaimed sandy and calcareous soils, and salt-affected soil of the North Delta. The responses of wheat cultivars to N, and patterns of N uptake and N loss, as affected by irrigation regime, were examined. A traditional cultivar Sakha 69 was found to be more responsive to applied N and assimilated N more efficiently than other varieties grown on different soil types.

In India, an experiment was carried out over four seasons, on a sandy loam soil. The regionally recommended application of 120 kg N ha^{-1} was compared with rates of 50% and 150% of this value. The application of 180 kg N ha^{-1} increased grain and dry-matter yields significantly. The highest fractional uptake of N was obtained at the 100%-N level, and additional fertilizer was utilized less efficiently. Efficiency of fertilizer nitrogen under the best management conditions at the 120 kg N ha^{-1} rate was only about 50%.

In Mexico, it is possible to improve N-uptake efficiency in wheat grown in the Yaqui Valley while maintaining grain yield and quality, by delaying most of the N application close to the time of the first auxiliary irrigation. Soil mineral N was relatively high at sowing and subsequent mineralization resulted in uptake of 90 kg N ha^{-1} from the zero-applied-N control plots.

In Romania, the optimum N fertilizer rate was locally regarded as 120 kg N ha^{-1}, or 80 kg N ha^{-1} after pea. Irrigation was applied to maintain soil moisture in excess of 75% field capacity. Wheat dry matter and grain-yield responses, and soil mineral-N content, were influenced by the previous crop. Yield benefits were greater from N applied at tillering than when applied at planting; similarly, higher values of fertilizer-N recovery were obtained after application at tillering. Fertilizer N use efficiency ranged from 25 to 35%, the highest value being recorded with N applied at 54 kg N ha^{-1} at tillering, after pea.

In the Syrian Arab Republic, two wheat cultivars were grown after fallow and after wheat with sprinkler irrigation. Four N fertilizer rates (0–150% of the recommended dose) were used. Dry biomass and grain yield of wheat after fallow were much higher than those of wheat after wheat. The effects of increasing amounts of N fertilizer were significant during the four seasons, but were more pronounced in wheat after wheat. The appropriate timing and amount of irrigation water contributed to high fertilizer-N recovery (between 44 and 75%). Plants recovered N fertilizer applied at tillering more efficiently than when it was applied at germination. Labelled N analysis showed no deep percolation of N fertilizer with water during the growing season. Water use efficiency of wheat after fallow was almost twice that of wheat after wheat, and N fertilization of wheat after wheat increased the water use efficiency two to three fold.

In Turkey, N fertilizer applied at tillering was utilized more effectively with proportionately less residual in the soil compared with that applied at planting. Subsequent crops of maize or cotton were positively affected by residual N. Crop water consumption showed strong positive relationships with N rate. No wheat-grain-yield benefits accrued from irrigation, although straw yields were increased. Tiller production increased with N fertilizer usage, but tiller survival decreased at high N and was highest at 160 kg N ha^{-1}. The data indicated that the rate of 160 kg N ha^{-1}, which is commonly used by the farmers of the region, is acceptable, not only for optimum grain yields but also to minimize the risks of leaching NO_3^- to groundwater.

Irrigation management and N losses

The timing of N fertilizer application affects its potential for leaching losses. It is often observed that the recovery of the first one third split application of N fertilizer (applied at planting) is usually less than the second two third split application (applied at tillering). Seven countries out of ten consistently made this observation throughout the 1995–1998 period: the Syrian Arab Republic, Morocco, Brazil, Romania, Turkey, Bangladesh and India. It was also observed that the percentage of fertilizer reserved for the second split application could be increased.

Type of irrigation can have a major influence on the losses of irrigation water and N fertilizer. Deep percolation losses of water generally occur with surface irrigation, because in order to apply sufficient water to replenish the root zone of the soil furthest from the source over irrigation occurs near the source. On the other hand, well scheduled sprinkler irrigation promoted N fertilizer recovery. Six of the participating countries practised surface irrigation: Bangladesh, China, Egypt, India, Mexico and Morocco. The results are illustrated below.

Significant losses were observed in a few countries: Egypt and China on sandy soils, and therefore large applications of N are likely to cause nitrate pollution of ground water. In Egypt, field experiments were conducted on three main soil types: old irrigated clay soil of the Nile Valley, newly reclaimed sandy and calcareous soils, and salt-affected soil of the North Delta. The responses of wheat cultivars to N, and patterns of N uptake and N loss, as affected by irrigation regime, were examined. Cultivar Sakha 69 was more responsive to applied N and assimilated N more efficiently than other varieties grown on different soil types. Nitrogen loss from the sandy soil was as high as 57% whereas average loss in the clay soil was 17%.

In India, the 150%-N level resulted in three- to five-fold more fertilizer-derived NO_3^--N in the soil solution below the root zone (120 cm depth). The experiment was carried out over four seasons, on a sandy loam soil, comparing the regionally recommended application of 120 kg N ha^{-1} with rates of 50% and 150% of this value. The soil water was depleted mostly from the upper 60 cm, below which moisture content remained unchanged during crop growth and was in excess of the upper limit of drainage, indicating a high potential for nitrate leaching.

In Morocco, ammonium sulfate fertilizer was applied at three levels: 0, 120 and 180 kg N ha^{-1}, with three irrigation regimes (100%, 80% and 60% maximum water requirement). It was found that the losses of water and N were intimately related to precipitation and depth of water applied through irrigation. Nitrogen applied at planting is likely to be lost to leaching and be a major source of groundwater pollution. The application of more than 120 kg N ha^{-1} results in high risk of losses and in low N-uptake efficiency. The highest N losses occurred during early growth. Irrigation had little effect on N loss when it was practiced efficiently. Also, for economic and environmental reasons, irrigation should be limited to 80% of the total requirement and to depths of 40 to 60 mm.

In Austria, with the use of a cover crop, between 22–36% of fertilizer N was immobilized and saved for the following crop, and only a small fraction of the applied N was leached.

In Bangladesh only a minor fraction of applied N moved down to 120 cm, indicating little likelihood of pollution of groundwater by NO_3^- from fertilizer.

In Brazil, the main loss of fertilizer N occurred as ammonia volatilization, which ranged from 5 to 12%. Loss of N by leaching was less than 1%, even with an application of 135 kg N ha^{-1}, which is higher than the rate locally recommended for irrigated wheat. The small leaching loss was due to little rainfall during the growing season and irrigation sufficient only to moisten the root zone.

In Mexico, N management practices that had resulted in reduction of trace-gas emissions while maintaining grain yield and quality were validated in Yaqui Valley farmers' fields. However, the soil supplied N which is not considered when farmers decide on the rate of fertilizer to be applied, is potentially contributing to high losses. The SPAD chlorophyll meter was found to be a promising tool for predicting grain-protein concentration. In conclusion, it is possible to improve N-uptake efficiency in wheat grown in the Yaqui Valley by delaying most of the N application close to the time of the first auxiliary irrigation.

In Syria, the appropriate timing and amount of irrigation water contributed to high fertilizer-N recovery of between 44 and 75%.

In Turkey, volatilization and leaching losses of applied N were small. The data indicated that the rate of 160 kg N ha^{-1}, which is commonly used by the farmers of the region, is acceptable, not only for optimum grain yields but also to minimize the risks of leaching NO_3^- to groundwater.

A database consisting of basic soil characteristics, water use efficiency, irrigation (type and uniformity), yield (average and irrigated), fertilizer N balance (recovery by crop, residue), grain (yield, protein), chlorophyll readings and economic analysis, was created.

Conclusions and recommendations

1. The recovery of the first one third split application of N fertilizer (applied at planting) was usually less than the second two third split application (applied at tillering). Seven countries out of ten consistently made this observation throughout the 1995–98 period [Arab Syrian Republic, Morocco, Brazil, Romania, Turkey, Bangladesh, India], and therefore the percentage reserved for the second split application could be increased.
2. Losses of irrigation water and N fertilizer were observed in a few countries [Egypt and China on sandy soils, India]. On the other hand, well scheduled sprinkler irrigation promoted N fertilizer recovery [Arab Syrian Republic].

3. The chlorophyll meter may be useful to define wheat N requirement if used in conjunction with well fertilized reference strips within the same field. Readings, generated from the leaves of irrigated wheat at particular growth stages, were normalized to the data obtained with locally recommended rates of fertilizer N, in Chile, China, India and Mexico. Normalizing permitted comparisons of crop-N status across growth stages, locations, cultivars, and years.
4. The Ceres-Wheat growth simulation model predicted rather closely the progress of dry matter production, leaf area index, seasonal evapotranspiration, phenological development and many other plant-growth attributes [Turkey, Arab Syrian Republic, Morocco, Brazil, Romania, India]. When combined with localised information, it allows better fertilizer N recommendations to be made.
5. Using appropriate geographical information system, the site specific information can be extended to a regional scale.

THE COLLECTION OF A MINIMUM DATASET AND THE APPLICATION OF DSSAT (DECISION SUPPORT SYSTEM FOR AGROTECHNOLOGY TRANSFER) FOR OPTIMIZING WHEAT YIELD IN IRRIGATED CROPPING SYSTEMS

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Abstract

A minimum dataset for testing of the CERES-Wheat model within DSSAT was collected during the course of an IAEA Co-ordinated Research Project on "The use of nuclear techniques for optimizing fertilizer application under irrigated wheat to increase the efficient use of nitrogen fertilizers and consequently reduce environmental pollution". A database entitled <*Irrigated Wheat Database.XLS*> which contained the following information was subsequently created: soil characteristics, average yield, fertilizer N recovered by crop and residual effect, grain protein content, regional average yield, relative grain yield at various fertilizer N rates, assessment of nitrate pollution, economics of irrigated wheat, water use by source, water use efficiency, atypical precipitation events, type and uniformity of irrigation, and chlorophyll meter readings. This article presents some of these overall results from the database, as well as simulated results from the CERES-Wheat model. Good agreement between observed and simulated results was obtained for most growth parameters in most of the simulations. The ability to validate the model means that it can be used to refine specific management strategies with respect to fertilizer applications, yield and other parameters.

1. INTRODUCTION

It has been commented that science has not done enough to make the knowledge it generates accessible to those who need it. While it is important for scientists to understand processes and mechanisms, it is equally important to synthesize from the acquired information, a capacity to predict outcomes and finally to enable clients to apply the predictive capability to control outcomes. This is particularly so in the agricultural sector with demand on resources for food production becoming critical and with decreasing funding and increasing cost of carrying out new and long term field trials. This problem can be partially overcome if knowledge and information generated is being used in the development of a simulation/decision support model.

Decision support models can provide effective information by extrapolating field experimental results to a range of production scenarios than is possible with field trials, reducing the amount of repetitive, laborious and time-consuming experimentation. For example, the effects of soil types and seasons, alternative production with direct reference to the farmers' resource base, sustainability and long term stability of production system, can all be studied. By doing so it can help to identify knowledge gaps, gain insights into situations where experimental results are lacking or are incomplete. This in turn may help to develop new or refine existing fertilizer recommendations for a wide range of production conditions. However, a model can only be developed with a reliable set of data. Hence, it is important that field experiments are well planned and set up and all procedures are properly followed.

2. CERES-WHEAT MODEL

Decision support system such as DSSAT (Decision Support System for Agrotechnology Transfer) contains various sub-models [1]. The CERES-Wheat within DSSAT [2; 3] can simulate the main processes of crop growth and development such as timing of phenological events, the development of canopy to intercept photosynthetically-active radiation, and dry matter accumulation.

It allows the inclusion of cultivar-specific information that makes it possible to predict the cultivar variations in plant ontogeny, yield component characteristics and their interactions with weather. The biomass calculated is partitioned between leaves, stems, roots, ears and grains. The proportion partitioned to each organ is determined by the stage of development and growing conditions, modified when deficiencies of water and nutrient supplies occur. Crop yields are determined as a product of the grain numbers per plant times the average kernel weight at physiological maturity. The grain weight is calculated as a function of cultivar-specific optimum growth rate multiplied by the duration of grain filling, which is reduced below the optimum value when there is an insufficient supply of assimilate from either the biomass produced or from stored biomass in the stem.

The model divides the soil into several horizontal layers. A daily time step is used. Soil N-transformation processes are described in the NTRANS submodel [4;5] which simulates mineralization, immobilization, nitrification, denitrification, etc. The soil water balance is simulated in the WATBAL submodel [6; 7]; it assumes piston flow. For each day, infiltration, surface runoff, drainage, evaporation and redistribution fluxes are computed. Potential evaporation is computed from daily solar radiation, albedo and air temperature using the Ritchie [8] approach, which also outlined the two-stage approach for actual evaporation calculation. The NFLUX submodel calculates the rate of nitrate movement between layers, by multiplying the rate of water movement and nitrate concentration in the layer.

This article presents a few of the summarised experimental results collected from the participating countries in this CRP between 1994–1998. A database was also created in Excel: "Irrigated Wheat Database.XLS". The data from this database were used in the CERES-Wheat simulation, some of the results are also given here.

3. EXPERIMENTAL RESULTS

One of the important factors that influence the movement of water and the fertility status and hence crop yield is soil type. Soil texture at the experimental sites of the participating countries ranged from very sandy (India) to very heavy clays in Chile and Egypt (Fig. 1).

The amount of rainfall gives an indication of the availability of water and hence the success or failure of a crop, although it is the distribution over the season that is more important. A wide range of rainfall was recorded for different countries; annual rainfall between 1000–2500 mm was common in Bangladesh while in Chile, as little as 300 mm was recorded, with Egypt having near zero rainfall (Fig. 2). The majority of the countries received rainfall of less than 500 mm and consequently supplemental irrigation was needed for adequate crop growth (Fig. 3). China and Egypt applied the most irrigation (over 450 mm per year) and some countries such as India and Mexico applied pre-season irrigation (not shown).

The average grain yield obtained during the four-year study and the average expected yield for the region, are shown in Fig. 4. Despite receiving the highest rainfall, Bangladesh did not produce the highest grain yield. Yield was highest in Chile and China with values above 6 tonnes/ha being recorded. There was a good relationship between grain yield and total biomass as shown in Fig. 5; Grain Yield = 0.46 x Total Biomass — 21.667 (with goodness of fit, R^2 = 0.96). A different relationship was needed to describe the data for China, Syria and Morocco.

Information on the cost of fertilizer and price of wheat was also gathered during the course of the CRP. The ratio of the cost of fertilizer to the price of wheat was plotted for all countries and is given in Fig. 6. It can be seen that it is expensive to produce wheat in Egypt and Romania compared with Bangladesh and Turkey. More summarised results from the above CRP can be obtained from the excel database mentioned earlier.

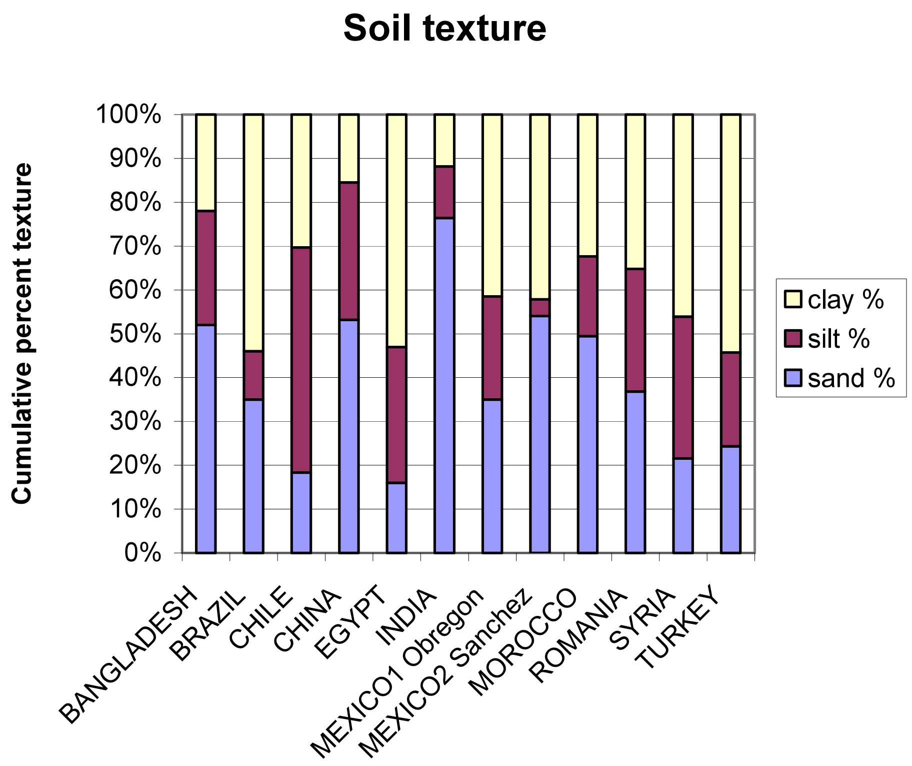

FIG. 1. The soil texture (percent sand, silt and clay) of the different experimental sites.

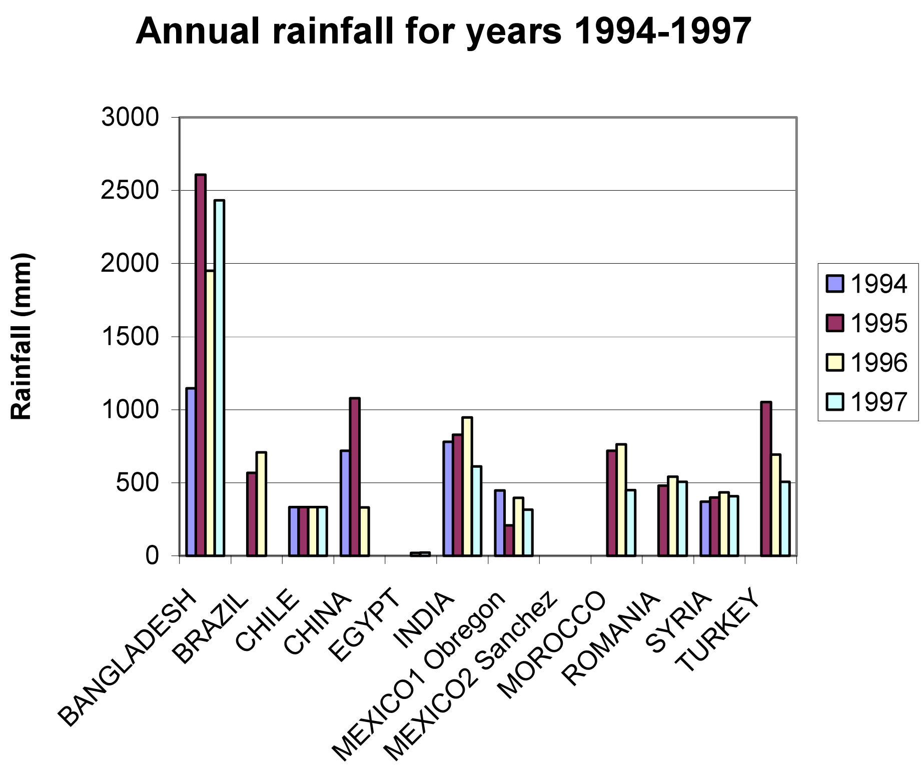

FIG. 2. Annual rainfall between 1994-97.

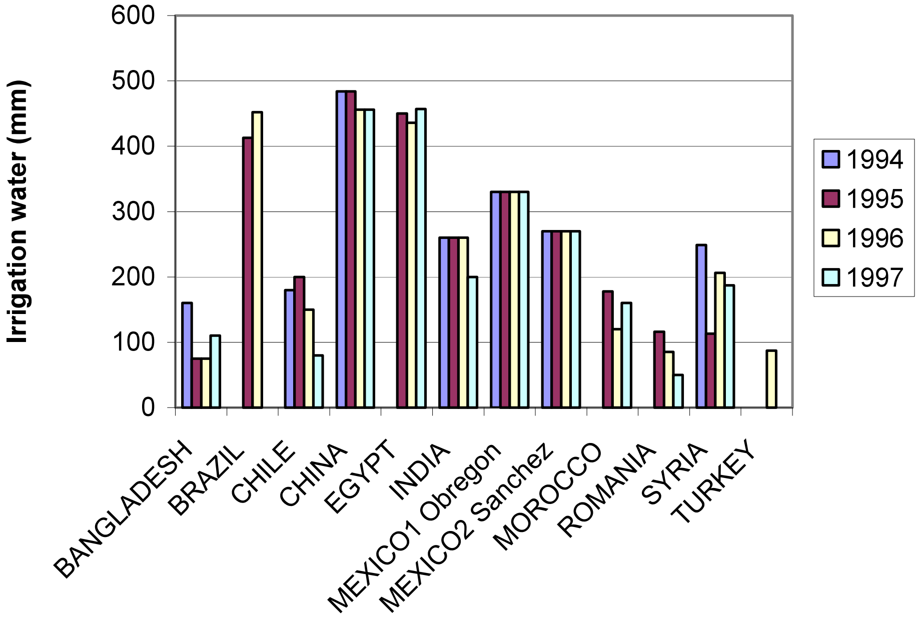

FIG. 3. Irrigation water applied in each country.

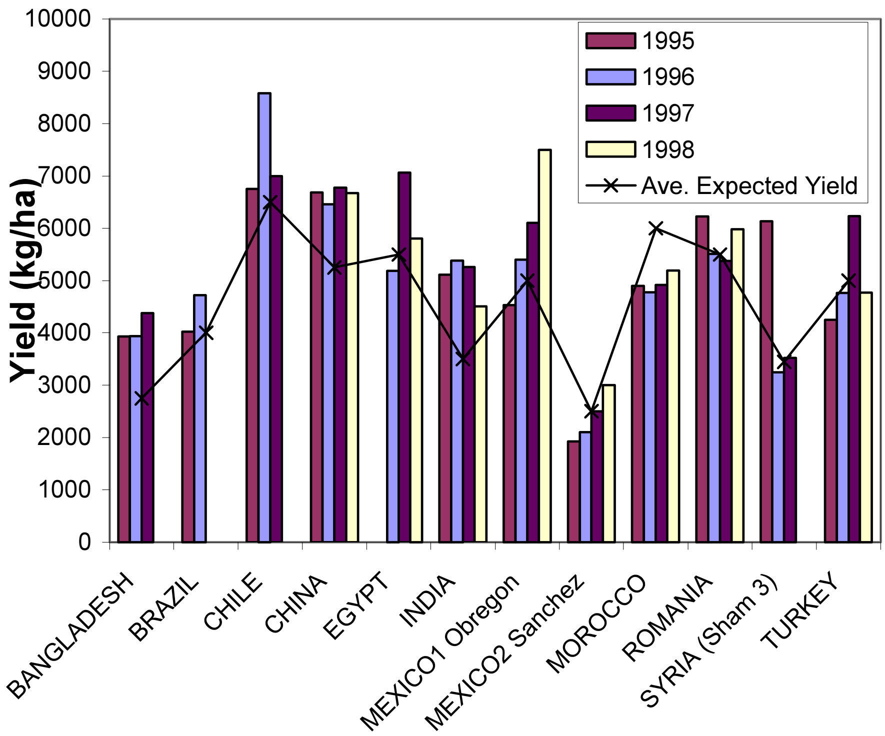

FIG. 4. Grain yield obtained from the various countries.

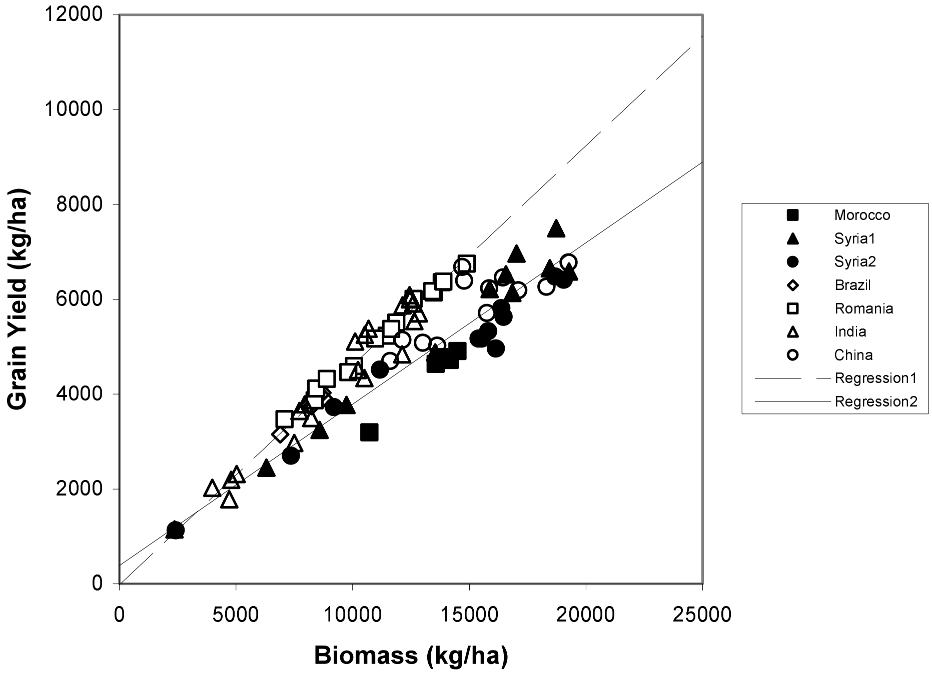

FIG. 5. The relationship between biomass production and grain yield.

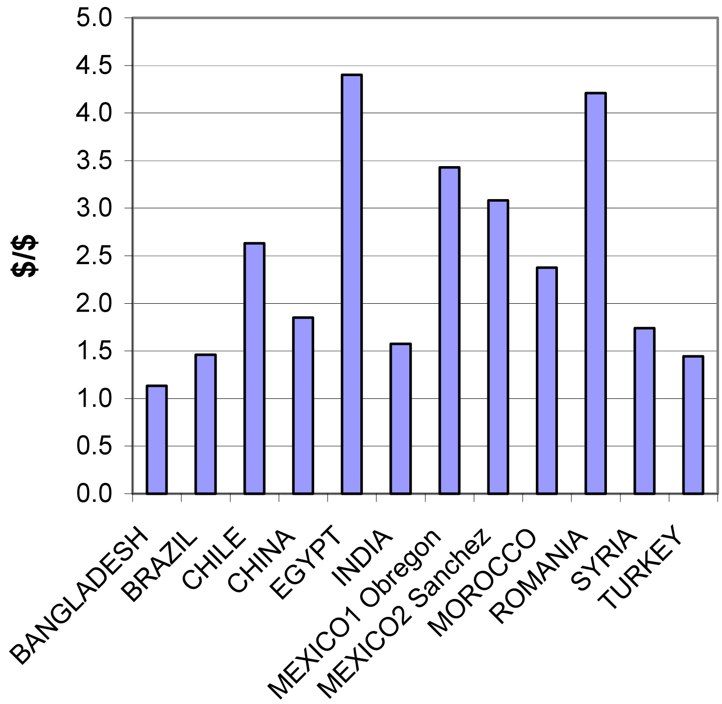

FIG. 6. The ratio of the cost of fertilizer to the price of wheat.

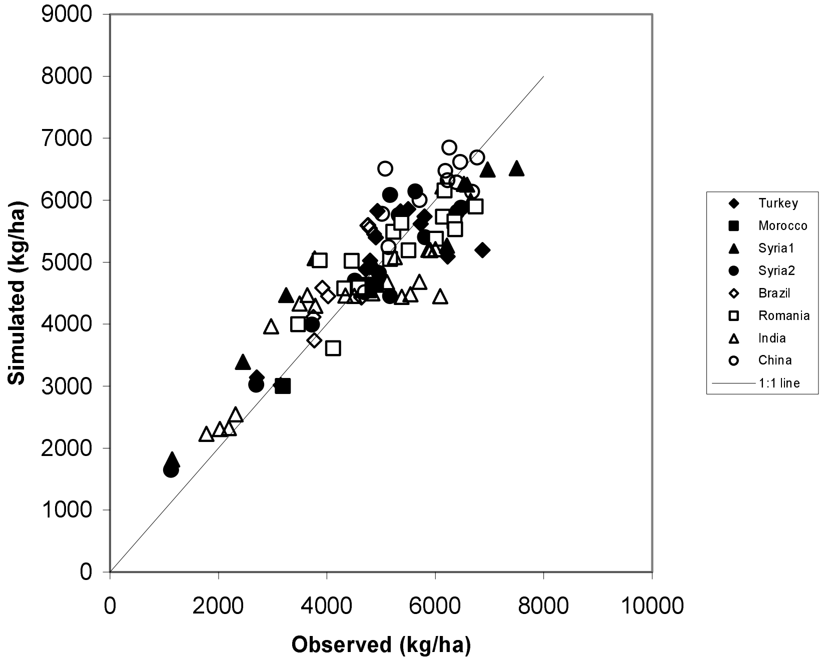

FIG. 7. The observed grain yield and that simulated using CERES-wheat.

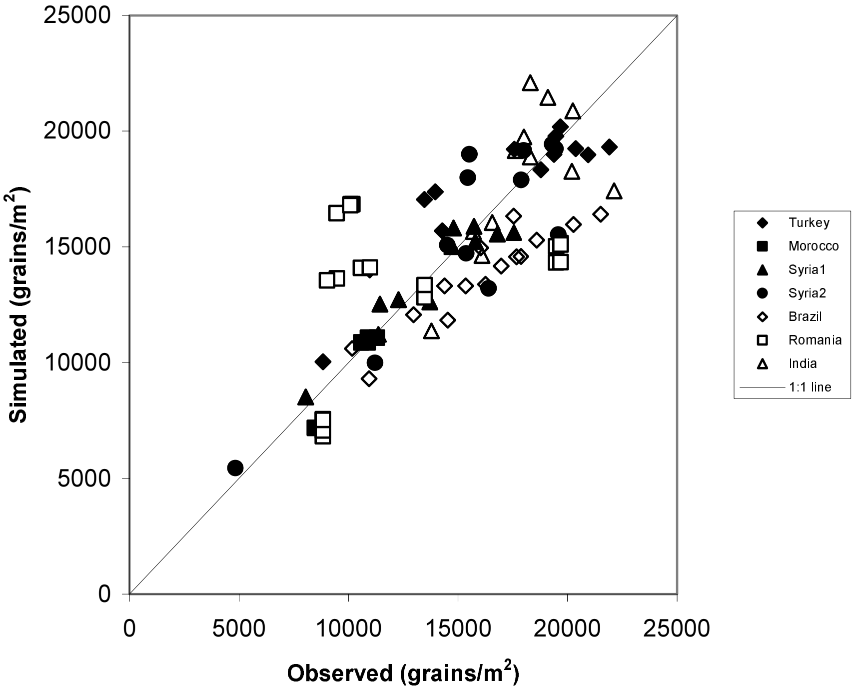

FIG. 8. The observed grains/m^2 and that simulated using CERES-wheat.

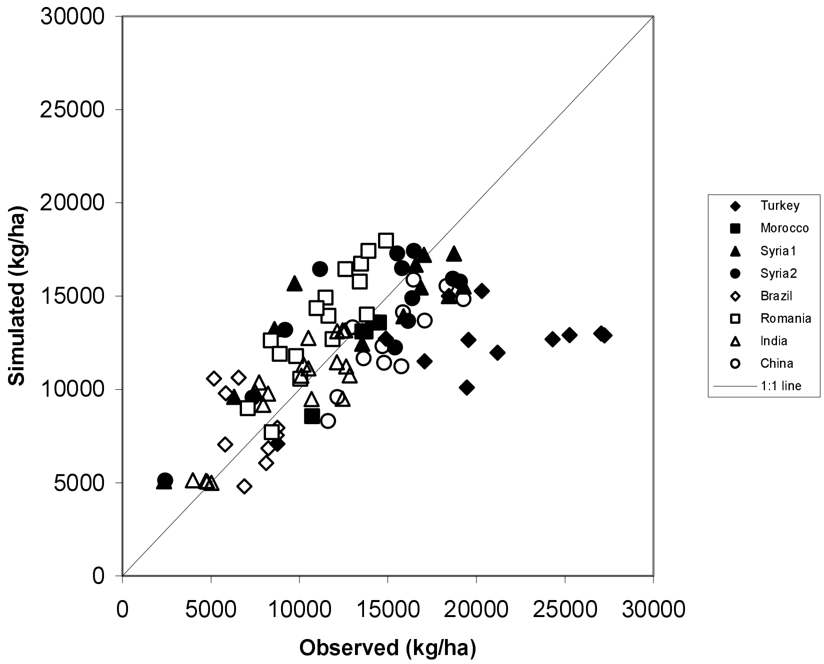

FIG. 9. Observed total biomass and that simulated using CERES-Wheat.

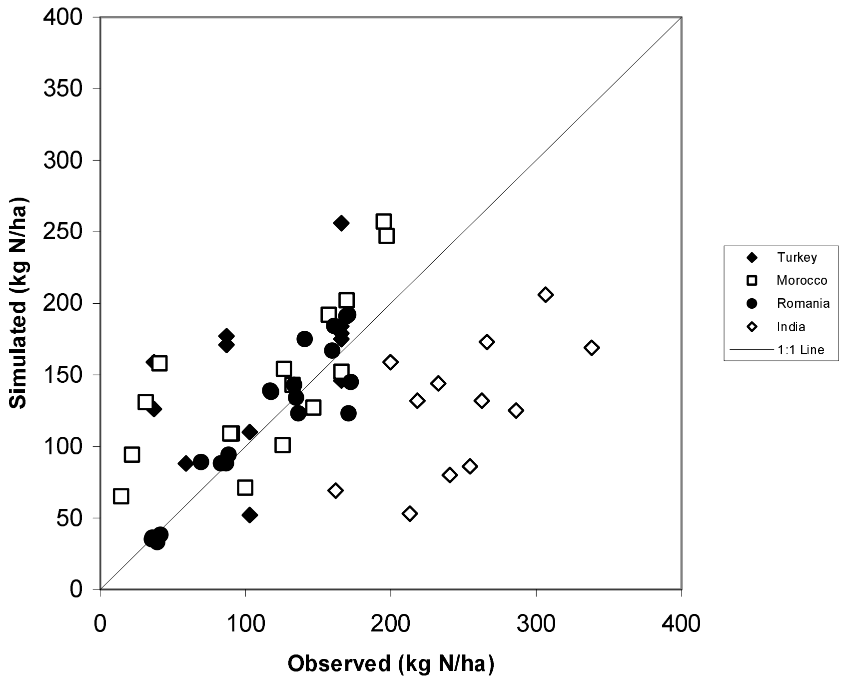

FIG. 10. Observed and simulated biomass nitrogen content.

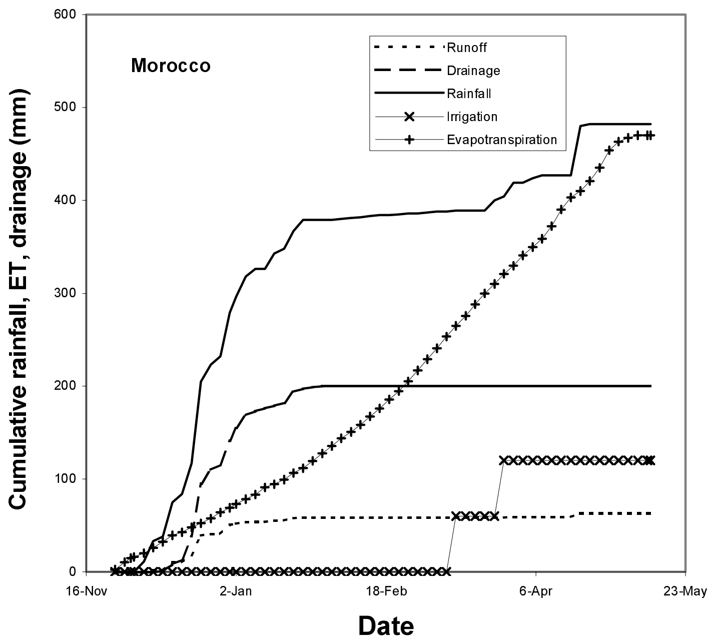

FIG. 11. Cumulative rainfall, evapotranspiration, drainage, irrigation and drainage for 1996/97.

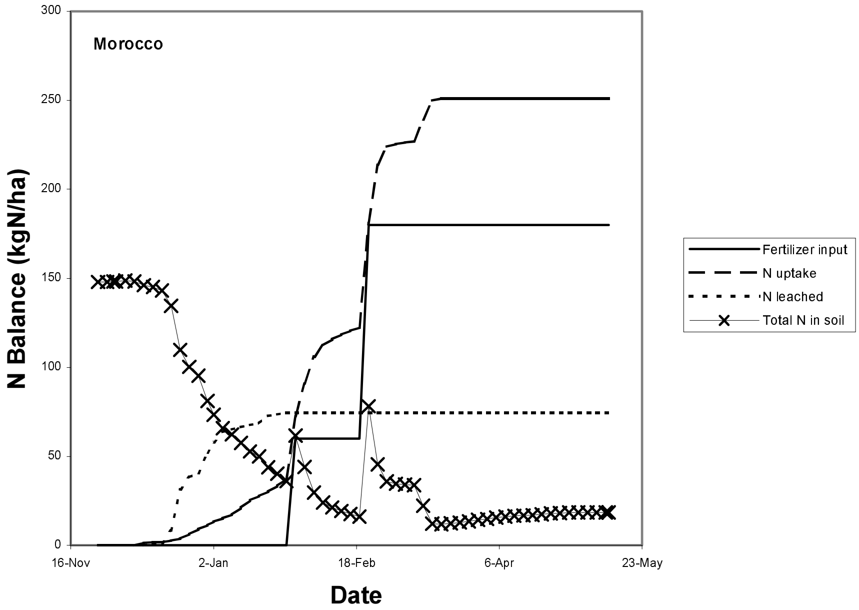

FIG. 12. Nitrogen balance for 1996/97.

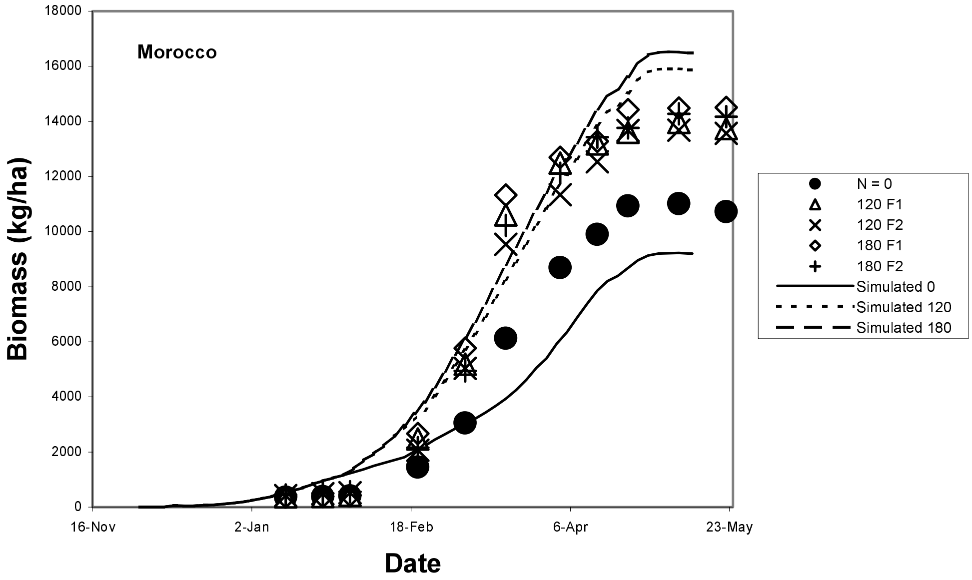

FIG. 13. Measured and simulated biomass for different N rates.

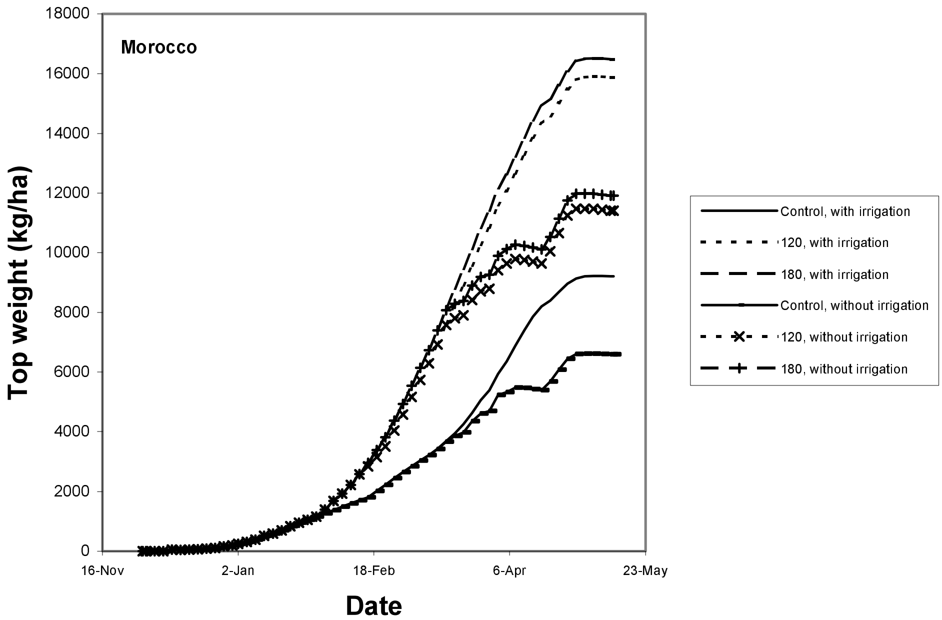

FIG. 14. The effect of irrigation and fertilizer on the simulated biomass production.

4. DSSAT SIMULATED RESULTS

The minimum dataset, as well as the experimental results shown above, were used to calibrate and test the CERES-Wheat Model. Calibration was done by matching the phenology of the crop (e.g. dates of anthesis and maturity) from the model with actual data. A 1:1 relationship between observed and simulated dates of anthesis and maturity was obtained (results not shown).

Once calibrated, the model was used in a predictive manner to simulate a range of scenarios and crop parameters which include grain yield, number of grains m^{-2}, total biomass, biomass and grain N, N leached, etc. There were general good agreements between observed and predicted grain yield (Fig. 7), grain number (Fig. 8), total biomass (except Turkey) (Fig. 9) and grain N values (Fig. 10). The ability of the model to predict these parameters implies that it can facilitate the screening of cultivars for selecting those that are best adapted to specific target environments. This can help in optimizing the use of resources and quantifying risks associated with plant, soil and weather variation.

Detail simulation using DSSAT was also carried out for most countries. Only results for Morocco are presented here. In the Doukkala region of Morocco, increasing nitrate concentrations in groundwater as a result of excessive fertilization and poor management of irrigation has been a cause for concern. It is hoped that with proper management of irrigation scheduling and split fertilizer application, it will be possible to reduce the amount of water loss and nitrate leached.

The distribution of rainfall, irrigation, evaporation, runoff and drainage for 1996/97 at Doukkala is shown in Fig. 11. Most of the rainfall occurred at the beginning of the growing season, with about 80% falling during the first 60 days when the requirement for crop growth was minimal. This together with the sandy nature of the soil resulted in significant amounts of deep drainage. Irrigation was applied later in the season. Two rates of ammonium sulfate fertilizer (120 and 180 kg N ha^{-1}) were applied; this was compared with a zero-N control. Three irrigation regimes (100%, 80% and 60% maximum water requirement) were also studied.

A large amount of N was lost through leaching during the early part of the growing season (Fig. 12). Although fertilizer was split applied and applied late in the season, significant nitrate was leached (68 kg N ha^{-1}), probably from mineralization of soil organic N. No N fertilizer should therefore be applied to wheat at planting, in order to limit N losses by leaching caused by the high precipitation.

The model was able to predict the biomass at different fertilizer N rates reasonably well except for the zero-N control (Fig. 13). The results show that fertilizer has a positive effect on biomass production, but the effect was minimal beyond 120 kg N ha^{-1}. The effect of irrigation and fertilizer application on simulated biomass production is illustrated in Fig. 14. A significant loss of production can occur at inadequate supply of water and fertilizer.

5. CONCLUSION

The CERES-Wheat model was able to simulate dry-matter production, leaf area index, seasonal evapotranspiration and various phenological events over a wide range of soil and weather conditions under irrigated wheat. This means that the model can be utilised for making decisions regarding optimum rates and timing of N-fertilizer application and irrigation scheduling. IAEA should continue to encourage the collection of past and future data sets (soil, plant and weather) for calibration and testing of models.

A wide range of possibilities exists with the current set of experimental data. For example, the WeatherMan generator within DSSAT can be used to generate long term weather data, filling missing data and compute statistics to help to assess the temporal variation of a production system. The Geographical Information Systems (GIS) component of DSSAT can be used to analyse within-field, site-specific farming systems, or allow viewing of simulated results over regional spatial scales.

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NITROGEN UPTAKE EFFICIENCY OF IRRIGATED WHEAT IN EGYPT

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Abstract

Egypt's current wheat production would be impossible without N fertilizers, the consumption of which has increased more than 75% in the last 20 years. The efficiency of uptake of applied N is low, and better management of both fertilizer and irrigation is needed to improve N recovery by crops and reduce losses from the plant/soil system. Field trials were conducted over a 3-year period, on Egypt's three main soil types: old irrigated land of the Nile valley, newly reclaimed sandy and calcareous soils, and salt-affected soil of the north delta. The responses of wheat cultivars to N, and patterns of N uptake and N loss, as affected by irrigation regime, were examined using ^{15}N. Cultivar Sakha 69 was more responsive to applied N and assimilated N more efficiently than other varieties under different soil types. Nitrogen loss from the sandy soil was as high as 57% whereas average loss in the clay soil was 17%. A higher water table in the salt-affected soil negatively affected N uptake. Irrigation with 75% of the required water for wheat had no effect on yield or N-uptake.

1. INTRODUCTION

Soil resources in Egypt are limited. Only 3.5% of the total area is agricultural, whereas desert occupies 96%. The old irrigated lands have the most fertile soils, which are alluvial, level, deep, dark brown and heavy to medium in texture; according to USDA taxonomy, vertisols predominate.

Agriculture in Egypt is almost entirely dependent on irrigation; there is no effective rain except in a narrow band along the north coast. The single main source of water is the Nile. Salinity is considered a threat to sustainability of agricultural production on old irrigated lands. It is estimated that 30% of cultivated soils, located mainly in the north delta region, are salt-affected. Intensive land-reclamation projects, started in the early 1950s, continue to develop and utilize new lands and to intensify and diversify agricultural and livestock production to meet growing national demands for food. The newly reclaimed soils are mostly sandy (84%) and calcareous, and depend on irrigation either from canals from the Nile or from groundwater. Modern sprinkler and pivot systems predominate.

Wheat is the staple food crop in Egypt. Production reached 5.8 Mt in 1997, 43% short of self-sufficiency. The contribution of newly reclaimed lands to wheat production increased from 112 kt in 1990 to more than 0.5 Mt in 1996. The potential for further increasing area and productivity is high; wheat became appealing to farmers with price increases that resulted from market-liberalization policies

Producing the massive quantities of food materials needed in Egypt would be impossible without fertilizers. Between 1980 and 1994, total fertilizer consumption increased by 69% and N-fertilizer use went up by 77%. Intensive farming systems, with rotations of two or three crops per year, newly cultivated areas, and gradual increases in recommended fertilizer rates for various crops are the main reasons for the higher consumption of fertilizers. Several studies have shown generally poor efficiency of use of applied N by various crops in Egypt, depending mainly on variety, soil type and irrigation regime. The leaching of fertilizer N to groundwater is not only an economic loss, but also constitutes pollution of water resources.

The objectives of field trials at three locations during growing seasons 1995–96, 1996–97, and 1997–98 were to 1) compare productivity of wheat cultivars on newly reclaimed sandy, calcareous soil, on old irrigated land of the Nile valley, and on salt-affected soil of the north delta; 2) assess the response of these cultivars to various N-fertilizer rates and irrigation regimes; 3) quantify water consumption and water-use efficiency for these cultivars; 4) using ^{15}N, estimate N losses and fertilizer-N-use efficiency values for these cultivars under different soil conditions.

2. MATERIALS AND METHODS

2.1. Old irrigated clay soil – Giza site

Chemical and physical properties of the soil are presented in Table I. The experiment was planted for growing seasons 1995–96, 1996–97 and 1997–98 with a split-split plot design, where two irrigation treatments represented the main plots, two wheat cultivars the sub-plots, and four N-fertilizer levels represented the sub-sub-plots, with three replicates. Each experimental unit had an area of 21 m^2. The two irrigation treatments, applied to the soil surface, were designated I1 (required level) and I2 (75% of the amount of irrigation water applied in I1 for 1995–96 and 1996–97, and 60% for 1997–98). Wheat cultivars, Sakha 69 (a traditional genotype) and Sids 6 (newly released, long-spike) were compared. The fertilizer levels were 0, 70, 140 and 210 kg N ha^{-1} as ammonium sulphate in two splits: a third was applied at planting and two thirds at the Z-31 growth stage.

Fertilizer enriched in ^{15}N was applied to 1 × 1 m micro-plots. Basal P was applied at 150 kg P_2O_5 ha^{-1}. Grain and straw weights from each plot were recorded to determine the effects of the tested variables on wheat yields, N uptake, and N losses from the system. The significance of differences between average values for the three replicates of each treatment was determined by analysis of variance (ANOVA) using the Student-Newman-Keuls test.

2.2. Newly reclaimed land

2.2.1. Sandy soil – Ismailia site

Chemical and physical properties of the soil are presented in Table II. The experiment was conducted during the 1995–96 and 1996–97 growing seasons using the same design as at the Giza site. For the first season, cvv. Sakha 69 and Sids 6 were compared, whereas in the second season cvv. Sakha 69, Sids 6 and Sids 1 were compared. The experimental unit was 42 m^2 in area. The fertilizer levels were 70, 140, 210 and 280 kg N ha^{-1} in three splits, with ^{15}N-enriched fertilizer applied to 1 × 1 m micro-plots. Irrigation was applied using a sprinkler system.

2.2.2. Calcareous soil – Nubaria site

This trial was conducted in a farmer's field at Nubaria. The results of chemical and physical analyses of the soil are presented in Table III. The experiment was conducted in the 1996–97 growing season. The experimental design, fertilizer rates, time of application and statistical analysis were the same as those used at Giza. Cultivars Sakha 69, Sids 6, and Sids 1 were compared. The experimental unit was 42 m^2 in area.

2.3. Salt-affected soil — El Serw site

This trial was conducted at El-Serw Agricultural Research Station, representing the salt-affected soils of the north delta. The soil chemical and physical properties are presented in Table IV. The experiment was conducted for 2 years. For the 1995–96 growing season, fertilizer was applied at 0, 70, 140 and 210 kg N ha^{-1}, in two splits as at Giza, to cv. Sakha 8, with three replications. The experimental unit was 42 m^2 in area, and irrigation treatments were again designated I1 (five irrigations) and I2 (four). In 1997–98, responses to applied fertilizer and N recoveries were studied with two water-table levels, i.e. by comparing plots close to a drain with those close to an irrigation canal. Cultivar, irrigation treatment, area of experimental plot and number of replications were as reported for the 1995–96 experiment.

TABLE I. CHEMICAL AND PHYSICAL PROPERTIES OF THE SOIL AT GIZA

Organic Matter	pH	CEC meq/100g soil	EC dS/m	Clay	Silt	Sand
				---------- %	-------------	
1.80	8.4	50	0.7	53	31	16

TABLE II. CHEMICAL AND PHYSICAL PROPERTIES OF THE SOIL AT ISMAILIA

Organic Matter	pH	CEC meq/100g soil	$CaCO_3$	Clay	Silt	Sand
			--------------------- %	-------------------------		
0.25	8.1	11	2.0	9	4	87

TABLE III. CHEMICAL AND PHYSICAL PROPERTIES OF THE SOIL AT NUBARIA

Organic Matter %	E.C mmoh/cm	pH	$CaCO_3$	Clay	Silt	Sand
			------------- %	-----------------		
0.67	0.9	8.7	28.7	16	8	76

TABLE IV. CHEMICAL AND PHYSICAL PROPERTIES OF THE SOIL AT EL SERW

Organic Matter %	E.C mmoh/cm	Na	Mg	Ca	pH	$CaCO_3$ %	Clay	Silt	Sand
		--- meq/liter-----					-------- % --------		
1.3	9	33	18	18	8.0	2.7	46	26	28

3. RESULTS AND DISCUSSION

3.1. Old irrigated clay soil – Giza site

For all N treatments, the grain and straw yields of cv. Sakha 69 were significantly higher than those of Sids 6 (Table V). The newly released cv. Sids 6 has longer spikes than the traditional Sakha 69, however, due to fewer tillers, its yield was lower in both growing seasons.

The application of N fertilizer resulted in significant increases in grain and straw yields of both cultivars, with higher percentage increases for Sakha 69 than for Sids 6 (Table VI). Sakha 69 assimilated more N than did Sids 6 for all applied-N rates for both seasons.

There were significant decreases in yield with 40% less irrigation in 1997–98 (Table VII). Yields of Sakha 69 were consistently higher than those of Sids 6 under all fertilizer treatments. The amounts of N uptake are presented in Table VIII for 1995–96 and 1996–97, and in Table IX for 1997–98; the irrigation treatments resulted in cultivar differences in N-uptake in the last season.

Nitrogen derived from fertilizer (Ndff) was higher for Sakha 69 than for Sids 6 when 140 kg N ha^{-1} was applied with the whole dose labelled with ^{15}N (Table X). However, Sids 6 had a higher Ndff value for the first of the split applications. Sakha 69 was more efficient in using the applied N than Sids 6, as shown by higher N-recovery values. Also the percentage of N lost under Sids 6 was more than double that lost under Sakha 69 (Table XI).

Text cont. on p. 28.

TABLE V. AVERAGE YIELD OF TWO WHEAT CULTIVARS (t/ha) AT GIZA FOR 1995–1996 AND 1996–1997

Cultivar	N-Level KgN/ha	Grain Yield (t/ha) 1995/96	Grain Yield (t/ha) 1996/97	Straw Yield (t/ha) 1995/96	Straw Yield (t/ha) 1996/97
Sakha 69	N000	3.676	5.013	7.598	14.237
	N070	4.876	6.157	11.382	14.337
	N140	5.181	7.066	13.174	16.848
	N210	6.555	7.754	14.860	16.858
	Average	**5.072**	**6.499**	**11.753**	**15.500**
Sids 6	N000	2.953	3.906	6.304	8.319
	N070	3.505	5.218	7.282	10.843
	N140	3.950	6.080	8.286	12.769
	N210	4.436	7.186	9.926	16.080
	Average	**3.711**	**5.573**	**7.949**	**12.003**
LSD (0.05) values for:					
diff. N-level & same cultivar		0.3715	0.538	0.745	1.400
same N-level & diff. cultivar		0.5343	0.535	1.2041	1.394
		ANOVA effect			
	N	*** (0.263)	(0.380)***	(0.524)***	(0.990)***
	Cultivar (c)	** (0.558)	(0.359)***	(1.200)***	(0.940)***
	I	NS	NS	NS	NS
	N X I	NS	NS	NS	NS
	N X C	***	NS	***	***
	C X I	NS	*	NS	NS
	N X C X I	NS	NS	NS	NS

Values between practices represent the LSD at 0.05 significant levels for the averages.
, * Significant at the 0.1, 0.01 and 0.001 probability levels, respectively.

TABLE VI. AVERAGE YIELD OF TWO WHEAT CULTIVARS (t/ha) AT GIZA (1997–1998 SEASON)

N-rate kg N/ha	I1		I2		Mean (N)	Cultivar	
	Sakha 69	Sids 6	Sakha 69	Sids 6		Sakha 69	Sids 6
N0	3.5	2.3	3.1	2.1	2.7d	3.3	2.2
N70	4.9	2.9	3.6	2.6	3.5c	4.3	2.8
N140	5.8	3.5	3.9	3.1	4.1b	4.9	3.3
N210	7.6	5.1	5.0	4.5	5.6a	6.3	4.8
Mean	4.5a		3.5b			4.7a	3.3b

TABLE VII. NITROGEN UPTAKE (kg N/ha) BY TWO WHEAT CULTIVARS AT GIZA FOR 1995–1996 AND 1996–1997

Variety	Control	70	140	210
Sakha 69				
1995/96	103.17	164.18	199.24	249.94
1996/97	106.21	167.00	210.24	251.64
Sids 6				
1995/96	83.69	113.25	141.36	150.73
1996/97	80.62	129.61	167.67	193.71

TABLE VIII. NITROGEN UPTAKE (kg N/ha) BY TWO WHEAT CULTIVARS AT GIZA FOR THE 1997–1998 SEASON

Variety	Control	70	140	210
Sakha 69				
Irrigation 1	112.4	174.9	198.5	253.5
Irrigation 2	89.8	118.7	128.6	167.2
Sids 6				
Irrigation 1	77.6	103.3	126.3	180.0
Irrigation 2	71.4	93.0	105.0	147.6

TABLE IX. NITROGEN DERIVED FROM FERTILIZER (Ndff) APPLIED AT RATE OF 140 kg N/ha AT GIZA FOR1995/96 AND 1996/97 SEASONS

Variety	**Dose applied as ^{15}N labeled fertilizer**	**Ndff (kgN/ha)**					
		Grain	**Straw**	**Total**	**Grain**	**Straw**	**Total**
			1995/96			**1996/97**	
Sakha 69	1/3	10.97	8.52	19.49	10.53	11.14	21.67
	2/3	65.02	37.82	102.84	67.30	38.20	105.50
	The whole	66.79	43.85	116.64	69.99	42.45	112.44
Sids 6	1/3	23.49	6.24	29.73	25.69	7.29	32.98
	2/3	43.78	11.74	55.52	45.90	12.14	58.04
	The whole	59.89	17.70	77.59	62.12	17.01	79.13

TABLE X. AVERAGE % ^{15}N RECOVERY AND N LOSSES FROM FERTILIZER APPLIED AT RATE OF 140 kg N/ha AT GIZA

Variety	Recovery in plant		Recovery in soil (depth — cm)			Losses
	Grain	Straw	0–20	20–40	40–60	
Sakha 69						
1995/96	47.71	31.32	1.30	0.90	0.80	17.97
1996/97	49.02	31.97	1.90	1.10	0.65	15.19
Sids 6						
1995/96	42.78	12.64	1.80	1.10	0.82	40.86
1996/97	47.76	30.65	2.12	1.05	0.91	17.51

TABLE XI. AVERAGE GRAIN YIELD OF TWO WHEAT CULTIVARS (t/ha) AT ISMAILIA (1995–1996)

Cultivar	N-Level	Grain Yield (t/ha)	Straw Yield (t/ha)
Sakha 69	N070	2.306	3.880
	N140	3.313	4.937
	N210	3.484	6.016
	N280	3.635	5.865
	Average	**3.184**	**5.174**
Sids 6	N070	1.751	3.328
	N140	2.431	3.986
	N210	2.587	4.287
	N280	2.773	4.893
	Average	**2.385**	**4.123**
LSD (0.05) values for:			
diff. N-level & same cultivar		0.5314	0.7965
same N-level & diff. cultivar		0.5228	0.8592
		ANOVA effect	
	N	*** (0.376)	*** (0.563)
	Cultivar (C)	** (0.339)	* (0.674)
	I	NS	NS
	N X I	NS	NS
	N X C	NS	NS
	C X I	NS	NS
	N X C X I	NS	NS

Values between practices represent the LSD at 0.05 significant levels for the averages.
*, **, *** Significant at the 0.1, 0.01 and 0.001 probability levels, respectively.

TABLE XII. AVERAGE YIELD OF THREE WHEAT CULTIVARS (t/ha) AT ISMAILIA (1996–1997)

Cultivar	N-Level (kg N/ha)	Grain Yield (t/ha)	Straw Yield (t/ha)
Sakha 69	N070	1.985	3.714
	N140	2.492	3.714
	N210	2.973	4.984
	N280	3.439	5.547
	Average	2.722	4.490
Sids 6	N070	1.646	3.129
	N140	2.151	3.527
	N210	2.437	3.827
	N280	2.828	4.992
	Average	2.266	3.869
	N070	2.117	3.564
Sids 1	N140	2.744	4.089
	N210	3.075	5.310
	N280	3.275	5.282
	Average	2.803	4.561
LSD (0.05) values for:			
diff. N-level & same cultivar		0.298	0.498
same N-level & diff. cultivar		0.346	0.580
		ANOVA effect	
	N	(0.172)***	(0.288)***
	Cultivar (C)	(0.258)***	(0.434)***
	I	NS	NS
	N X I	NS	NS
	N X C	NS	NS
	C X I	NS	NS
	N X C X I	NS	NS

Values between practices represent the LSD at 0.05 significant levels for the averages.
*, **, *** Significant at the 0.1, 0.01 and 0.001 probability levels, respectively.

TABLE XIII. NITROGEN UPTAKE (kg N/ha) BY THREE WHEAT CULTIVARS AT ISMAILIA (1996–1997)

Variety	70	140	210	280
Sakha 69				
1995–96	63.05	102.86	134.50	147.26
1996–97	44.70	67.09	112.01	135.01
Sids 6				
1995–96	47.75	99.08	107.53	129.13
1996–97	31.37	51.71	82.12	104.81
Sids 1				
1996/97	41.11	68.37	111.64	123.82

TABLE XIV. N DERIVED FROM FERTILIZER (Ndff) AS AFFECTED BY N-RATE AND WHEAT VARIETY AT ISMAILIA

Variety	**N- rate kgN/ha**	**Ndff (kgN/ha) Grain**	**Straw**	**Total**
Sakha 69	70	32.50	13.55	46.05
	140	66.72	23.86	90.58
	210	89.30	36.27	125.57
	280	100.79	37.98	138.77
Sids 6	70	26.22	10.95	37.17
	140	60.26	20.31	80.57
	210	67.01	25.93	92.94
	280	80.63	36.18	116.81

TABLE XV. AVERAGE % ^{15}N RECOVERY AND N LOSSES AS AFFECTED BY N-RATE AND VARIETY AT ISMAILIA

Variety	N- rate kg N/ha	Recovery in plant Grain	Straw	Losses
Sakha 69	70	46.43	19.36	33.91
	140	47.66	17.04	35.30
	210	42.52	12.95	44.53
	280	36.00	13.46	50.44
Sids 6	70	37.46	15.64	46.90
	140	43.04	14.51	42.45
	210	31.91	12.35	55.74
	280	28.80	12.92	58.28

TABLE XVI. AVERAGE YIELD OF THREE WHEAT CULTIVARS (kg/ha) AT NUBARIA (1996–1997)

Cultivar	N-Level (kg N/ha)	Grain Yield (t/ha)	Straw Yield (t/ha)
Sakha 69			
	N00	1.574	5.593
	N70	2.792	7.875
	N140	2.999	9.333
	N210	3.518	9.981
	Average	**2.721**	**8.200**
Sids 6	N00	1.218	4.466
	N70	1.933	6.900
	N140	2.345	7.155
	N210	2.991	8.342
	Average	**2.122**	**6.716**
	N00	1.989	5.602
Sids 1	N70	3.232	10.309
	N140	3.883	9.534
	N210	4.494	10.507
	Average	**3.400**	**8.988**
LSD (0.05) values for:			
Diff. N-level & same cultivar		0.519	1.804
Same N-level & diff. cultivar		0.862	2.071
	N	ANOVA effect	
	Cultivar (C)	(0.300)***	(1.041)***
	N X C	(0.772)***	(1.492)***
		NS	NS

Values between practices represent the LSD at 0.05 significant levels for the averages.
*, **, *** Significant at the 0.1, 0.01 and 0.001 probability levels, respectively.

TABLE XVII. NITROGEN UPTAKE (kg N/ha) BY THREE WHEAT CULTIVARS AT NUBARIA (1996–1997)

Variety	00	70	140	210
Sakha 69	23.45	54.73	97.05	129.69
Sids 6	18.39	41.08	78.47	104.01
Sids 1	26.21	66.01	115.25	149.85

TABLE XVIII. AVERAGE GRAIN AND STRAW YIELDS OF TWO WHEAT CULTIVARS AT EL SERW (1995–1996)

Cultivar	N-Level	Grain Yield (t/ha)	Straw Yield (t/ha)
Sakha 69	N000	5.03	10.16
	N070	6.01	13.63
	N140	7.60	17.94
	N210	8.40	16.99
	Average	**6.766**	**14.68**
Sakha 8	N000	3.50	5.72
	N070	5.20	8.29
	N140	6.08	11.29
	N210	6.22	11.09
	Average	**5.230**	**9.100**
LSD (0.05) values for:			
diff. N-level & same cultivar same		1.163	2.527
N-level & diff. cultivar		1.258	2.354
		ANOVA effect	
	N	*** (0.822)	*** (1.786)
	Cultivar (c)	* (0.992)	*** (1.234)
	I	NS	NS
	N X I	NS	NS
	N X C	NS	NS
	C X I	NS	NS
	N X C X I	NS	*

Values between practices represent the LSD at 0.05 significant levels for the averages.
*, *** Significant at the 0.1, 0.01 and 0.001 probability levels, respectively.

TABLE XIX. NITROGEN UPTAKE (kg N/ha) BY TWO WHEAT CULTIVARS AT EL SERW (1995–1996)

Variety	Control	70	140	210
Sakha 69	100.8	146.5	200.0	267.9
Sakha 8	56.9	101.7	176.7	190.7

TABLE XX. NITROGEN DERIVED FROM FERTILIZER (NDFF) APPLIED AT RATE OF 140 kg N/ha AT EL SERW (1995/1996)

Variety	**Dose applied as ^{15}N labeled fertilizer**	**Ndff (kg N/ha)** Grain	Straw	Total
Sakha 69	1/3	13.10	5.99	19.09
	2/3	77.66	26.61	104.27
	The whole	79.77	30.86	110.62
Sakha 8	1/3	22.71	11.45	34.16
	2/3	49.85	17.91	67.75
	The whole	59.24	27.46	86.70

TABLE XXI. AVERAGE % ^{15}N RECOVERY AND N LOSSES FROM FERTILIZER APPLIED AT RATE OF 140 kg N/ha AT EL SERW (1995–1996)

Variety	Recovery in plant		Recovery in soil (depth — cm)			Losses
	Grain	Straw	0–20	20–40	40–60	
Sakha 69	56.98	22.04	1.8	1.1	0.85	17.23
Sakha 8	42.31	19.61	1.9	1.5	0.72	33.96

TABLE XXII. NITROGEN DERIVED FROM FERTILIZER (NDFF) AND NITROGEN DERIVED FROM SOIL (NDFS) UNDER WHEAT AS TREATED WITH N FERTILIZER AT RATE OF 140 kg N/ha AT EL SERW (1995–1996)

Variety	Ndff	Ndfs
	kgN/ha	
Sakha 69	110.62	89.39
Sakha 8	86.70	90.05

TABLE XXIII. AVERAGE GRAIN YIELD OF WHEAT (t/ha) AS AFFECTED BY IRRIGATION, N-RATES AND WATER TABLE LEVEL

N-rate	I1 (4 irrigations)		I2 (5 irrigations)		Mean (N)
	Shallow	Deep	Shallow	Deep	
N0	2.1	2.2	1.8	2.3	2.1d
N70	3.5	3.9	2.5	3.0	3.3c
N140	4.3	4.6	3.5	4.6	4.4b
N210	5.0	5.7	5.1	5.1	5.4a
Mean	4.0a		3.6b		

LSD (0.05) for N-rates = 0.36
LSD (0.05) for irrigation = 0.21

3.2. Newly reclaimed land

3.2.1. Sandy soil – Ismailia site

The grain and straw yields under the sandy-soil conditions of Ismailia (Table XII) were lower than those obtained at Giza for the 1995–96 season. Grain yield from the without-N control at Giza (3.68 Mg ha^{-1}) was higher than that obtained at Ismailia with 70 kg N ha^{-1} (2.31 Mg ha^{-1}), reflecting the poor chemical and physical properties of that sandy soil (Table II). Similar to its performance on the clay soil, the yield of Sakha 69 was significantly higher than that of Sids 6.

When three cultivars were compared in the 1996–97 season, Sids 6 yielded more poorly than both Sakha 69 and Sids 1 (Table XIII). Nitrogen-fertilizer applications resulted in significant increases of yield of all three.

Although the average grain yields of the three cultivars were similar for all N rates, Sids 1 was more responsive to the low rate of 70 kg N ha^{-1} (Table XIV). The relatively low yield of Sakha 69 could have been due to wheat rust.

Cultivar Sakha 69 used fertilizer N more efficiently than did Sids 6 for all rates applied (Table XV). Residual fertilizer N was not detectable by ^{15}N analysis, probably due to the high-sand content of the Ismailia soil. Nitrogen losses ranged between 34 and 58%, depending on cultivar and rate of N applied (Table XVI). Percent Ndfs values were low at Ismailia, as compared with the other two sites, with an average of 15%.

3.2.2. Calcareous soil – Nubaria site

Cultivar Sids 1 was more responsive to applied N than was Sakha 69 or Sids 6, and produced the highest grain and straw yields (Table XVII). Nitrogen-use-efficiency values (kg grain kg^{-1} N) were 39, 28 and 46 for Sakha 69, Sids 6 and Sids 1, respectively (Table XVIII).

3.3. Salt affected soil – El Serw site

For the 1995–96 growing season, a grain yield of 4.3 t ha^{-1} was obtained from the check plots, reflecting high soil fertility, with Sakha 69 yielding 29% more than did Sakha 8 (Table XIX). The data show that although Sakha 69 yielded more than did Sakha 8, the former was less responsive to applied N, especially at the low rate: fractional increases in grain yield of Sakha 69 were 19, 51 and 67% to applications of 70, 140, and 210 kg N ha^{-1}, respectively, whereas the corresponding responses for Sakha 8 were 49, 74 and 78%. Sakha 69 assimilated more applied N than did Sakha 8 (Table XX).

Although higher Ndff values were obtained for Sakha 69 than for Sakha 8, Ndff for the first of the split applications was higher for Sakha 8 (Table XXI). Percent N recoveries with 140 kg N ha^{-1} were 79 and 62 for Sakha 69 and Sakha 8, respectively, with an average of 26% lost (Table XXII). About 90 kg N ha^{-1} were derived from soil (Ndfs, Table XXIII).

For the 1997–98 season, water table levels were measured every 3 days; average depths were determined to be 52 and 83 cm for plots close to the irrigation canal and those close to the drain, respectively. There were significant decreases in grain yields due to the shallower water table and to five irrigations. Nitrogen fertilization resulted in significant increases in yield.

4. CONCLUSIONS

In these field trails, wheat cultivars were planted in Egypt's main soil types, representing the old irrigated clay soils, newly reclaimed sandy and calcareous soils, and salt-affected soil of the north delta. Yield responses to N fertilizer were affected by cultivar as well as by soil type. In the clay soil, Sakha 69 was more responsive to applied N than were the other two varieties, more responsive than Sids 6 in the sandy soil, and in the saline soil more responsive than Sakha 8. However, Sids 1 had higher grain and straw yields in the calcareous soil. In the salt-affected soil, the higher water table negatively affected N uptake and yield. Recovery of fertilizer N, estimated using ^{15}N, was always higher for Sakha 69, however, Sids 6 and Sakha 8 more efficiently assimilated the first of the split doses of applied N. Losses of applied N ranged between 17 and 59%, with the higher values obtained for the sandy soil.

OPTIMIZING NITROGEN UPTAKE EFFICIENCY BY IRRIGATED WHEAT TO REDUCE ENVIRONMENTAL POLLUTION

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Abstract

Two wheat cultivars (Sham 3 and Sham 6) were grown after fallow for two seasons and after wheat for another two seasons, with sprinkler irrigation. Four N-fertilizer rates (0, 50, 100, and 150% of the recommended dose) were used. A neutron moisture probe was used to determine the time and amount of irrigation. Nitrogen-15 was used to determine the fate of fertilizer N. Porous ceramic samplers were installed at different depths in micro-plots fertilized with ^{15}N to monitor its movement in the soil. Dry biomass and grain yield of wheat after fallow were much higher than those of wheat after wheat. The effects of increasing amounts of N fertilizer were significant during the four seasons, but were more pronounced in wheat after wheat. The appropriate timing and amount of irrigation water contributed to high fertilizer-N recovery (between 44 and 75%). Plants recovered N fertilizer applied at tillering more efficiently than when it was applied at germination. Labelled N analysis showed no deep percolation of N fertilizer with water during the same growing season. Water use efficiency of wheat after fallow was almost twice that of wheat after wheat, and N fertilization of wheat after wheat increased the water use efficiency two to three fold. Chlorophyll readings with all treatments were high during the first and second seasons, especially those fertilized with the recommended N rate or more. These results were in agreement with Ceres-Wheat model output, where it did not predict any N stress. Nitrogen deficit was observed by eye, and was indicated by the Ceres-Wheat model and chlorophyll-meter readings on plants fertilized with low rates of N during the last two seasons. Acceptable agreement was observed between model prediction of soil-water content and that determined using isotopic techniques, and between observed and predicted grain yields and biomass, N yields of grain and total N yields. However, predictions of the model for some variables were weak, indicating a need for refinement of the parameters controlling these variables. The model outputs during the first and second seasons showed that the Ceres-Wheat model is a promising tool to decide the time and rate of N fertilization and water applications, and yield predictions under specified conditions.

1. INTRODUCTION

Wheat, the main source of nutrition in the Syrian diet, is widely planted. Yields fluctuate, especially when grown under rainfed conditions, which has led to increases in irrigation. The limited availability of irrigation water, the necessary importation of large amounts of N fertilizer and the possibility of groundwater pollution due to its application, dictate the need for appropriate management strategies. The use of isotopically labelled fertilizer and the neutron probe to monitor soil moisture [1] can assist in determining optimum amounts and timing of fertilizer and irrigation. Furthermore, the effects of management practices may be determined on the portions of fertilizer N (i) recovered by the crop, (ii) remaining in the soil and available for the succeeding crop, (iii) volatilized and (iv) leached below the root zone. Recommendations for other soils, climatic conditions, and management practices can be achieved using computer-simulation models after their validation with data from experiments using isotopic techniques. These computer models can rapidly simulate years of land treatment, plant growth and yield; SWATRE [2], NTRM [3], NLEAP [4] and Ceres-Wheat DSSAT-3 [5] are examples of such models.

In this study, we set up a four-season experiment in which durum- and bread-wheat cultivars were grown under irrigated conditions. We used isotopic techniques, recorded daily weather conditions and used a chlorophyll meter to fulfill the following objectives:

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– Measure percent recovery of fertilizer N by wheat, percent remaining in the soil for a succeeding crop, and percent lost,
– Evaluate the possibility of groundwater pollution by the applied N,
– Evaluate the chlorophyll meter as a tool for crop-N-deficiency determination,
– Test the applicability of computer-simulation models such as Ceres-Wheat for yield prediction and other crop-growth components, and groundwater pollution.

2. MATERIALS AND METHODS

2.1. Site

The 2-ha field was located in a wheat-growing area of Aleppo Province, about 30 km southwest of the city of Aleppo, 36°05'N 36°55'E, altitude 300 m. The average rainfall in the area is about 350 mm, most of which falls between November and April; it is classified as semi-arid. Soil samples at 15-cm intervals to a depth of 120 cm were collected to determine the physical and chemical properties (Tables I and II). The soil had been fallow for 17 months before planting the first and second seasons. Wheat was the previous crop for the third and fourth growing seasons.

TABLE I. SOME PHYSICAL PROPERTIES OF THE SOIL AT SURBAYA (SYRIA)

Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Texture	K_{sat} (m/s)	FC_v (%)	PWP_v (%)
0–15	29.45	33.58	36.97	CL	0.048	40.40	26.66
15–30	24.18	32.49	43.33	C	0.042	41.30	26.97
30–45	16.15	31.10	52.75	C	0.033	41.90	27.73
45–60	16.46	32.34	51.20	C	0.038	42.50	28.26
60–75	16.46	32.34	51.20	C	0.038	42.90	29.53
75–90	16.31	32.39	51.30	C	0.038	44.20	29.10
90–105	16.69	26.87	56.44	C	0.057	45.70	28.70
105–120	16.69	26.87	56.44	C	0.035	45.90	29.20

K_{sat} = Saturated hydraulic conductivity; FC_v = Field capacity; PWP_v = Permanent wilting point

TABLE II. SOME CHEMICAL PROPERTIES OF THE SOIL AT SURBAYA (SYRIA)

Depth (cm)	EC_e (dS/m)	PH	OM (%)	CEC (cmol/kg)	SAR
0–15	1.00	8.00	0.70	36.53	0.38
15–30	0.80	8.20	0.70	37.73	0.22
30–45	0.70	8.00	0.50	38.04	0.24
45–60	0.80	8.00	0.50	36.72	0.55
60–75	0.80	8.10	0.50	35.49	2.17
75–90	0.70	8.20	0.50	35.97	2.11
90–105	0.80	8.30	0.50	35.05	2.01
105–120	1.00	8.20	0.50	33.61	2.21

2.2. Design

For the four growing seasons, 1994–5 to 1997–8, four N-fertilizer rates were applied as follows: N_0 unfertilized check, $N_{0.5}$ 50% of the recommended rate, $N_{1.0}$ 100% the recommended rate, and $N_{1.5}$ 150% the recommended rate. The selected recommended rate ($N_{1.0}$) was 100 kg N ha^{-1} in the second growing season otherwise it was 120 kg N ha^{-1}. Ammonium sulfate was the source of N in the first season, and urea was applied in the other seasons.

Triticum durum cv. Sham 3, designated "V1," and *Triticum aestivum* cv. Sham 6, "V2," were selected. When soil-moisture content of the upper 45 cm reached 50% of field capacity, sprinkler irrigation was applied such that the whole soil profile of plots of the treatment N_1V1 to 95% achieved field capacity. Seeding rate was 187 kg ha^{-1} and row spacing 20 cm.

A completely randomized factorial experimental design was used for the eight treatments N_0V1, $N_{0.5}V1$, N_1V1, $N_{1.5}V1$, N_0V2, $N_{0.5}V2$, N_1V2, and $N_{1.5}V2$. The area of each plot was 5.85×11.7 m (68.5 m^2).

One neutron-probe access tube was installed in each plot (total of 32 tubes) to a 120-cm depth, to monitor moisture changes during the growing period. Two ceramic cups were installed in the plots of the N_1V1 and $N_{1.5}V1$ treatments in 1×1 m micro-plots at depths of 50 and 90 cm to collect water extracts to assess the possibility of groundwater pollution by applied fertilizer that was enriched in ^{15}N fertilizer. Three ceramic porous cups were installed at depths of 30, 60 and 90 cm in each N_1V1 plot during the last two seasons. A Minolta SPAD chlorophyll meter was used to monitor relative crop-N status.

The N-fertilizer rates were split in two applications. One third was applied at complete seedling emergence and two third at Zadoks growth-stage 30. Phosphate-fertilizer was applied each season depending on the initial P level in the topsoil. Preceding crop, planting date, amount of N fertilizer applied, the date of the important phenological stages, and other management practices are presented in Table III.

TABLE III. SCHEDULE OF ACTIVITIES DURING THE FOUR GROWING SEASONS

	Growing seasons			
Activities	1994/5	1995/6	1996/7	1997/8
N Fertilizer rate (kg/ha) (N1)	120	100	120	120
Type of fertilizer	Amm. sulfate	Urea	Urea	Urea
Rain before planting (mm)	127.1	73.1	74.3	114.1
Rain during the season (mm)	243.6	325.9	359.2	292.6
Irrigation (mm)	249.0	113.2	206.3	186.8
Planting date	6/11/94	29/11/95	24/11/96	11/12/97
Full emergence	27/12/94	23/12/95	6/1/97	28/12/97
Zs-30	23/3/95	13/3/96	12/3/97	11/3/98
Anthesis	26/4/95	26/4/96	28/4/97	1/5/98
Physiological maturity	29/5/95	3/6/96	2/6/97	2/6/98
Harvest	20/6/95	19/6/96	23/6/97	23/6/98

2.3. Nitrogen-15

Nitrogen-15 at 10% a.e. was applied [6] as follows in order to determine fertilizer-uptake efficiency and groundwater pollution:

– The one third applied after emergence was enriched in ^{15}N and the two thirds applied at the end of tillering was unenriched. Plant samples were taken at physiological maturity to calculate the recovery of first-split N,
– The one third applied after emergence was unenriched and the two thirds applied at the end of tillering was enriched in ^{15}N. Plant samples were taken at physiological maturity to calculate the recovery of second-split N,
– Nitrogen-15 enriched fertilizer was applied to the micro-plots (one third at emergence and two thirds at complete tillering) in order to study N-fertilizer movement in the soil below the root zone possibly contributing to groundwater pollution.

2.4. Soil and water analyses

Soil samples were taken at 15-cm intervals to a depth of 105 cm at planting, full tillering and final harvest. These samples were analyzed for mineral N using Kjeldahl's method. Soil-moisture readings of the 32 plots were taken at emergence and final harvest, in addition to some readings before irrigation, and 2 days after each irrigation to monitor moisture changes with time, in addition to calculations of crop-water requirement and water-use efficiency (WUE). The moisture readings of the surface 15 cm for the first two seasons were taken using a surface neutron probe (Troxler 3401-B) after its calibration in the field. A depth neutron probe (CPN 503) was used in the last two seasons after its calibration [2] for measuring the moisture content of the surface 15 cm. The CPN 503 was used for soil-moisture determinations below 15 cm depth after in situ calibration [8]. Field capacity was determined in the field using a neutron probe after obtaining the appropriate calibration curves. Water use was calculated from the following water balance equation

$$I + P(D + ET) = \pm \Delta S$$

where

I	is irrigation,
P	is precipitation,
D	is deep percolation,
ET	is evapotranspiration,
ΔS	is change in soil moisture.

Physical and chemical properties of the soil were determined [8, 9] (Tables I and II). Clay content was generally high and increased with depth in association with reduction in saturated hydraulic conductivity. The elevated clay content and swelling-type clay minerals kept the moisture content at field capacity and permanent wilting point high, in addition to the cation-exchange capacity. The organic matter content of the soil was low, and it was neither saline nor alkaline.

2.5. Climate

Daily air-temperature maxima and minima, precipitation, and solar radiation were collected daily from a nearby weather station.

2.6. Yield

Two types of harvest were made on each plot: machine harvest of an area of 12 m^2 and hand harvest from 2 m^2. Average yields were calculated from both.

3. RESULTS AND DISCUSSIONS

3.1. Yield

Grain yields were generally high for the 1994–5 and 1995–6 seasons (Table IV), attributable to high soil NO_3^--N (Table V) and moisture content at sowing (Fig. 1) after fallow. Positive effects of applied N were clear: increases of 14, 16 and 23% were obtained in response to the $N_{0.5}$, $N_{1.0}$ and $N_{1.5}$ treatments, respectively compared with the unfertilized check N_0. During both seasons, there was severe lodging with the $N_{1.5}V1$ treatment and to a lesser degree with N_1V1 and $N_{1.5}V2$. Moreover, differences between the yields obtained with $N_{1.5}$ and $N_{1.0}$ were small, therefore, we suggest that fertilizer not be applied at high rates of N when mineral-N and moisture contents are high at planting. In the last two seasons, when grown after wheat, grain yields were lower as a consequence of lower NO_3^--N and less soil moisture at sowing. Unusually low temperatures for long periods and elevated temperatures at anthesis during the last two seasons may have contributed to low grain yields. During these seasons, lodging occurred only with the $N_{1.5}V1$ treatment. Reducing plant density,

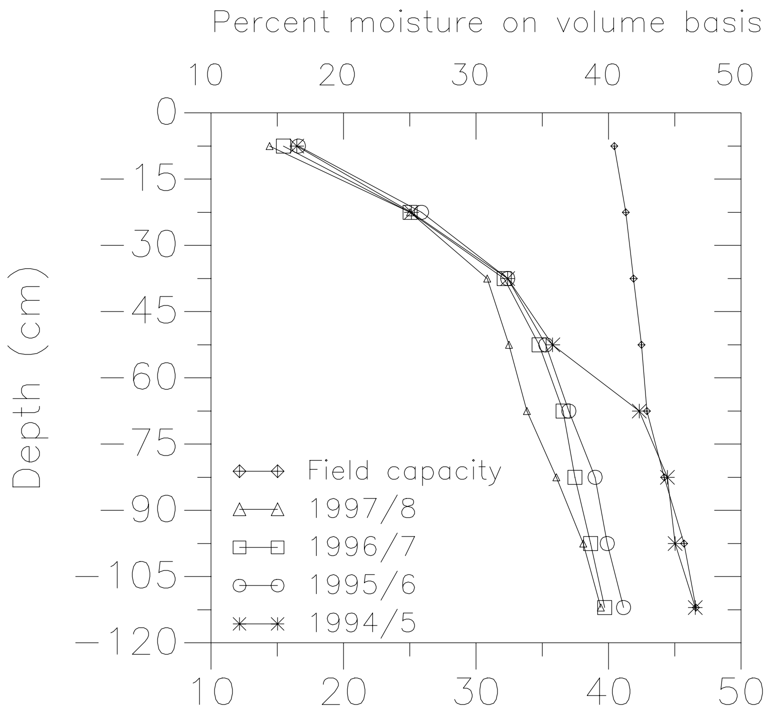

FIG. 1. Percent moisture in each soil layer at the start of the four seasons.

TABLE IV. AVERAGE DRY GRAIN YIELD (kg/ha) AND HARVEST INDEX

		N fertilizer rate							
		N_0		$N_{0.5}$		N_1		$N_{1.5}$	
Season	Cultivar	DGY	HI	DGY	HI	DGY	HI	DGY	HI
1994/5	Sham 3	6213	0.391	6527	0.394	6968	0.409	7500	0.400
	Sham 6	4963	0.307	5328	0.337	5172	0.333	5631	0.342
1995/6	Sham 3	4881	0.383	6659	0.384	6133	0.387	6587	0.363
	Sham 6	5168	0.338	5815	0.379	6413	0.359	6478	0.370
1996/7	Sham 3	1146	0.486	2450	0.389	3247	0.378	3775	0.388
	Sham 6	1129	0.467	2670	0.367	3728	0.405	4518	0.404
1997/8	Sham 3	1082	0.241	2727	0.253	3517	0.275	3693	0.290
	Sham 6	1481	0.272	2860	0.305	4019	0.301	4120	0.291

DGY= Dry grain yield, HI = Harvest index

TABLE V. MINERAL N IN THE SOIL (kg/ha) AT SOWING, FULL TILLERING AND HARVEST TIME OF N1V1 TREATMENT

	1994	1995	1996	1997	1998
NO3-N reserves at sowing (Kg N/ha)	136.15	131.35	40.66	34.80	
NH4-N reserves at sowing (Kg N/ha)	13.67	2.60	69.17	69.30	
NO3-N reserves at ZS 30 (Kg N/ha)		152.83	157.40	107.35	10.56
NH4-N reserves at ZS 30 (Kg N/ha)		69.35	33.27	48.81	13.07
NO3-N reserves at harvest (Kg N/ha)		96.98	62.50	26.53	7.56
NH4-N reserves at harvest (Kg N/ha)		32.26	65.08	52.05	24.40

TABLE VI. DRY WEIGHT OF 1000 GRAIN OF SHAM 3 AND SHAM 6 CULTIVARS UNDER THE DIFFERENT N FERTILIZER APPLICATION RATES AT SURBAYA STATION DURING THE FOUR GROWING SEASONS

		N application			
Season	Cultivar	N0	N0.5	N1	N1.5
1994/5	Sham 3	A 42.42 a	A 41.53 ab	A 38.87 b	A 40.03 b
	Sham 6	B 32.88 a	B 33.19 a	B 32.04 ab	B 30.08 b
1995/6	Sham 3	A 42.42	A 41.99	A 41.44	A 41.91
	Sham 6	B 33.47	B 32.33	B 33.07	B 33.48
1996/7	Sham 3	A 27.96	A 30.44	A 28.55	A 28.19
	Sham 6	B 23.27	B 24.06	B 22.72	B 23.06
1997/8	Sham 3	A 30.95 b	A 31.64 b	A 34.38 a	A 31.52 b
	Sham 6	B 29.52 b	B 31.61 a	B 31.80 a	B 28.53 b

Difference in capital letter means significant difference at 1% confident level in cultivar within the same season.
Difference in small letter means significant difference at 1% confident level in fertilizer level for the same cultivar within the same season.

top-dressing at anthesis, and ethephon application are management practices that minimize lodging [11].The atypical temperatures during the last season affected harvest index (HI) values (Table IV). The 1,000-grain weight was also affected by soil and weather conditions; high values were obtained during the first two seasons, 40.7 and 41.9 g, respectively, for cv. Sham 3, compared with 28.8 and 32.1 g during the last two seasons (Table VI). Yields during the last two seasons were 121, 200 and 233% with $N_{0.5}$, $N_{1.0}$ and $N_{1.5}$, respectively, compared with the unfertilized check.

Attempts to correlate grain yield with N-application rate have produced first- and second-order equations [12, 13, 14]. Similar work revealed multi-linear relationships of grain yield as a function of more than one independent variable, the equations being applicable for the same soil, climatic conditions, cultivar and management practice. Such equations help decision making regarding economic N-fertilizer rates and adequate irrigation.

In this study, we obtained the following four first-order equations for grain yield of cv. Sham 3 as a function of N fertilizer rate during the four consecutive seasons:

$$Y = 5{,}890 + 5.58\ NR \qquad r^2 = 0.954$$
$$Y = 5{,}376 + 9.18\ NR \qquad r^2 = 0.519$$
$$Y = 1{,}189 + 15.0\ NR \qquad r^2 = 0.915$$
$$Y = 1{,}461 + 14.4\ NR \qquad r^2 = 0.873$$

where

Y is grain yield (kg ha^{-1}),
NR is N rate (kg N ha^{-1}).

The correlation coefficients were high except that for the second season, which was due to a relatively high yield in one replicate of the second N rate. The intercepts of the first- and second-season equations were similar as were those of the third and fourth seasons, attributable to the previous crop (fallow for the first two, and wheat for the last two seasons). The higher slopes of the regression lines for the latter two seasons reveal stronger grain-yield responses to applied N after wheat, i.e. low mineral N and moisture at planting. The first order response of the four seasons together is represented in the following:

$$Y = 4{,}439 + 86.25\ NR \qquad r^2 = 0.099$$

The very low coefficient demonstrates that this type of equation is applicable only to one season, soil, climatic conditions and management practice. Stronger coefficients were obtained for the five yield-response equations (0.957, 0.735, 0.999, 0.999, and 0.133, respectively) using second-order equations, because yield differences between the $N_{1.5}$ and $N_{1.0}$ treatments were smaller than the differences between $N_{0.5}$ and $N_{1.0}$. The coefficient of the lumped data can be improved by increasing the number of the independent variables that affect yield: initial mineral-N content, initial soil moisture, precipitation, irrigation, etc. There was no need to develop such equations because computer-simulation models (see below) are considered a better tool after validation with data generated in many parts of the world, in different soils, climatic conditions, management practices, and cultivars.

3.2. Nitrogen recovery

Fractional N-recovery values were generally high at 75, 58, 66 and 44% in the four seasons respectively (Tables VII and VIII). Smaller recovery values (8 to 26%) were reported for 1992 to 1995 in the same climatic and soil conditions, but without irrigation [15, 16]. Percent N recovery of the first application split (one third of the total) was smaller than that for the second split in all treatments and during all seasons, which encourages adding a larger portion of N at full tillering and less, if any, at planting. Our high N-recovery values are indications of good irrigation management, i.e. no percolation below the root zone. Moreover, amounts and intensity of rains were low and did not raise soil moisture above water-holding capacity.

TABLE VII. PERCENT N RECOVERY OF SHAM 3 AND SHAM 6 CULTIVARS UNDER THE DIFFERENT N APPLICATION RATES FOR WHEAT GROWN AFTER FALLOW

				N application rate		
Season	Cultivar	Plant part	Split	N 0.5	N 1	N 1.5
1994/5	Sham 3	Spikes	First	44.34	40.42	42.23
		Straw	First	11.05	13.34	16.76
		Spikes	Second	77.14	56.36	67.70
		Straw	Second	16.29	15.45	19.97
		Spikes	Total	66.21	51.05	59.21
		Straw	Total	14.54	14.75	18.90
	Sham 6	Spikes	First	40.20	36.67	40.08
		Straw	First	17.53	19.43	21.06
		Spikes	Second	58.25	63.99	54.54
		Straw	Second	20.50	27.45	27.32
		Spikes	Total	52.24	54.95	47.72
		Straw	Total	19.51	24.78	25.23
1995/6	Sham 3	Spikes	First	24.76	30.94	37.37
		Straw	First	6.38	6.65	10.58
		Spikes	Second	42.46	49.88	62.19
		Straw	Second	11.58	7.55	16.47
		Spikes	Total	36.56	43.57	53.92
		Straw	Total	9.84	7.35	14.51
	Sham 6	Spikes	First	43.51	27.06	41.06
		Straw	First	9.38	5.42	12.39
		Spikes	Second	49.15	45.13	80.83
		Straw	Second	8.56	9.77	12.22
		Spikes	Total	47.27	39.10	67.57
		Straw	Total	8.84	8.32	12.28

TABLE VIII. PERCENT N RECOVERY OF SHAM 3 AND SHAM 6 CULTIVARS UNDER THE DIFFERENT N APPLICATION RATES DRING FOR WHEAT GROWN AFTER WHEAT

				N application rate		
Season	Cultivar	Plant part	Split	N 0.5	N 1	N 1.5
1996/7	Sham 3	Spikes	First	24.39	30.57	29.22
		Straw	First	11.10	12.53	14.89
		Spikes	Second	54.35	50.25	44.08
		Straw	Second	25.79	21.46	21.20
		Spikes	Total	44.36	43.69	39.13
		Straw	Total	20.89	18.49	19.10
	Sham 6	Spikes	First	35.16	26.93	32.40
		Straw	First	11.22	12.67	16.67
		Spikes	Second	74.58	49.87	47.68
		Straw	Second	25.25	22.82	23.16
		Spikes	Total	61.91	42.22	42.59
		Straw	Total	20.57	19.44	21.00
1997/8	Sham 3	Spikes	First	24.76	30.94	37.37
		Straw	First	6.38	6.65	10.58
		Spikes	Second	45.17	30.21	25.98
		Straw	Second	22.09	18.09	17.60
		Spikes	Total	36.70	25.56	22.66
		Straw	Total	17.86	15.01	15.26
	Sham 6	Spikes	First	19.82	18.85	22.92
		Straw	First	5.79	6.55	10.46
		Spikes	Second	43.95	36.75	35.28
		Straw	Second	12.25	12.58	15.14
		Spikes	Total	35.91	30.78	30.16
		Straw	Total	10.10	10.57	13.58

TABLE IX. PERCENT N FERTILIZER REMAINED IN EACH SOIL LAYER OF N1V1 TREATMENT DURING THE FOUR GROWING SEASONS CALCULATED FROM THE LABELED FERTILIZER

	Growing season			
Depth (cm)	1994/5	1995/6	1996/7	1997/8
0–15	68.44	59.95	53.62	46.31
15–30	22.01	19.70	33.99	31.64
30–45	6.37	14.00	8.90	17.47
45–60	1.36	5.91	2.53	2.87
60–75	0.68	0.44	0.45	0.63
75–90	0.00	0.00	0.57	0.55
90–105	1.14	0.00	0.00	0.53

Soil samples analyzed for ^{15}N showed that over 93% of the applied N not taken up by the wheat remained in the top 45 cm (Table IX). These results are in agreement with previous reports that 80% of applied ^{15}N-fertilizer was in the top 20 cm in March as was about 70% at harvest under rainfed conditions in similar climatic and soil conditions [15, 16]. Therefore, the fraction of unrecovered N was consistently small, at 13, 7.4, 1.4 and 18% in the four seasons, respectively. Twenty to 40% of the applied N remained in the soil at final harvest (Table X) mainly in the top 45 cm.

TABLE X. PERCENT FERTILZER N UNRECOVERED BY CROP

Season	1994–5	1995–6	1996–7	1997–8
N remained	21.21	40.80	36.43	40.62
N leached	Trace	Trace	Trace	Trace
N unaccounted	12.99	7.49	1.39	18.47

TABLE XI. GRAIN N% OF SHAM 3 AND SHAM6 CULTIVARS UNDER THE DIFFERENT N FERTILIZER APPLICATION RATES AT SURBAYA STATION DURING THE FOUR GROWING

		N application rate			
Season	Cultivar	N0	N0.5	N1	N1.5
1994–5	Sham 3	2.07	2.28	2.41	2.55
	Sham 6	1.85	2.11	2.16	2.31
1995–6	Sham 3	1.91	2.22	2.63	2.55
	Sham 6	1.84	2.29	2.32	2.46
1996–7	Sham 3	2.05	2.20	2.27	2.89
	Sham 6	1.99	1.88	2.44	2.46
1997–8	Sham 3	2.08	1.67	1.90	2.21
	Sham 6	2.07	1.70	1.85	2.31

TABLE XII. ACTUAL EVAPOTRASPIRATION OF SHAM 3 AND SHAM 6 CULTIVARS UNDER THE DIFFERENT N APPLICATION RATES DRING THE FOUR GROWING SEASONS

		N application rate			
Season	Cultivar	N_0	$N_{0.5}$	N_1	$N_{1.5}$
1994/5	Sham 3	474.5	479.6	511.4	545.9
	Sham 6	508.6	497.7	511.4	524.4
1995/6	Sham 3	413.0	481.6	497.5	498.7
	Sham 6	423.2	450.0	469.6	498.8
1996/7	Sham 3	511.4	555.9	553.5	579.7
	Sham 6	511.2	560.3	531.5	508.2
1997/8	Sham 3	418.9	448.0	447.7	478.9
	Sham 6	410.4	416.3	457.5	479.7

The amounts of N applied affected %N in the grain (Table XI). The four-season averages for the two cultivars were 2.0, 2.0, 2.2 and 2.5% for the N_0, $N_{0.5}$, $N_{1.0}$, and $N_{1.5}$ application rates, respectively.

3.3. Water use

Percent moisture at the start of the growing season was highest for the first year, followed by the second, third and fourth (Fig. 1). Grain yields were proportional to initial soil-moisture content. The higher WUEs of the first and second seasons compared with those of the third and fourth seasons (Table XIII) were attributable to high initial water content deep in the profile (Fig. 1). Even distribution of the rain, high initial mineral-N values and the previous fallow were also contributory.

TABLE XIII. WATER USE EFFICIENCY (kg/m^3) OF SHAM 3 AND SHAM 6 CULTIVARS UNDER THE DIFFERENT N APPLICATION RATES DRING THE FOUR GROWING SEASONS

		N application rate			
Season	Cultivar	N_0	$N_{0.5}$	N_1	$N_{1.5}$
1994/5	Sham 3	1.31	1.36	1.36	1.37
	Sham 6	0.98	1.07	1.01	1.07
1995/6	Sham 3	1.18	1.38	1.23	1.32
	Sham 6	1.22	1.29	1.37	1.30
1996/7	Sham 3	0.22	0.44	0.59	0.65
	Sham 6	0.22	0.48	0.68	0.74
1997/8	Sham 3	0.26	0.61	0.79	0.77
	Sham 6	0.36	0.69	0.88	0.86

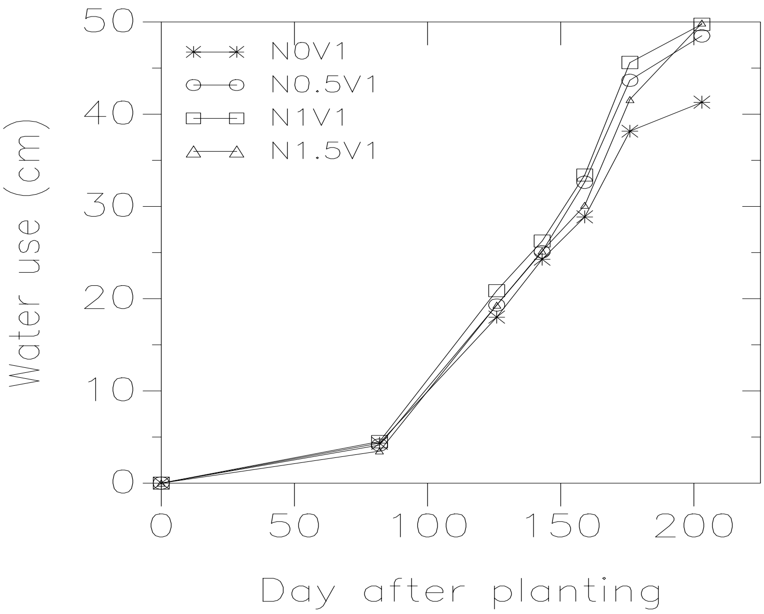

FIG. 2. Cumulative water use for Sham 3 cultivar under the N application rates during 1995/96 season.

The even distribution of the irrigation water and rainfall did not result in even water use in the different treatments, as calculated from the water-balance equation. Actual water use values among the various treatments differed significantly after 50 days (Figs 2 and 3), due to treatment-effects on vegetative growth that influenced water demand by the plants. Water need was generally higher for the bigger plants with the $N_{1.5}$ treatment, which resulted in less remaining in the soil at final harvest (Figs 4 and 5). Grain yield (kg ha^{-1}) / evapotranspiration (m^3 ha^{-1}) values for the $N_{1.0}$ treatments were 1.29, 1.19, 0.661, and 0.840 for the first to the fourth seasons, respectively. And the increases in grain yield (kg ha^{-1}) / amount of irrigation water (m^3 ha^{-1}) applied in each season were 1.89, 2.71, 1.14 and 1.04 for the four seasons, respectively. Adding increasing amounts of N to wheat after wheat increased WUE two to three fold, whereas the increases were less than 25% for wheat after fallow.

Text cont. on p. 46.

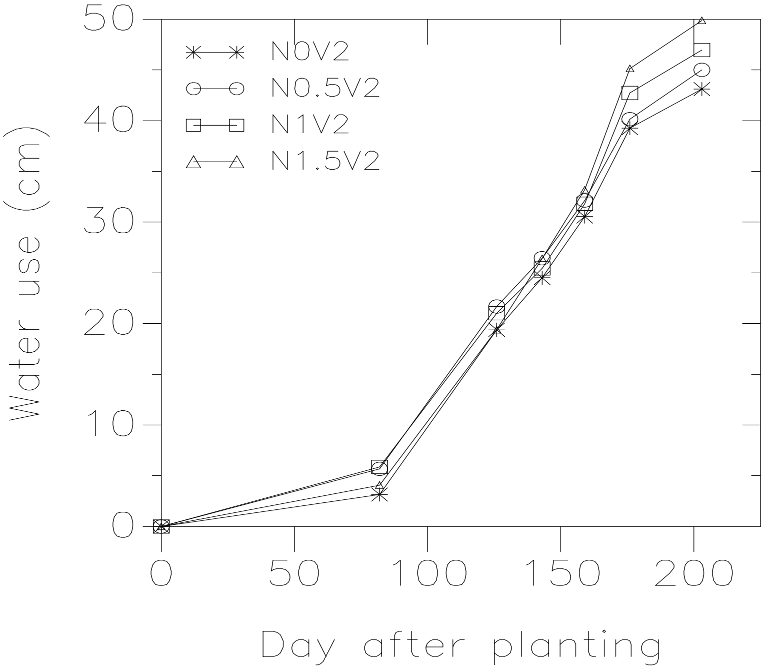

FIG. 3. Cumulative water use for Sham 6 cultivar under the N application rates during 1995/96 season.

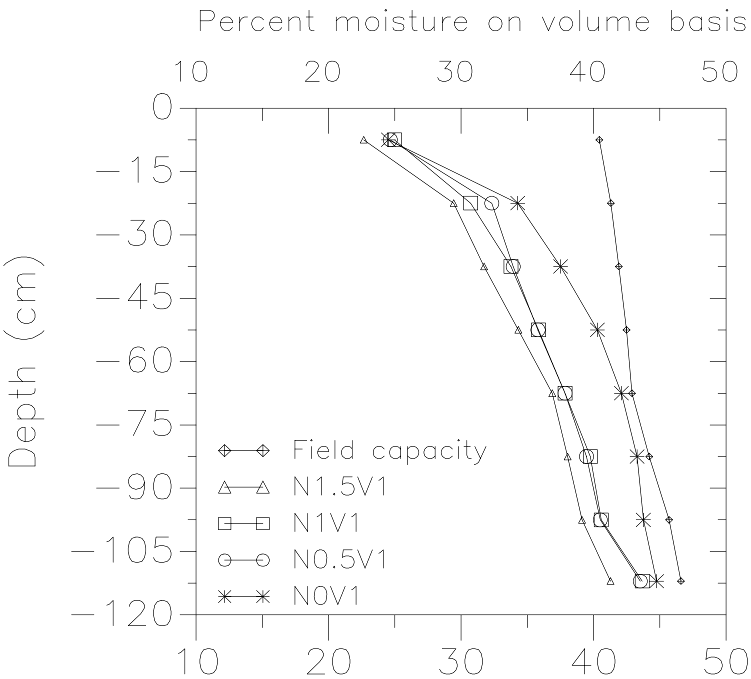

FIG. 4. Percent moisture in the soil profile at the end of the fourth growing season under N application rates of Sham 3 cultivar.

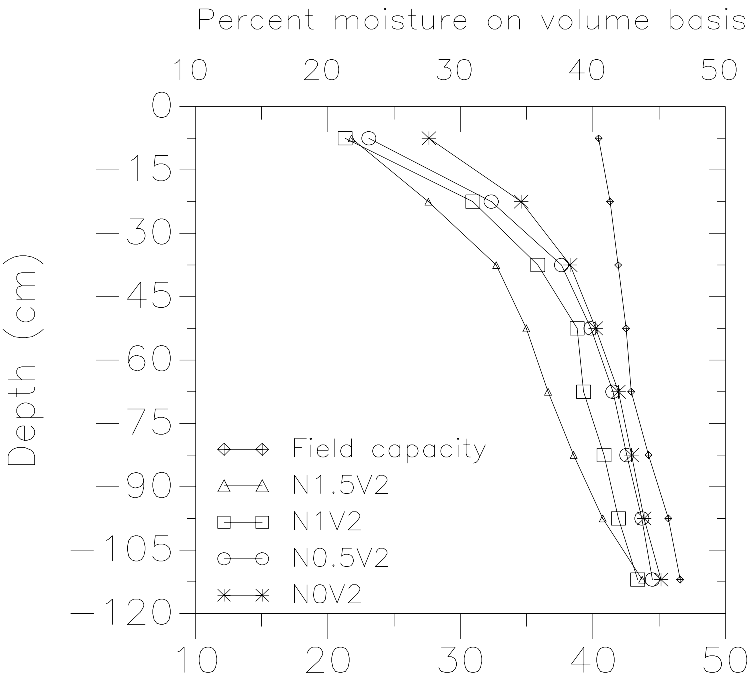

FIG. 5. Percent moisture in the soil profile at the end of the fourth growing season under the N application rates of Sham 6 cultivar.

TABLE XIV. CHLOROPHYLL METER DATA FOR N1V1 TREATMENT

Stage	Treatment	1995	1996	1997	1998
ZS # 20	N_0	NA	35.8	25.1	31.7
	$N_{0.5}$	NA	35.5	31.3	34.1
	N_1	NA	35.9	33.9	35.9
	$N_{1.5}$	NA	36.1	32.7	36.4
ZS # 31	N_0	46.9	41.9	28.0	25.8
	$N_{0.5}$	45.1	42.2	32.9	30.7
	N_1	45.9	39.9	36.8	38.9
	$N_{1.5}$	46.2	41.8	37.1	41.8
ZS # 39	N_0	44.8	44.9	27.9	25.0
	$N_{0.5}$	47.7	46.4	39.1	36.7
	N_1	48.5	47.0	40.1	38.5
	$N_{1.5}$	48.9	48.8	43.4	42.3
ZS # 50	N_0	40.5	41.9	31.3	22.5
	$N_{0.5}$	45.9	49.4	39.9	32.0
	N_1	51.0	47.9	42.5	37.5
	$N_{1.5}$	52.6	49.3	49.4	42.3

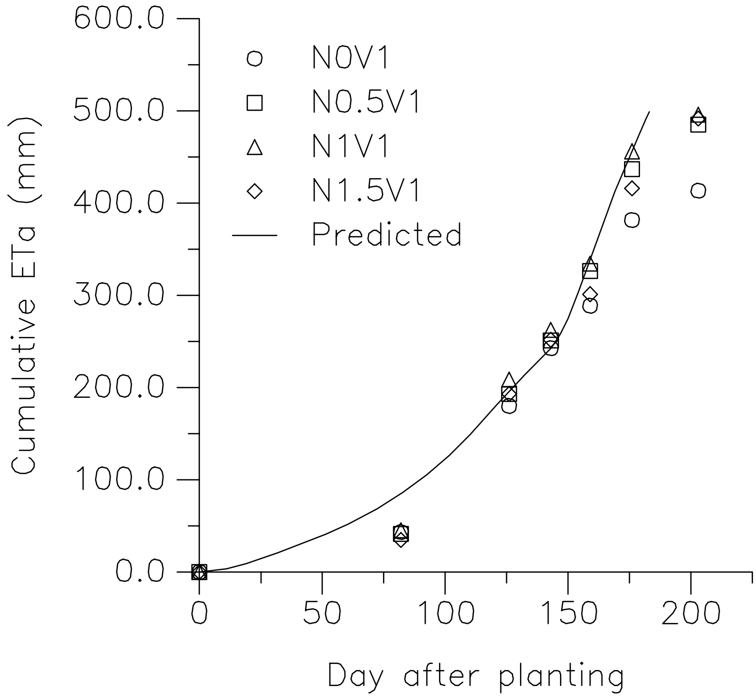

FIG. 6. Cumulative average predicted ETa and observed ETa of Sham 3 cultivar during the second growing season.

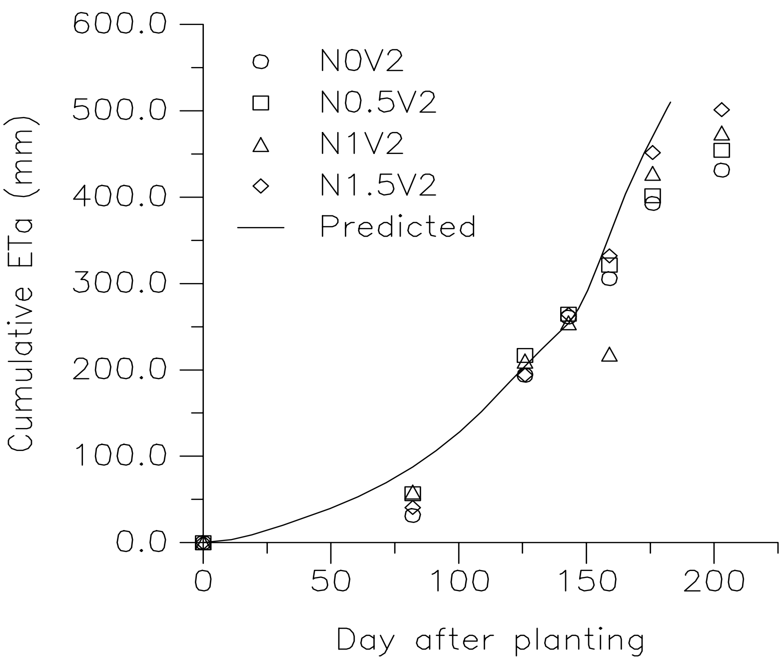

FIG. 7. Cumulative average predicted ETa and observed ETa of Sham 6 cultivar during the second growing season.

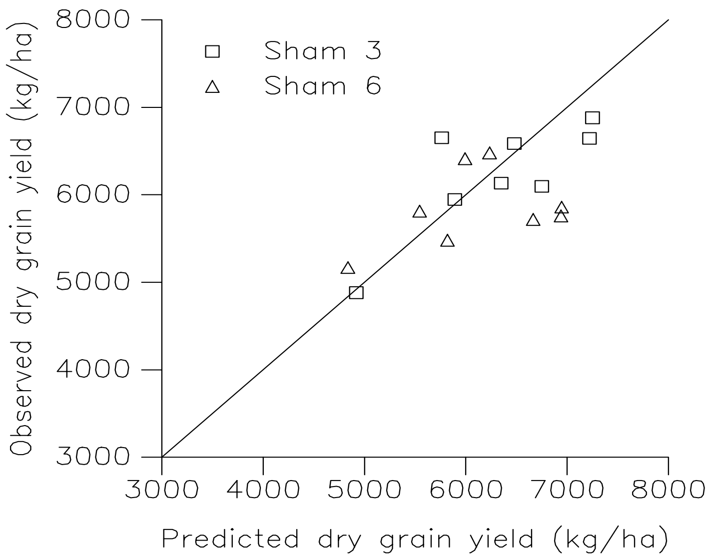

FIG. 8. Observed and predicted dry yield around one to one line during the first and second growing season.

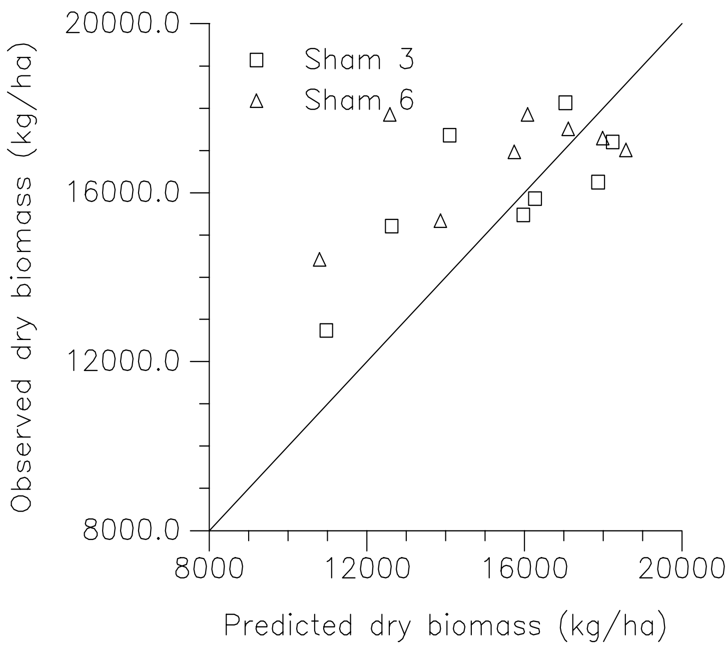

FIG. 9. Observed and predicted dry biomass yield around one to one line during the first and second growing seasons.

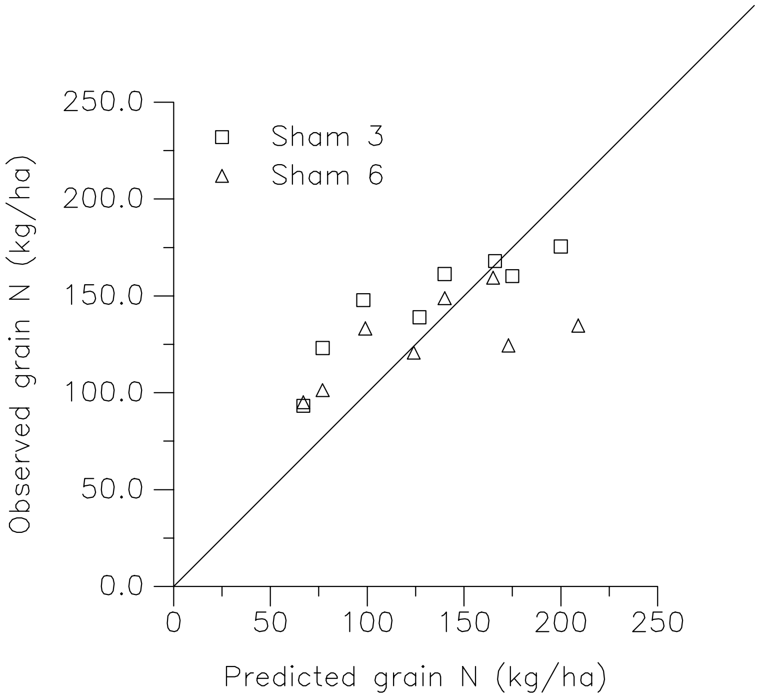

FIG. 10. Observed and predicted grain N around one to one line during the first and second growing seasons.

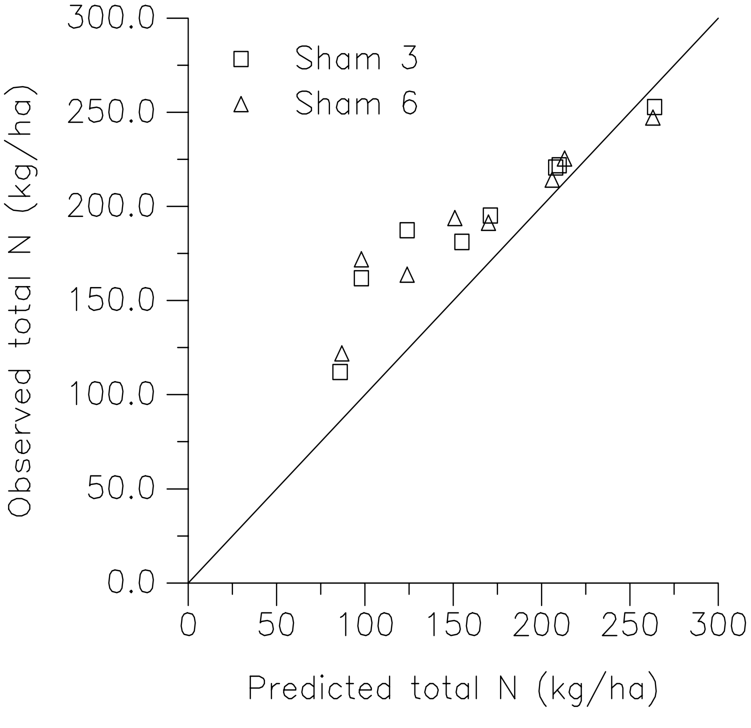

FIG. 11. Observed and predicted biomass N around one to one line during the first and second growing seasons.

3.4. Chlorophyll-meter readings

The effects of increasing rates of N fertilizer resulted in significant differences in the SPAD chlorophyll-meter readings (Table XIV). These differences were clearer during the last two seasons, when wheat was grown after wheat and differences in the N-status of the leaves were more pronounced. The data indicate that, in the future, the chlorophyll meter will have utility for indicating the onset of N deficiency in wheat.

3.5 Ceres-Wheat model

The results with the highest N-fertilizer rate in the first season were used to find the genetic coefficients of the two cultivars. After getting these coefficients, runs of the model were made to verify the performance of some parts of it, in addition to its validation of data collected from the two cultivars with four N rates for two seasons. The predicted values of ETa were close to those measured by neutron probe (Figs 6 and 7). However, the predicted differences in ETa among N treatments were small and did not reflect the differences in dry biomass yield as did the measured ETa (Figs 6 and 7). Since the predicted ETa values for each season and cultivar were similar, we drew one line for the cumulative ETa predicted by the model with four sets of symbols for that measured by neutron probe. The model did not predict water stress except for slight stress at the end of the two seasons, as expected from water management of the experiment. Nitrogen deficits were predicted in the unfertilized check and to a some degree in the $N_{0.5}$ treatment, whereas no N stress was observed with $N_{1.0}$ or $N_{1.5}$ with either cultivar during the first two seasons, as expected.

4. CONCLUSIONS

- Nitrogen fertilizer recovery values were high, ranging between 44 and 75% and there was negligible movement of N below the root zone. Almost all of the N that the plants did not recover remained in the upper 45 cm of the soil. These results indicate appropriate irrigation and fertilization management during the course of the study,
- Nitrogen applied at full tillering was taken up more efficiently than that applied at complete emergence. High initial fertility and the moist soil were reasons for high WUEs in the first two seasons, when wheat was grown after fallow; WUE values for wheat after fallow were almost twice those for wheat after wheat. The application of the recommended rate of N fertilizer during the last two seasons resulted in the highest WUE, with a value triple that obtained with the unfertilized check,
- Chlorophyll-meter readings were proportional with plant N status, however, more work is needed to determine the amount of N required to correct N deficits indicated by SPAD-meter data or to predict grain-protein content at maturity from readings at a specific growth stage,
- Acceptable agreements were found between measured and DSSAT-3 model predictions of grain N, total biomass, total N yield, N loss below the root zone and ETa. However, the model did not accurately predict differences in ETa values, as measured by neutron probe, for the various N-application rates. Nevertheless, the DSSAT-3 model is a promising tool for predicting the time and the rate of N fertilization, water applications, and yield predictions under specified conditions.

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IMPROVING EFFICIENCIES OF IRRIGATION AND NITROGEN UPTAKE IN WHEAT

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Abstract

Three years of field studies and lysimeter experiments on irrigated wheat had the objective of finding ways of managing irrigation and N fertilization to minimize losses and reduce contamination of groundwater. Applied N had significant positive effects on crop-water consumptive use. The highest N losses occurred during early growth. Irrigation had little effect on N loss when it was practiced efficiently. Under the prevailing conditions, it is recommended that no N be applied to wheat at planting, in order to limit N losses by leaching caused by the high precipitation that usually occurs during early development when crop-N requirements are small. No more than 120 kg N ha^{-1} should be applied in total to minimize groundwater pollution and maximize N-uptake efficiency and economic returns. Also, for economic and environmental reasons, irrigation should be limited to 80% of the total requirement and to depths of 40 to 60 mm.

1. INTRODUCTION

One of the major problems facing the project area in the Doukkala region of Morocco is increasing N in groundwater as a result of excessive fertilization and poor management of irrigation. Values exceeding the limit of 50 mg N L^{-1} have been found in several wells that are sources of drinking water. The objective of the present study was to develop ways of managing irrigation and fertilization so as to minimize N losses and simultaneously decrease pollution of the environment. The optimal application of N without yield penalty, its timing with respect to irrigation and crop-growth stage are key elements that must be better understood through research, and implemented as soon as possible through extension.

The scope of the project was to conduct field experiments and use lysimeters, with ^{15}N, to monitor patterns of N uptake and loss, and determine water balances under irrigated wheat.

2. MATERIALS AND METHODS

The study at a Moroccan Government Experiment Station (32°64'N 8°26'E, altitude 146 m), within an irrigated area of 60,000 ha where wheat and sugar beet are intensively cropped. The climate is semi-arid, with highly variable precipitation around a mean of 288 mm $year^{-1}$, concentrated between October and March. Mean annual temperature for the past 28 years is 18.6°C, but the daily maximum can exceed 45°C during July; frosts occur, but are exceptional. The annual sunshine duration is over 3,000 h and mean relative humidity is 75 to 80%. Class-A pan evaporation is approximately 1,700 mm, with daily values varying between 2 and 8 mm, depending on the season. Winds are moderate, with speeds above 4 m s^{-1} only on a limited number of days each year.

2.1. Planting

The experimental field had been previously planted to sugar beet. It was deep plowed during summer then, prior to planting, was plowed again and fertilized with 90 kg phosphate ha^{-1} and 120 kg K ha^{-1}. Mechanical sowing of wheat, cv. Karim, took place on December 12, at the 200 kg seed ha^{-1}. This genotype is recommended for cultivation under irrigation because of its high yield potential.

2.2. Layout

The experiment consisted of a split-plot design with two factors: amount of N fertilizer (0, 120, or 180 kg N ha^{-1} as ammonium sulphate) and irrigation regime [T1: 100%, T2: 80%, or T3: 60% of maximum water requirement (ETM)] of wheat, which was determined based on daily reference

TABLE I. FORM, TIMING AND AMOUNT OF N APPLIED TO THE DIFFERENT TREATMENTS

Watering regime	N supply (kg N/ha)	Microplot	N supply stage	
			early tillering	Zadocks-30
		MP1	40*	80
T1	120	MP2	40	80*
		MP1	60*	120
	180	MP2	60	120*
		MP1	40*	80
T2	120	MP2	40	80*
		MP1	60*	120
	180	MP2	60	120*
		MP1	40*	80
T3	120	MP2	40	80*
		MP1	60*	120
	180	MP2	60	120*
	120	L1	40*	80*
T2	180	L2	60*	120*

*: treatment enriched with ^{15}N.

evapotranspiration estimated by the Penman-Monteith method multiplied by crop coefficients for wheat as determined locally.

As the soil was found to contain relatively high levels of N at planting, fertilizer applications were split, with one third applied at early tillering and the remainder added at Zadoks growth stage 30 (Z-30) [1], i.e. when crop requirement for N is highest.

Watering regime was applied on a main-plot basis, and N level to the sub-plots. Each of the nine plots had an area of 10 × 30 m. Within each 120 and 180 kg N ha^{-1} sub-plot, two micro-plots of 2 m^2 each were supplied with ammonium sulfate enriched in ^{15}N at 5% a.e.

In addition, two non-weighing drainage lysimeters, cropped with wheat, received 120 kg N ha^{-1} with 80% ETM (lysimeter L1) or 180 kg N ha^{-1} with 80% ETM (L2). The applied N was partitioned as described above, and was labelled with ^{15}N. The lysimeters, each 4 m^2 in area, were treated exactly as the field experiment. They served to determine the amount of percolating water and quantify amounts of leached fertilizer and soil N. Table I shows the amount of N supplied to each treatment as well as their timing and origin.

2.3. Monitoring

Water content of the soil was monitored with a neutron probe throughout the growing season. Access tubes were installed in plots of each treatment, and measurements were taken twice weekly early in the morning at soil depths 0 to 20, 20 to 40, 40 to 60 and 60 to 80 cm. Simultaneously, the neutron probe was calibrated in situ, in two plots located in the middle of the experimental site. In addition, mercury tensiometers were installed around the neutron probe access tube, at the same five depths, with two tensiometers per depth.

Reference evapotranspiration (ETo) and ETM values were estimated on a daily basis using the Penman-Monteith formula, and the data were collected locally with an automatic weather station installed within a conventional weather station adjacent to the trial site. The actual crop-water use was determined based on the in situ water balance method, taking into consideration all components except surface runoff. Drainage below the root zone was quantified using the unsaturated soil hydraulic conductivity that was also determined in situ and the soil-water content and potential that were monitored above and below the depth of 75 cm.

Soil physical and chemical characteristics were determined from composite samples for the following soil layers: 0 to 20, 20 to 40 and 40 to 60 cm. These samples were analyzed in the laboratory for initial soil-N content, determined by the distillation method following extraction with 0.005 M $CaCl_2$ in a soil:solution of 1:10. Soil mineral-N values were determined also immediately before the first fertilizer application, at Z-30, at anthesis and at final harvest. In the micro-plots that received labelled N, soil samples were taken at 20-cm intervals through the root zone to determine total N and ^{15}N content. In addition, the soil solution was extracted using tensionics from the labelled plots of irrigation treatments T1 and T2 receiving 120 kg N ha^{-1}. The soil solution was extracted following irrigation, at depths of 20, 65 and 105 cm.

Drainage water from the lysimeters was collected and measured after each receipt of water, precipitation or irrigation, and preserved frozen pending total-N and ^{15}N-enrichment analyses.

Throughout the growing season, crop development was assessed regularly by monitoring various components, including leaf-area index using portable equipment. Chlorophyll content was followed using a SPAD meter, by taking twenty measurements in each treatment every 15 days. Plant materials were collected and analyzed for total N immediately before the first fertilizer application, at Z-30, at anthesis and at maturity. Total N was determined by the Kjeldahl method based on all aerial materials, except at maturity when grains were separated from the rest.

2.4. Final harvest

At maturity, the crop yields and components thereof were determined from plants collected from two 4-m^2 areas in each plot. Simultaneously, the two central wheat rows of each micro-plot were harvested and sub-samples taken for ^{15}N-enrichment and total-N determinations in the roots and shoots. In addition, grain and straw materials were treated separately. Total-N determinations were made on the soil, plant parts and water using the Kjeldahl method. Nitrogen-15 enrichment values were determined using dried samples that were sent to the Seibersdorf Laboratory of the International Atomic Energy Agency.

2.5. Previous trials

2.5.1. 1995–96

This experiment had the following salient features:

- Four N levels: 0, 60, 120, 180 kg N ha^{-1} with a complete randomized block design,
- Split applications of N, one third at 10 days after planting and two thirds at Z-30,
- Two lysimeters treated with 120 and 180 kg N ha^{-1}, respectively,
- A precipitation total of 485 mm, mostly between November and March with 49% in January.

2.5.2. 1996–97

This experiment had the following salient features (Table II):

- Three N levels: 0, 120; 180 kg N ha^{-1}, with a complete randomized block design,
- Split applications of N: F1 = one third the after emergence and the remainder at Z-30, F2 = one third at planting and the remainder at Z-30,
- Two lysimeters, with 120 kg N ha^{-1}, with F1 and F2, respectively,
- A precipitation total of 486 mm, 80% of which fell in December and January.

TABLE II. FORM, TIMING AND AMOUNT OF N APPLIED TO THE DIFFERENT TREATMENTS IN 1996–1997

Treatment	N supply (kg N/ha)	Microplot	N supply stage		
			Crop installation	After emergence	Zadocks-30
		MP1	0	40*	80
T1	120	MP2	0	40	80*
		MP1	0	60*	120
T2	180	MP2	0	60	120*
		MP1	40*	0	80
T3	120	MP2	40	0	80*
		MP1	60*	0	120*
T4	180	MP2	60	0	120*
T1	120	L1	0	40*	80*
T3	180	L2	40*	0	80*

*: Treatment enriched with ^{15}N.

3. RESULTS AND DISCUSSION

3.1. Soil characteristics

The soil had a sand content of approximately 50% to a depth of 1 m (Table III), and clay content increased slightly with depth. Bulk density also increased slightly with depth, whereas the organic matter content, which was relatively low, decreased with depth. The mean P content over the rooting depth, as extracted by the Olsen method, was also low by the standards of the California Fertilizer Association. The soil-exchangeable K content, however, was satisfactory by Moroccan standards. The initial N content in the surface 60 cm was around 105 kg ha^{-1}, residual from the previous crop of fertilized sugar beet. The water-holding capacity was approximately 100 mm per m of soil.

3.2. Soil moisture and hydraulic conductivity

Equations relating volumetric soil-water content (Hv in %) and the ratio between the neutron-probe count in the soil and the standard count (X), as determined by simple regression for each soil layer, were as follows:

0 to 20 cm	$Hv = 12.1 + 6.44X$	$r^2 = 0.85$
20 to 40 cm	$Hv = 5.33 + 10.5X$	$r^2 = 0.83$
40 to 60 cm	$Hv = 8.37 + 8.38X$	$r^2 = 0.72$
60 to 80 cm	$Hv = 12.9 + 8.74X$	$r^2 = 0.56$

The unsaturated hydraulic conductivity was determined in situ by the internal-drainage method. Variation of the stock of water in the soil was related to time with a relationship of the type: $S = a.t^b$. These equations allowed for the slopes dS/dt to be determined. Similarly, the variation of the total hydraulic gradient with depth was modelled for each time at which measurements were taken, which allowed for the slopes dH/dz to be determined for each depth. The unsaturated hydraulic conductivity, $K(\theta)$, was obtained for each water-content value as the ratio of these two slopes. The values of $K(\theta)$, as obtained by applying this technique to different depths, yielded a relationship of the type $K(\theta) = A.\theta^B$ with a correlation coefficient of 0.92 for all depths.

TABLE III. PHYSICAL AND CHEMICAL CHARACTERISTICS OF THE SOIL

Layer (cm)	C.S. (%)	F.S. (%)	C.L. (%)	F.L. (%)	Clay (%)	H_{fc} (cm^3/cm^3)	H_{pwp} (cm^3/cm^3)	B.D. (g/cm^3)
0–20	22.3	28.1	6.5	8.5	34.5	32.31	19.57	1.43
20–40	21.7	27.6	6.3	8.3	38.2	29.90	19.21	1.51
40–60	22.2	26.5	6.0	8.4	38.0	28.30	18.37	1.59
60–80	21.6	26.3	6.1	8.6	38.1	29.70	19.67	1.56

Layer (cm)	pH	E.C. (mmhos/cm)	O.M. (%)	P_2O_5-P (mg/kg)	K_2O (mg/kg)	H_{FC} (%)	H_{PWP} (%)	BD (g/cm^3)
0–20	7.5	1.4	1.4	17.3	296.5	22.3	11.7	1.46
20–40	7.7	1.6	1.3	15.9	168.7	22.9	12.6	1.51
40–60	7.4	1.7	1.1	5.0	106.7	22.3	12.3	1.56
60–80						21.1	11.5	1.60

C.S.: coarse sand F.S.: fine sand F.L.: fine loam F.L.: fine loam B.D.: soil bulk density

3.3. Weather

Rainfall for the growing season was above normal for the region, with a total of 357 mm; the mean for the previous 20 years was 281 mm. The precipitation was irregular, and 92% fell from late September to early February, whereas during the period of greatest need for moisture, mid-February to late May, there were only 27 mm.

The mean air temperatures fluctuated between 24°C in September and 12°C in late January. The maximum was approximately 30°C and the minimum 6°C. Generally speaking, except for precipitation shortage causing a water deficit, the climatic conditions of the growing season were favorable for wheat.

During the growing season, the ETo values started at about 5.5 mm day^{-1} in September then decreased until reaching the lowest values of slightly above 1 mm day^{-1} in January before increasing up to 5 mm day^{-1} in May.

3.4. Water use

The water requirements of the wheat crop, as estimated using reference evapotranspiration and crop coefficients determined locally, amounted to 413 mm, in comparison with 323 mm during the previous season, due to higher temperatures. Water requirements were minimal early in the season at less than 1 mm day^{-1} and increased to a maximum of 4.3 mm day^{-1} in April.

As the year was relatively dry, especially during the period of high water requirement, irrigation was necessary to achieve reasonable yields. Treatment-T1 plots, to satisfy total water requirements, received four irrigations, whereas T2 and T3, to receive 80% and 60%, were irrigated thrice and twice, respectively.

The actual evapotranspiration (ETa) or crop-water-use values, as determined using the in situ water balance method, are given in Table IV. The control depth was 75 cm, slightly below the average rooting depth, 60 cm, of wheat in that region. The variables necessary for evaluating the actual water use by the crop, and especially soil-water content and potential, were monitored from January 14 and at harvest on May 21. During the months between planting and January 14, ETa was estimated using the method described in FAO Bulletin 33.

Applied N had a significant positive effect on crop-water consumptive use. The 180 kg N ha^{-1} treatment used the highest amount at 3,390 m^3 ha^{-1} compared with 3,150 m^3 for T2 and 3,080 m^3 for T3. This result can be explained by the fact that the higher the N level the more intense was the photosynthetic activity, resulting in denser and deeper rooting. Similarly, the greater the amount of water applied through irrigation, the higher was the ETa. During the previous growing season, under water stress for all treatments, N level was found not to affect ETa, showing that N benefit was less evident under such conditions.

The daily means for actual evapotranspiration by the crop varied from less than 1 mm day^{-1} to a maximum of about 4.5 mm day^{-1}. The ETa values decreased during periods of no or limited precipitation and increased following each application of water, whether from irrigation or precipitation. The mean ETa over all treatments was 310 mm. Compared to the maximum water requirements of 413 mm, the crop-water use was relatively important, hence the deficit was generally low, between 18 and 37% of requirements. The mean water deficit over all treatments was just over 100 mm, i.e. around 25% of total requirement.

3.5. Yields

Yields responded positively to applied N and, to a lesser extent, to irrigation (Table IV). The highest grain yield, 5.52 Mg ha^{-1}, was obtained with 180 kg N ha^{-1} irrigated at 100% ETM, whereas the lowest, 2.32 Mg ha^{-1}, occurred with the unfertilized plants under 60% ETM. The overall mean grain yield was relatively low at 4.20 Mg ha^{-1}, because of weeds and limited crop-production technology. Statistical analysis showed no significance in the yield difference between the 100% and 80% ETM irrigation treatments. However, at 60% ETM, the yield was significantly lower because of water stress. The 80% ETM may have received more because surface irrigation was used with the application of an irrigation-efficiency coefficient to account for eventual losses associated with the system; part of the increment to account for losses may have profited the crop.

TABLE IV. YIELD AS RELATED TO WATER CONSUMPTIVE USE AND EFFICIENCY

Irrigation treatment	T1			T2			T3		
N supply (kg N/ha)	0	120	180	0	120	180	0	120	180
ETa (mm)	271	330	339	269.2	327.1	334	262	324	334
TDM (kg/ha)	9826	13780	15000	9698	13529	14700	8291	12480	13000
GY (kg/ha)	2801	5190	5520	2864	5092	5450	2322	4465	4530
TDM/ETa (kg/ha/mm)	36.26	41.74	44.4	36.02	41.36	43.9	31.64	38.52	38.8
GY/ETa (kg/ha/mm)	10.33	15.73	16.3	10.63	15.56	16.3	8.86	13.78	13.5

ETa: water consumptive use. TDM: total dry matter. GY: grain yield

Applied N had strong effects on yield. Without N fertilizer, yields were about 50% lower. The interaction effect was also significant, especially from an economic standpoint: the best treatment was 120 kg N ha^{-1} irrigated at 80% ETM.

Total dry-matter yields had the same pattern as grain yields, except for the difference between treatments with 120 and 180 kg N ha^{-1} on one hand and the unfertilized control plants on the other which were less than for grain. The mean total dry-matter yields varied between 11.3 and 12.9 Mg $ha^{-1,}$ for the control and the maximum applied N, respectively. Most yield components were affected by the amount of applied N.

Although the maximum yield was obtained with 180 kg N ha^{-1}, there seemed to be a plateau at around the value for 120 kg N ha^{-1}, a result found for all three seasons. The relationships between yield ($\times$100 kg ha^{-1}) and N applied (kg N ha^{-1}) were as follows:

(1) Irrigation treatment T1 (100% ETM)

– Grain	$Y = -0.0008X^2 + 0.295X + 28.0$	$r^2 = 0.98$
– Straw	$Y = -0.0004X^2 + 0.192X + 68.6$	$r^2 = 0.90$
– TDM	$Y = -0.0012X^2 + 0.492X + 96.6$	$r^2 = 0.88$

(2) T2 (80% ETM)

– Grain	$Y = -0.0007X^2 + 0.269X + 28.6$	$r^2 = 0.91$
– Straw	$Y = -1\text{ E-}05X^2 + 0.135X + 68.3$	$r^2 = 0.85$
– TDM	$Y = -0.0007X^2 + 0.404X + 97.0$	$r^2 = 0.87$

(3) T3 (60% ETM)

– Grain	$Y = -0.0009X^2 + 0.294X + 23.0$	$r^2 = 0.89$
– Straw	$Y = -0.0009X^2 + 0.276X + 59.9$	$r^2 = 0.86$
– TDM	$Y = -0.0018X^2 + 0.570X + 82.9$	$r^2 = 0.91$

In comparison, the results from previous seasons gave the following similar relationships:

(1) 1996–97

– Grain	$Y = -0.0006X^2 + 0.199X + 31.9$	$r^2 = 0.88$
– Straw	$Y = -0.0001X^2 + 0.130X + 75.4$	$r^2 = 0.99$
– TDM	$Y = -0.0007X^2 + 0.329X + 107$	$r^2 = 0.97$

(2) 1995–96

– Grain	$Y = -0.0007X^2 + 0.239X + 29.7$	$r^2 = 0.99$
– Straw	$Y = 2\text{E–}05X^2 + 0.124X + 67.8$	$r^2 = 0.99$
– TDM	$Y = -0.0007X^2 + 0.363X + 97.4$	$r^2 = 0.99$

3.5. Chlorophyll readings

The variations in SPAD numbers between treatments confirmed the effects of applied N and, to a lesser extent, of irrigation. These numbers, which directly relate to chlorophyll content, hence to plant-N, were measured from the first N application at early tillering until 2 weeks before final harvest. Initially, there were no difference between treatments, and the SPAD numbers were low at around 30. After the first N application, differences became evident with the highest values corresponding to 180 N kg ha^{-1} followed by those of 120 kg N ha^{-1} and then by the unfertilized control. With time, the numbers increased for all treatments until they reached values of around 50 with 180 kg N ha^{-1} following the second N application. Difference between the treatments persisted throughout the monitoring period and became larger following the second application of N. Towards the end of the monitoring period, the numbers decreased and the differences among the three N treatments largely disappeared. Irrigation also affected SPAD numbers, with higher values registered in treatments T1 and T2 than in T3, throughout the monitoring period.

3.6. Water-use efficiency

Applied N had significant effects on water-use efficiency (WUE) (Table IV). The WUE values varied from 34.6 kg ha^{-1} mm^{-1}, when no N was applied, to 42.4 kg ha^{-1} mm^{-1} with 180 kg N ha^{-1}. This difference was due less to the amounts of water used than to the yield responses to N. However, irrigation affected WUE, with higher values (over 40 kg ha^{-1} mm^{-1}) obtained with treatments T1 and T2 than with T3 (36 kg ha^{-1} mm^{-1}) under water deficit. It is noteworthy that there were no difference in WUE based on grain yield or total dry matter between the 100% and 80% ETMs, due to the fact that the two treatments differed by only one irrigation. In addition, because surface irrigation was used, it was not possible to evenly apply the desired depth, hence the small differences obtained between irrigation treatments in terms of ET and most other variables.

In terms of grain yield and WUE for producing grain, the Table shows that the differences between the 120 and 180 kg N ha^{-1} treatments were modest. As a result, 120 kg N ha^{-1} may be recommended for economic and environmental reasons. This result confirms those from the two previous growing seasons. With regard to irrigation, as just discussed, treatment T2 performed in the same manner as T1, which leads to recommendation of the former for the future, for environmental and economic reasons.

3.7. Nitrogen budget

The labelling of the fertilizer with ^{15}N allowed determination of the fate of fertilizer N, sources of N in the plant: N derived from fertilizer (Ndff) and from soil (Ndfs)

3.7.1. Nitrogen from fertilizer

The N derived from the first application of fertilizer varied from 12% with 120 kg N ha^{-1} and irrigated at 60% ETM, to 51% with 180 kg N ha^{-1} at 60% ETM. The effect of the applied-N level on this variable was evident both for grain and straw, especially between 120 and 180 kg N ha^{-1}; the fraction of N derived from the first application was much higher with 180 than with 120 kg N ha^{-1}.

The N derived from the second application also varied, between 41%, with 120 kg N ha^{-1} at 60% ETM, and 67% for the same N level at 80% ETM. The difference can be explained by a greater uptake of N from the second application during rapid plant development; some 85% of total N was assimilated before anthesis.

Irrigation regime also affect Ndff, with a distinct difference between T1 and T2 on the one hand and T3 on the other. The latter registered the lowest values for Ndff, which may be attributed to water stress.

These results are similar to those from the previous growing seasons. During 1995–96, the N derived from the first application was influenced by the amount applied, with a slight increase between 120 and 180 kg N ha^{-1}. During the following season, the fertilizer-N uptake was influenced more by the time of application than by the amount applied. With one third applied after *emergence* and two thirds at Z-30, the Ndff values for the first application corresponding to 120 and 180 kg N ha^{-1} were 14% and 22%, respectively, whereas Ndff values of only 5.1% and 7.7% were obtained when one third was applied at *planting* and the rest at Z-30. With the second application, Ndff increased significantly with the fertilizer level applied.

In conclusion, it can be said that fertilizer constituted a major source of N for the crop. Uptake of N increased with the amount applied and was generally lower for the first application. The same results were obtained during the previous seasons, in particular the low contribution of the N applied early in the season, which can be explained by small N requirements during early growth in conjunction with loss by leaching.

3.7.2. Nitrogen from soil

Soil analysis prior to planting revealed the existence of 113 kg N ha^{-1} in the surface 60 cm. This relatively high quantity was the result of application of large quantities of N to the previous sugar-beet crop. Similar results had been obtained during previous seasons.

Values for Ndfs varied between 12% with 180 kg N ha^{-1} irrigated at 100% ETM, and 39% with 120 kg N ha^{1} at 60% ETM (Table V). These were lower than those found during the previous seasons, which varied between 38% and 68% in 1996–97 with 180 kg N ha^{-1} applied as F1, and 120 kg ha^{-1} applied as F2, respectively. The difference may be due to leaching loss of most of the N applied during the early stages of the previous year. Moreover, conditions for soil-N mineralization may have been more favourable in 1996–97.

TABLE V. ORIGIN OF PLANT NITROGEN

Irrigation treatment	Nitrogen kg/ha	Ndff (%)	Ndfs (%)
T1	120	71,2	28.8
	180	87,8	12.2
T2	120	82,2	17.8
	180	-	-
T3	120	81,4	38.6
	180	74,	25.4

In the 1997–98 season, Ndfs values decreased with the increase in applied fertilizer. With treatment T1 (100% ETM) the soil's contribution decreased from 29% to 12% when the N level increased from 120 kg ha^{-1} to 180 kg ha^{-1}, respectively.

The Ndfs values decreased also with the number of irrigations. The values corresponding to treatments T1 and T2 were lower than that for T3, which can be explained by water stress with T3.

3.7.3. Nitrogen-uptake efficiency

For the first application, actual N-uptake efficiency varied from a minimum of 13% for 180 kg N ha^{-1} irrigated at 60% ETM, to a maximum of 59% with 120 kg N ha^{-1} at 80% ETM. Between 120 and 180 kg N ha^{-1} the mean decrease was 8%.

For the second application of N, N uptake was higher, with 36% for 120 kg N ha^{-1} 60% ETM, and 61% with the same N level irrigated at 80% ETM.

These results follow trends observed in previous seasons. In 1995–96, uptake of 180 kg ha^{-1} was 46% for the first application and 49% for the second. During the following season, a higher value was obtained with the first application (after emergence) than with the second at Z-30; but when applications were made at planting and at Z-30 (F2), uptake was higher from the second application.

Based on these results and given the prevailing weather conditions, especially precipitation, current technologies used for growing wheat, and the yields attained, it is concluded that 120 kg N

TABLE VI. RESIDUAL NITROGEN (Nr) FROM THE DIFFERENT TREATMENTS. 1997–1998

Irrigation treatment	Nitrogen (kg/ha)	MP	Depth (cm)	Residual N (kg N/ha)	Nr/layer (kg N/ha)	Total Nr (Kg N/ha)	Total Nr (%)
			0–20	2400	6.23		
		MP1	20–40	2516	7.84	19.41	48.52
T1	120		40–60	1729	5.34		
			0–20	2524	7.13		
		MP2	20–40	2326	5.27	19.54	24.42
			40–60	1543	7.14		
Total						**38.95**	**32.46**
			0–20	2700	9.12		
		MP1	20–40	2115	5.28	21.61	36.02
T1	180		40–60	1972	7.21		
			0–20	2456	7.50		
		MP2	20–40	2329	5.45	18.18	15.15
			40–60	2103	5.23		
Total						**39.79**	**22.10**
			0–20	2825	8.50		
		MP1	20–40	2604	6.30	20.27	50.67
T2	120		40–60	1613	5.47		
			0–20	2900	6.48		
		MP2	20–40	2342	7.83	19.44	24.30
			40–60	1920	5.13		
Total						**39.71**	**22.06**
			0–20	2600	7.85		
		MP1	20–40	2412	6.78	22.08	36.08
T2	180		40–60	2035	7.45		
			0–20	2891	5.46		
		MP2	20–40	2200	7.86	18.53	15.44
			40–60	1837	5.21		
Total						**40.61**	**22.56**
			0–20	2628	7.81		
		MP1	20–40	2341	6.31	19.60	49.00
T3	120		40–60	2165	5.48		
			0–20	2368	7.35		
		MP2	20–40	1945	6.97	19.55	24.44
			40–60	1568	5.23		
Total						**39.15**	**32.62**
			0–20	2854	9.33		
		MP!	20–40	2415	8.34	22.96	38.27
T3	180		40–60	2157	5.29		
			0–20	2947	8.23		
		MP2	20–40	2547	7.51	21.03	17.52
			40–60	2324	5.29		
Total						**43.99**	**24.44**

TABLE VII. RESIDUAL NITROGEN (Nr) FROM THE N APPLICATIONS. (SEASON 1996–97)

Treatment	MP	Depth (cm)	Residual N (kg N/ha)	Nr/layer (kg N/ha)	Total Nr (Kg N/ha)	Total Nr (%)
		0–20	2900	8.120		
	MP1	20–40	2416	4.832	15.30	38.27
T1		40–60	1570	2.355		
		0–20	3480	8.468		
	MP2	20–40	2265	5.879	17.19	21.49
		40–60	1727	2.847		
Total T1					**32.50**	**27.08**
		0–20	2900	5.878		
	MP1	20–40	2416	7.981	16.45	27.42
T2		40–60	1884	2.593		
		0–20	2900	5.210		
	MP2	20–40	2416	8.680	18.40	15.34
		40–60	1570	4.513		
Total T2					**34.85**	**19.36**
		0–20	2900	6.380		
	MP1	20–40	2416	3.866	11.65	29.15
T3		40–60	1570	1.413		
		0–20	2900	12.760		
	MP2	20–40	1812	7.973	23.87	29.84
		40–60	1570	3.140		
Total T3					**35.53**	**29.61**
		0–20	2465	8.535		
	MP1	20–40	2114	3.809	15.29	25.50
T4		40–60	1361	2.955		
		0–20	2320	12.503		
	MP2	20–40	2416	8.680	24.94	20.79
		40–60	1570	3.760		
Total T4					**40.24**	**22.36**

ha^{-1}can be recommended for implementation in the region. Moreover, where the initial soil-N content is relatively high, application of N at planting is not recommended. These practices would limit N losses to leaching caused by the high precipitation that often occurs during early growth. When N is applied later in the season, between early tillering and Z-30, yield advantages result from:

– The improvement of the capacity of the crop to absorb N because of a well developed root system,
– The N application coinciding with active development of the crop during which N requirements and uptake are high.

3.7.4. Residual N

Tables VI and VII show the N residual from the various treatments at harvest, for the 1997–98 and 1996–97 trials, respectively. With the former, 39.3 and 41.5 kg N ha^{-1} were residual from applications of 120 and 180 kg N ha^{-1}, respectively. Thus, the effect of the applied level was insignificant; the same occurred in 1996–97.

In the 1997–98 experiment, the amounts of N left in the soil from the first application were higher than those from the second. For example, with 180 kg N ha^{-1} irrigated at 80% ETM, 21.6 kg N ha^{-1} were residual from first application and 18.2 kg N ha^{-1} from the second. This result can be explained in terms of the first application being less efficiently used by the crop than the second application, for the reasons discussed above.

These results differed from those obtained in the previous two seasons during which N-uptake efficiencies were lower with the first applications (Table VII). The difference could be due to high precipitation that followed the first applications during the previous seasons that may have leached most of the N applied. During the 1997–98 season, such high precipitation did not occur and irrigations were applied at depths of around 40 mm each time, hence a larger fraction of the N applied early in the growing season remained in the soil.

3.7.5. Nitrogen losses

The amounts of water drained by the lysimeters were monitored throughout the growing season. Drainage occurred essentially after water application by irrigation or precipitation. The total depth drained amounted to 115 mm (average of the two lysimeters). This figure was below those of the previous years (220 and 238 mm) The drainage occurred mainly during the early stages of crop growth and was largely the result of precipitation, showing that most of the irrigation water was used by the crop and not lost to greater depths.

The N content of the drainage water was monitored during the entire growing season. Immediately after the first fertilizer application, the N concentration increased until it reached 30 and 45 mg L^{-1} for lysimeters L1 and L2, fertilized with 120 and 180 kg N ha^{-1}, respectively. Then it decreased before increasing again following the second application of N. In addition, the concentration in the lysimeter that received 180 kg N ha^{-1} was consistently higher than that fertilized with 120 kg N ha^{-1}. Therefore, the N losses to leaching, and hence the pollution of groundwater, were proportional to the applied amounts.

The amounts of N lost to leaching during the entire season represented 51 and 68 kg N ha^{-1} with 120 and 180 kg N ha^{-1}, respectively, lower than in previous seasons (94 kg in 1995–96).

For all three seasons, the highest N losses occurred during early growth; it is recommended that any early N application be small, in order to minimize losses and limit groundwater pollution. The N-uptake values for the early application were as low as 20%, as during the 1996–97 experiment. As it is not possible to control the amount of precipitation, the only possibility left for reducing N losses is by applying less fertilizer during early crop growth. As for irrigation, its effect on N loss was slight when it was practiced efficiently, i.e. when only small depths were applied and in accordance with the crop requirements. Therefore, irrigation may cause leaching of N only when it is not practiced judiciously; otherwise it poses no hazard for groundwater.

The use of ^{15}N allowed the determination of amounts of N derived from fertilizer that were lost by leaching. These figures were low at 2.2% for L1 and 2.8% for L2, but generally higher in previous seasons, i.e. in 1996–97, 0.2% with 120 kg N ha^{-1} applied as F1 and 4% from the same treatment applied as F2, and, in 1995–96, 13% and 15% for 120 and 180 kg N ha^{-1}, respectively. During both seasons, leaching losses increased with increased application.

3.7.6. Nitrogen in soil solution

The soil solution was extracted with tensionics when moisture content was high enough to allow sufficient water to be extracted, i.e. after water applications. The tensionics were installed in treatments T1 and T2 within the micro-plots enriched with ^{15}N in order to follow the dynamics of the applied N.

High concentrations were noted following the first application of N. As N leaching occurred, it was noted that the concentration decreased near the surface and increased downward. This phenomenon was also a result of N uptake by the crop from the surface layers of soil. Nitrogen concentration then decreased progressively before it increased again following the second N application. It was noted also that greater concentrations were found with the irrigation treatment T1 (100% ETM) compared to T2 (80%).

These results are similar to those found during the 1996–97 season when the N treatment split as F2 resulted in higher losses in depth, estimated at about 22 kg N ha^{-1}. At the same time, the F1 partitioning of N resulted in only limited losses, estimated at about 3 kg N ha^{-1}.

Enrichment in ^{15}N generally followed the same pattern as N concentration, with higher values at the soil surface immediately after the first application. Then, as the growing cycle progressed, the enrichment values decreased near the surface and increased at greater depths. Similar results were found during the previous season, especially with the F2 N split for which high enrichment values were traced at depth.

Therefore, it can be concluded that N losses to leaching were closely related to the applied amounts of both water and fertilizer. They were also affected by the timing and splitting of N applications. Losses to leaching can be reduced by limiting or avoiding the application of N at planting. Moreover, given that surface irrigation was used, it is important to control the depth of application in order to limit N losses later in the cycle.

3.7.7. Gaseous losses

By combining the ^{15}N-enrichment data from the soil and the crop, it is possible to estimate applied N lost, as well as the nature of that loss. Knowing the amount of N leached, it is possible to determine, by difference, gaseous losses that are otherwise difficult to measure directly in the field.

The budget is obtained by comparing the amount of N applied with the amount residual in the soil, the N recovered by the crop and the amount lost to leaching. The part not accounted for in represents, in principle, gaseous N resulting from denitrification and ammonia volatilization.

As evaluated using this technique, gaseous losses represented 11% and 19% for treatments with 120 and 180 kg N ha^{-1}, respectively (Table VIII). These estimates were close to those from the previous seasons, which were as follows: 16% and 22% of 120 kg N ha^{-1} for F1 and F2 in 1996–97, respectively, and only 7% of the same amount (120) in 1995–96. The differences may be explained in terms of soil temperature and water content on denitrification.

TABLE VIII. FERTILIZER NITROGEN BALANCE (kg N/ha)

	1995–1996				1996–1997*				1997–1998*			
Treatment	Nr	Gas	Le	AUE	Nr	Gas	Le	AUE	Nr	Gas	Le	AUE
120-F1					32.5	19.9	0.2	67.4	33.6	14.2	2.6	69.6
180-F1					35.5	26.7	4.8	53.0	55.8	34.6	5.0	84.6
120-F2	26.4	8.0	14.7	70.9	34.9	36	0.6	108.5				
180-F2	47.0	16.7	29.5	86.8	40.2	63	0	76.8				

Nr: residual N Le: leached N AUE: actual use efficiency

* Treatment F1 is slightly different between the seasons 1996–1997 and 1997–1998. In 1996–1997 it corresponds to the N partitioning of 1/ 3 after emergence and 2/3 at Zadocks-30, whereas in 1997–1998 it corresponds to 1/3 at tillering and 2/3 at Zadocks-30.

4. CONCLUSIONS

Synthesis and recommendations are as follows:

- Losses of water and N are intimately related to precipitation and depth of water applied through irrigation,
- Nitrogen applied at planting is likely to be lost to leaching and be a major source of groundwater pollution,
- The application of more than 120 kg N ha^{-1} results in high risk of losses and of groundwater pollution, and in low N-uptake efficiency and hence in low economic returns.

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OPTIMIZING NITROGEN-FERTILIZER APPLICATION TO WHEAT UNDER IRRIGATION

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Abstract

The responses of wheat to urea, its time of application and the fate of the applied N under irrigation were studied over 2 years. Also studied was the recovery of residual N by soybean planted in the same plots. Maximum grain productivity was obtained with 90 kg N ha^{-1}. Urea-N uptake ranged from 52% for application at sowing, to 85% when applied at tillering. The main loss of fertilizer N occurred as ammonia volatilized, which ranged from 5 to 12%. Loss of N by leaching was less than 1%, even with an application of 135 kg N ha^{-1}, which is higher than the rate locally recommended for irrigated wheat. The small leaching loss was due to little rainfall during the growing season and irrigation sufficient only to moisten the root zone. The residual N after wheat harvest represented around 40% of that applied: 21% in soil (to a depth of 60 cm), 3% in roots and 16% in the wheat straw. Soybean recovered less than 2% of the N applied to the wheat.

1. INTRODUCTION

In 1987, Brazil almost achieved self-sufficiency in wheat, with a production of approximately 6.1 Mt, compared to a requirement of 6.7 Mt. Since that time, the area planted to wheat has decreased; in 1995, less than 2 Mt of grain were produced (Fig. 1). Many factors contributed to this decline, the most important of which was increased importation from neighbouring countries. Since 1995, wheat production has increased due to implementation of a government stabilization plan in 1994. Productivity has increased from 1.2 Mg ha^{-1} in 1990 to a current level of 1.9 Mg ha^{-1}, chiefly due to increasing availability of irrigation.

In Brazil, wheat is cultivated in nine states, two of which, Paraná and Rio Grande do Sul, are responsible for 91% of total production. This paper describes experiments carried out in São Paulo State, which produces only 3%, with a range of productivity of 0.84 to 4.3 Mg ha^{-1} depending on management practices. Fertilizers and irrigation are chiefly responsible for recent increases in productivity. Wheat is grown in Paraná State without the necessity of irrigation, however, disease is a significant yield constraint. Sprinkle irrigation is used in São Paulo, Minas Gerais and Goias States, in which the highest levels of productivity are obtained.

Research carried out in São Paulo State has shown good responses in wheat to N fertilization, depending on moisture conditions (Fig. 2) and the previous crop (Fig. 3). The maximum rate of N for irrigated wheat in São Paulo State is recommended to be 120 kg ha^{-1}, one third of which is applied at seeding and the remainder at tillering.

In Brazil, IAEA-sponsored research on wheat using ^{15}N, which started in the late 1960s and continued until 1974, showed that various sources of N (urea, ammonium sulphate and ammonium nitrate) had similar values for efficiency of uptake, 5 to 27%, that were most strongly influenced by the time of application [1]. Other work showed similar uptake of N from fertilizer whether applied at seeding or at tillering [2].

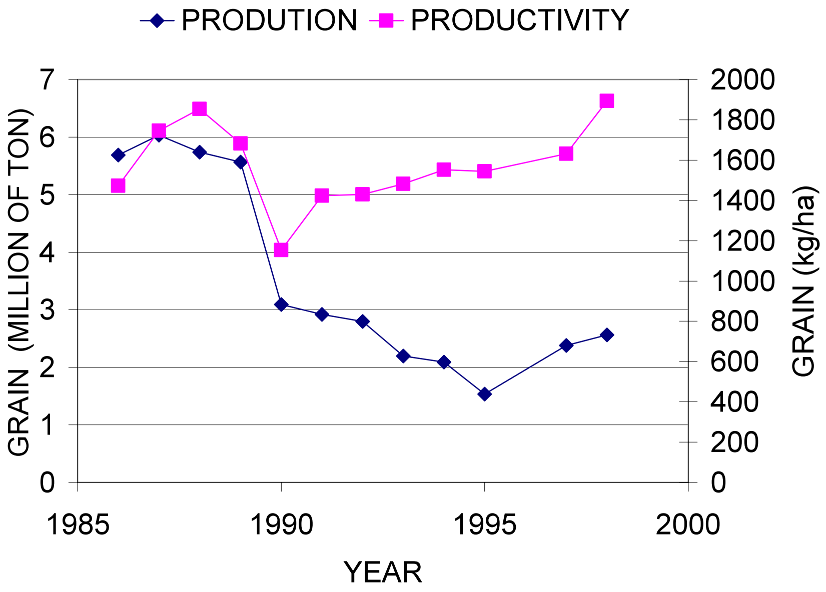


FIG. 1. Production and productivity of wheat (grain) in Brazil (1986–1998).

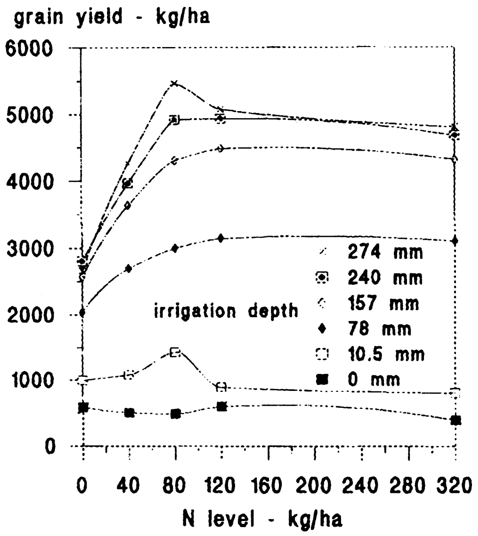


FIG. 2. Interaction between N level and amount of water applied by sprinkle irrigation [3].

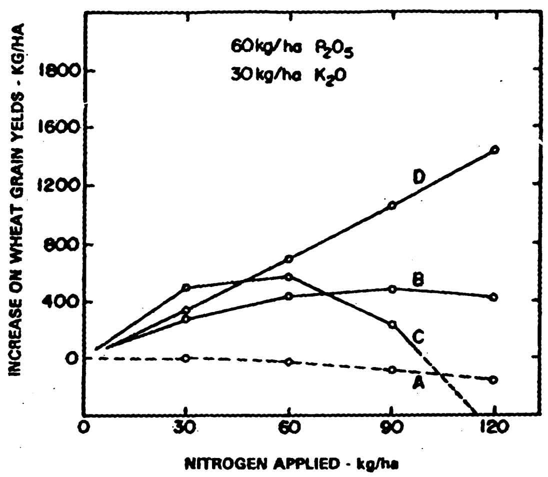


FIG. 3. Wheat response to N fertilization. A = after lab-lab, B = after bean crop, C = after no cultivation, D = after rice crop [4].

Achieving a balance between maximum productivity of a cultivar by supplying N while minimizing pollution of environment from excessive N was the goal of this work. On one hand, demands for food are increasing due to population growth, and, on the other, there are environmental and ethical pressures to minimize pollution caused by N fertilizers. Ideally, the hope is for maximum productivity and profit with minimum pollution. However, many factors, such as weather patterns, make it difficult to achieve the optimal balance.

This paper describes data for 2 years of experiments, in 1995 and 1996, with wheat fertilized with various rates of urea and grown under irrigation.

2. MATERIALS AND METHODS

The experimental site was located at the research farm of the Instituto Agronômico de Campinas, Campinas, São Paulo State (22°54'S 47°05'W, altitude 674 m). The previous crop was soybean. Treatments are shown in Table I. Urea, triple superphosphate and KCl were applied at seeding in the planting furrow under the seeds and the remainder of the urea was broadcast between the rows at tillering. Labelled urea was applied at sowing and tillering in different micro-plots within the main plots. Table II shows the rainfall and temperature patterns during the wheat growing season in São Paulo State. The soil of the experimental site is a dark red latosol (Eutrudox), with a V of 54% and high P and K contents.

TABLE I. NITROGEN RATES AND TIME OF APPLICATION

1995		1996	
Sowing	Tillering	Sowing	Tillering
kg ha^{-1} of N		kg ha^{-1} of N	
0	0	0	0
10*	20*	15	30
20*	40*	30*	60*
30*	60**	45*	90**
40*	80*	60	120

* ^{15}N as urea ** ^{15}N as urea was applied at sowing and at tillering in the same micro-plots

TABLE II. RAINFALL AND TEMPERATURE DURING THE WHEAT GROWING SEASON

	RAINFALL		LOWEST TEMPERATURE		HIGHEST TEMPERATURE	
Month	1995	1996	1995	1996	1995	1996
	mm		°C		°C	
June	33	40	12.6	11.1	24.8	25.3
July	20	5	14.1	11.1	25.8	24.7
August	1	27	15.1	14.0	29.1	28.6
September	69	159	15.4	15.6	27.8	26.6
October	174	163	16.6	17.5	27.1	28.6
Total	297	394				

Sufficient water was supplied after sowing to saturate the soil to a depth of 40 cm, following the recommendation for wheat. In both years, irrigation was applied whenever tensiometers placed at 20 cm depth reached the value of 0.06 MPa. The amount of supplied water was estimated by the amount of water evaporated from a class-A tank and the crop coefficient (K_c).

Many genotypes have been grown in São Paulo State, but cultivar IAC 24 predominated in 70% of the cultivated area in 1995 and 1996. The growth cycle of IAC 24 is around 130 days, it is aluminium tolerant, and is recommended for both irrigated and non-irrigated areas. With a potential grain yield under irrigation of 5.0 Mg ha^{-1}, it was chosen for this work.

After harvesting, the plants were separated as straw and grain, then dried at 65°C and analyzed for total N and ^{15}N. Grain yields were expressed in terms of 12% moisture.

Wheat straw remained on the soil surface in the respective plots after the wheat harvest, then soybean was sown in the same plots, with the objective of determining the amount of N applied to the cereal absorbed by the legume. At the end of the soybean cycle, samples of plants were harvested, dried at 65°C, and analyzed for total N and ^{15}N.

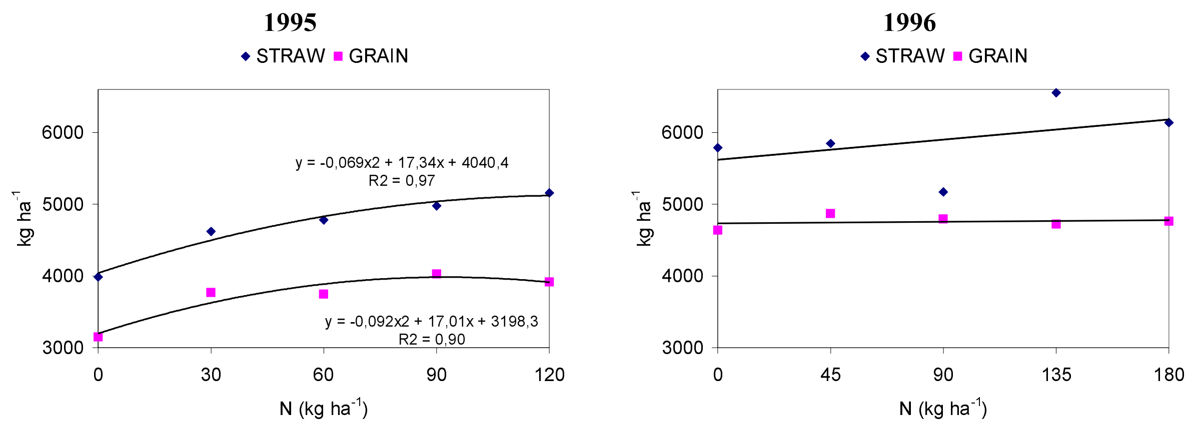


Fig. 4. Effect of N rates on wheat straw and grain productivity.

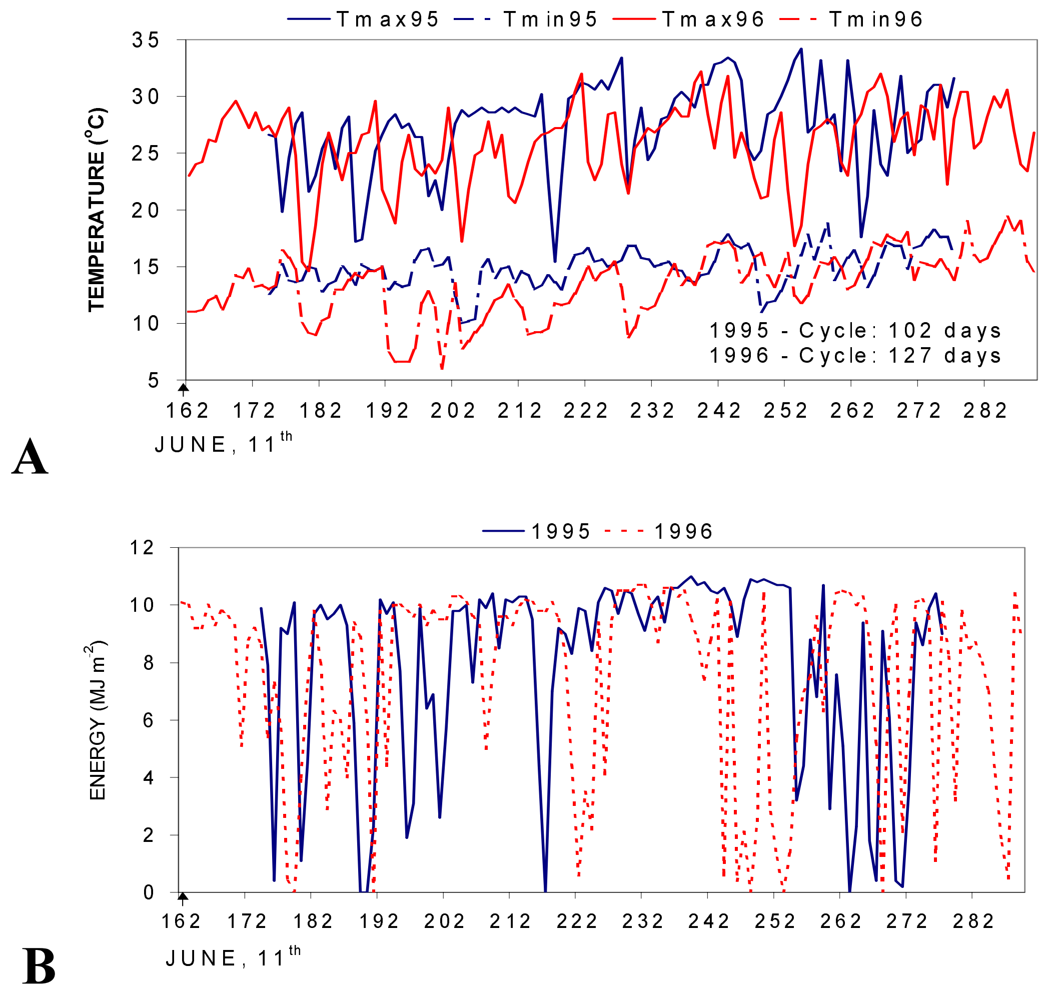
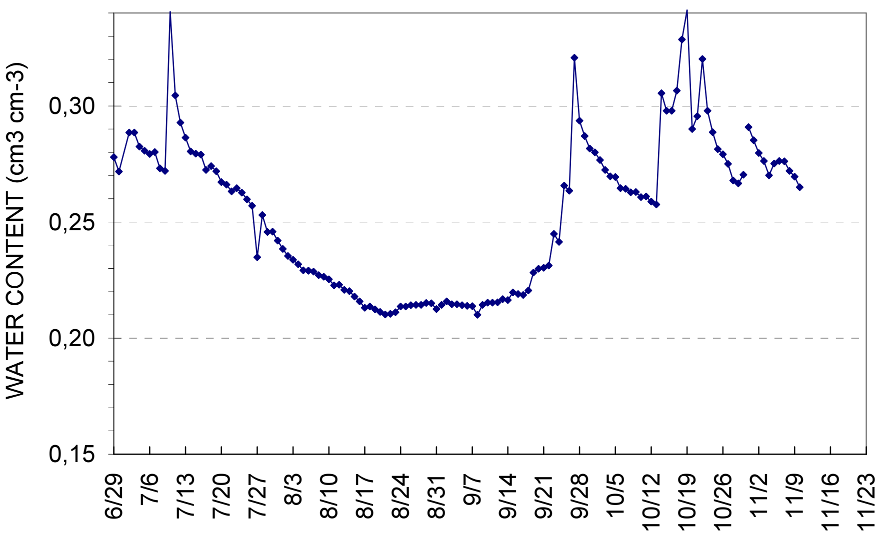
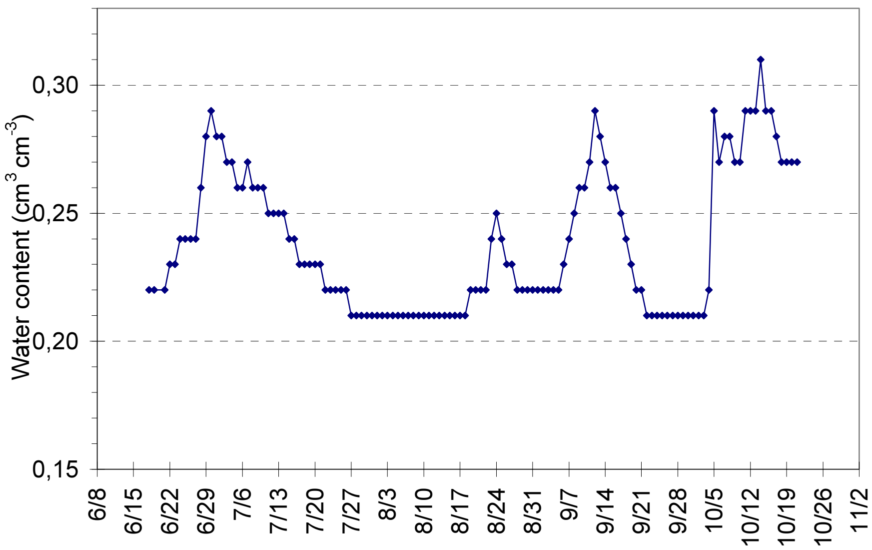


FIG. 5. Maximum and minimum temperatures (A) and insolation (B) during the wheat cycle in 1995 and 1996.



1995



1996

FIG. 6. Soil water content at Z_r = 50 cm.

To estimate the N leached during the wheat cycle, soil-water content was monitored using mercury tensiometers installed at depths of 20, 40, 90 and 110 cm. Soil-water content, hydraulic gradient and drainage values were calculated for depths of 50 and 100 cm.

Soil solution was extracted from 50 and 100 cm of soil depths by porous ceramic cups that were evacuated for approximately 2 hours, twice per week. The collected soil solutions were immediately placed in glass cups and deep-frozen pending analysis for nitrate- and ammonium-N. Soil-solution samples were subjected to micro-diffusion and sent to the Seibersdorf Laboratory for ^{15}N analysis.

As the urea was broadcast at tillering, ammonia volatilization was estimated using semi-open static-type collectors. Water equivalent to the amount applied by irrigation was put inside the collectors after irrigation.

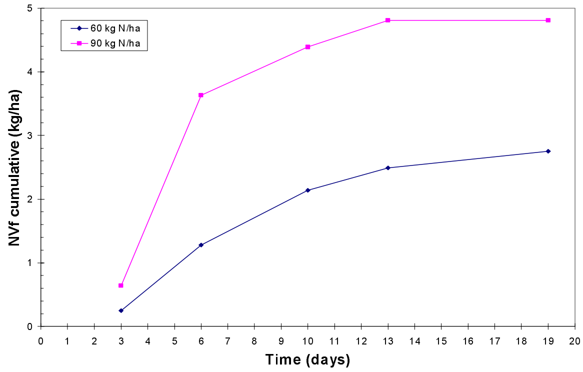


FIG. 7. Cumulative N loss by ammonia volatilization from applied urea (NVf) in 1996.

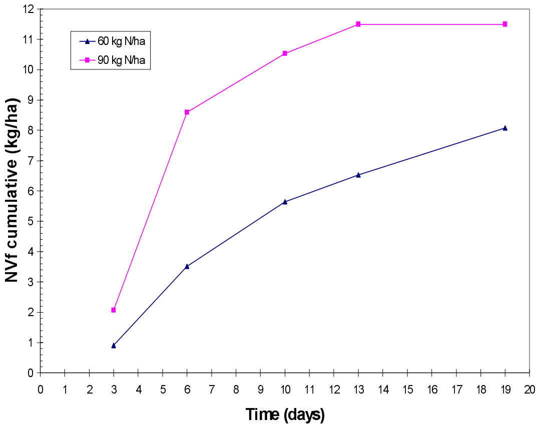


FIG. 8. Cumulative N loss by ammonia volatilization from applied urea (NVf) in 1996 considering the collector efficiency.

Leaf-chlorophyll-content readings, which correlate with leaf-N concentration, were made at tillering, using a Minolta SPAD meter.

3. RESULTS AND DISCUSSION

3.1. Yields

The application of 90 kg N ha^{-1} produced the highest yield of grain in 1995, whereas no effect of N was observed in 1996 (Fig. 4). In both years, the yields of grain were higher than the state average for São Paulo of less than 2 t ha^{-1}. Although the grain yield in 1995 was lower than the genotype potential under irrigation of 5 t ha^{-1}, this potential was almost reached in 1996. The difference in yield between the two years was probably due to higher temperatures (above 28°C) during ear formation, and high insolation, in 1995 (Fig. 5). Soil moisture was sufficient in both years (Fig. 6).

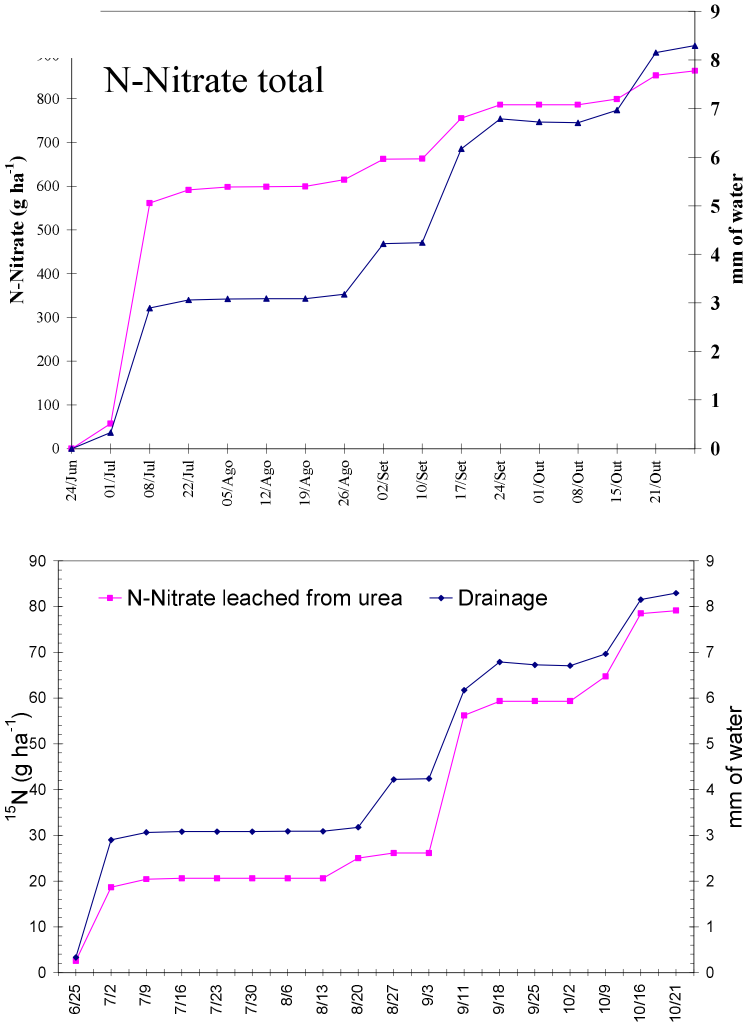


FIG. 9. Cumulative losses of water and nitrate during the experiment of 1996, z_r=50 cm.

3.2. Fate of urea N

3.2.1. Uptake

The uptake of applied N by a crop depends on the time of its application, among others factors [5]. In this work, the recovery of fertilizer N was high in both years. Broadcasting at tillering promoted N uptake compared to application at seeding, probably due to synchrony with the wheat's greatest requirement for it (Tables III and IV).

3.2.2. Volatilization

Urea was broadcast at tillering between the plant rows, without incorporation into soil. The amount of N volatilized depended on the rate of application and ranged from 2.8 to 4.8 kg ha^{-1} (Fig. 7). Considering the collector efficiency, these amounts represent 15 to 12% of the total N applied at tillering (Fig. 8).

TABLE III. WHEAT RECOVERY OF N FROM UREA APPLIED AT SOWING AND TILLERING (1995)

Time of application		Wheat N recovery from applied urea				
Sowing	Tillering	Straw		Grain		Total
N rate (kg ha^{-1})		kg ha^{-1}	%	kg ha^{-1}	%	%
10*	20*	4.4	15	18.0	60	75
20*	40*	9.4	16	33.7	56	72
30*	60*	15.7	17	53.1	59	76
40*	80*	19.3	16	63.6	53	69

*^{15}N-urea

TABLE IV. WHEAT RECOVERY OF N FROM UREA APPLIED AT SOWING AND TILLERING (1996)

Time of application		Wheat N recovery from applied urea				
Sowing	Tillering	Straw		Grain		Total
N rate (kg ha^{-1})		kg ha^{-1}	%	kg ha^{-1}	%	%
30*	60	4.4	15	7.7	37	52
45*	90	9.0	20	15.7	35	55
30	60*	12.5	21	38.7	64	85
45*	90*	31.5	23	74.9	56	79

^{15}N-urea

TABLE V. RESIDUAL N REMAINED IN WHEAT ROOT SYSTEM AFTER THE HARVEST. (MEANS OF TREATMENT: 90 kg.N.ha^{-1} IN 1995)

Depth	Root dry matter	N	^{15}N	Recovery
cm	kg ha^{-1}	kg ha^{-1}	g ha^{-1}	%
0–5	2860	35	2170	2.5
5–10	1113	13	270	0.3
20–40	135	1	50	0.1
40–60	153	1	40	<0.1
>60	102	<1	20	<0.1

TABLE VI. RESIDUAL N REMAINED IN SOIL AFTER THE WHEAT HARVEST. (MEANS OF TREATMENT: 90 kg N. ha^{-1} IN 1995)

Depth	^{15}N	Recovery
cm	g ha^{-1}	%
0–5	6800	8
5–15	4200	5
15–30	1300	2
30–60	2800	3
>60	2900	3

TABLE VII. SOYBEAN N RECOVERY FROM RESIDUAL N APPLIED TO WHEAT

Time of application in wheat crop		^{15}N	RECOVERY	
Sowing	Tillering		Shoot	Root
	kg ha^{-1}	g ha^{-1}	%	%
30	60*	1690	3	
45*	90*	6430	5	<1

*^{15}N

3.2.3. Leaching

Nitrates in soil can be leached below the root zone. The quantity of percolating water and the rate of applied fertilizer determine the amount of leaching N.

The wheat was sown in June and harvested in October, months with low rainfall. Irrigation was controlled to moisten only the root zone. Considering that the necessary conditions for nitrate leaching were not present, it may be assumed that no N would leach below the root zone. The cumulative losses of nitrate at 50 cm depth were less than 1 kg N ha^{-1}. Only a small portion (90 g ha^{-1}) of it was derived from the applied urea, approximately 1% (Fig. 9).

The 1996 data corroborated those obtained in 1995. As the values were obtained from the plot that received 135 kg N ha^{-1}, which is higher than the rate recommended for wheat under irrigation in São Paulo State, the N loss by leaching would be less in a normal crop.

3.2.4. Residual

In the 1995 experiment, less than 3% of the 90 kg N ha^{-1} treatment remained in the wheat root system after harvest (Table V).

Approximately 21% of applied N remained in the soil immediately after harvest (Table VI). As was expected [5], this residual N was recovered from the surface layer of soil.

3.2.5. Residual recovered by soybean

Soybean was grown in the plots previously cultivated to wheat. The wheat straw that remained on the soil after the wheat-grain harvest contained 25 kg N ha^{-1}, of which 16 kg N ha^{-1} had been applied as fertilizer (of the 90 kg ha^{-1} treatment in the 1995 experiment). Approximately 36 kg N ha^{-1} remained in the soil (Table V), corresponding to 40% of the N applied to the wheat. This value was estimated by adding the amount of N remaining in the soil (Table V) to the amount of N in the wheat root (Table VI) and straw. Soybean recovered around 1.5 kg ha^{-1} of that N, less than 2% of that applied to the wheat. Similar results were obtained in the 1996 experiment (Table VII). These data are consistent with those of Strong [5] who found that recovery of residual ^{15}N by a crop rarely exceeds 5% of the total originally applied.

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3.3. Chlorophyll readings

If SPAD chlorophyll-meter readings are to be useful as criteria for deciding the rate of N, if any, to be applied to correct deficiency they must be made at early stages of development, tillering at the latest. However, the SPAD data obtained in both years, 1995 and 1996, showed no correlation with amount of N applied or with shoot-N concentration at tillering.

4. CONCLUSIONS

Wheat responses to N fertilization cannot be predicted by soil or tissue analysis. The fertilizer-N recommendations for wheat in São Paulo State are based on the prior crop and the availability of irrigation. The optimum rate of N is that which maximizes fertilizer-N recovery and minimizes its losses. To maximize N uptake and minimize loss the major portion should be applied at the tillering stage. In the conditions that prevail in São Paulo State, the main loss of N occurs through ammonia volatilization from urea applied by surface broadcast. To minimize such losses, the soil should not be irrigated immediately after fertilization. Nitrate leaching beyond the root zone is minor when irrigation is judiciously controlled, even when the rate of N is above the crop's needs. Only a small portion (less than 5%) of residual N in soil was recovered by a subsequent crop.

By following these recommendations, wheat producers would succeed in optimizing N-fertilizer use, improving the recovery of N under irrigated conditions, and, consequently, reducing the risk of pollution.

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WHEAT-YIELD RESPONSES TO IRRIGATION AND NITROGEN FERTILIZERS IN ROMANIA

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Abstract

This 4-year study investigated the effects of applied N on growth and yield of winter wheat. Rates ranged from 40 to 180 kg N ha^{-1}, applied as urea or ammonium sulphate, enriched in ^{15}N, one third at sowing in the fall and the rest at tillering in the spring. The optimum rate was locally regarded as 120 kg N ha^{-1}, or 80 kg N ha^{-1} after pea. Irrigation was applied to maintain soil moisture in excess of 75% field capacity. Wheat dry-matter and grain-yield responses, and soil mineral-N content, were influenced by the previous crop. Yield benefits were greater from N applied at tillering than when applied at planting; similarly, higher values of fertilizer-N recovery were obtained after application at tillering.

1. INTRODUCTION

This investigation, at Oradea on the plains of the Crisul Repede river, was initiated in the autumn of 1994 and continued until 1998. The effects of fertilizer N on irrigated winter wheat were examined after various previous crops,. The fertilizer was enriched with ^{15}N so that its fate could be ascertained, and distinguished from mineral N from the soil. Furthermore, the effects of fertilizer N on water-use efficiency were determined.

The data are discussed in terms of optimum fertilizer rate for maximizing fertilizer-N recovery by the crop while minimizing nitrate contamination of groundwater.

2. MATERIALS AND METHODS

2.1. Site

The experimental site was located at 47°03'N 21°56'E, at an altitude of 136 m. The brown luvic soil is a clay loam of flat topography, with the physical and chemical characteristics shown in Table I. Unusual aspects were the presence of clay migration to the B horizon, depth of the soil profile, high bulk-density values due to compaction with low porosity and hydraulic conductivity.

The soil was acidic with low Ca levels. The mobile Al content in the A-horizon would be expected to inhibit the growth of some crops (e.g. clover). There were adequate levels of available K and P. The humus content should not cause distortions in neutron-probe determinations of soil moisture (Table I). Ground water was located at a depth of 6 to 8 m.

2.2. Climate

2.2.1. Prior years

For the period 1976–94, the months April–May had averages of 220 mm of rainfall, a temperature sum of 1369°C, and 687 h of sunshine.

Climatic indices allow appraisal of the suitability of specific weather conditions for crop growth. The hydroheliothermic index (Ihst) has recently been found to be superior to the Palfay and de Martonne indices, for expressing the climate-yield connection.

TABLE I. THE MAIN PROPERTIES OF THE BROWN LUVIC SOIL OF ORADEA, ROMANIA

Depth cm	Sand	Silt	Clay	OC	TN	LLW	ULS	pH	RGF
0 - 5	43,5	28,3	28,2	1,25	0,185	0,120	0,324	6,3	1,00
5 - 15	41,8	28,4	29,8	1,12	0,167	0,129	0,341	6,4	0,75
15 - 30	40,0	28,5	31,5	1,02	0,157	0,135	0,349	6,3	0,40
30 - 60	32,0	28,0	40,0	0,99	0,157	0,162	0,381	6,6	0,30
60 - 90	24,1	36,7	39,2	0,29	0,092	0,178	0,397	6,6	0,06
90 - 150	35,1	27,3	37,6	0,17	0,065	0,191	0,401	6,5	0,00

OC - organic C%

TN - Total nitrogen in %

LLW - lower limit water content in cm^3/cm^3 ($\frac{WP \times BD}{100}$)

ULS - uper limit (saturated) water content in cm^3/cm^3 ($\frac{Fc \times BD}{100}$)

RGF - root growth factor (0 = no roots, 1,00 = many roots)

TABLE II. HYDROHELIOTHERMIC INDEX VALUES IN THE 1976-1994 PERIOD

Excesiv	Very drought	Drought	Middle drought	Middle	Wet I	Wet II	Wet III	Excesiv
DROUGHT				Wet				
< 3	3-5	3-7	7-9	9-12	12-15	15-18	18-25	> 25
April - August								
0	1	5	7	4	2	0	0	0
April								
0	3	5	3	3	1	1	2	0
May								
2	4	3	2	2	3	1	2	0
June								
0	2	3	4	2	3	4	1	0
July								
5	3	4	2	1	2	0	1	1
August								
3	6	7	1	0	2	0	0	0

The following formula was used:

$$\text{Ihst} = \frac{100R}{\sum T + \sum S}$$

where

R is rainfall or irrigation (mm),
T is temperature (°C), and
S is sunshine duration (h).

For the 19 years of data, there was drought in 52% of the periods April to June, and for June it was 47% (Table II). Irrigation provided 35 to 54% of moisture needs to ensure maintenance of field capacity to a soil depth of 50 cm.

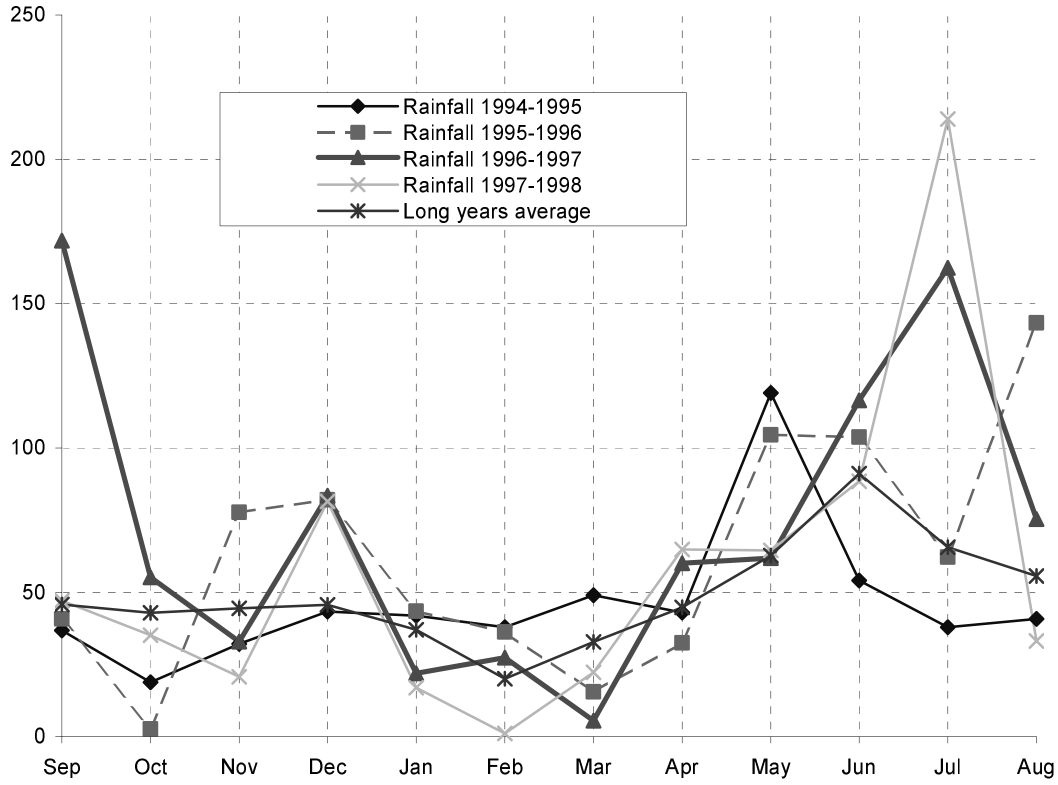

FIG. 1. Comparison of monthly average rainfall during the growing seasons of 1994-95, 1995-96, 1997-98 with long years average of 30 years.

2.2.2. During the experiment

Rainfall from sowing to harvesting ranged between 479 mm in 1995 to 565 mm in 1998, and during actual crop growth totaled between 276 mm (1995) and 387 mm (1998) (Fig. 1). The hydroheliothermic index showed that May was the driest month (Table II).

To maintain soil moisture at field capacity to a depth of 50 cm irrigations were necessary each year, in June and July. In irrigated plots the ratio value water/temperature/light had grown in comparison with non-irrigated plots with 66%, in May and 40% in June, ranging between 29 and 59% in May and between 17 and 56% in June.

2.3. Fertilizers

Four N-fertilizer rates were variously used for the four successive field experiments. The plot size was 6 × 10 m, divided longitudinally in half. One half was used for soil and plant samplings and the other undisturbed half was used for yield determination. Micro-plots of 1.0 m^2 were treated with ^{15}N as described below.

The N fertilizations were split, with one third applied in autumn at sowing and two thirds at Zadoks growth-stage 30 (end of tillering, 10% of main stems with knots detectable). Basal applications of P and K were made at 120 kg P_2O_5 ha^{-1} and 80 kg K_2O ha^{-1}, at seed-bed preparation. Measures to control pests, diseases and weeds were made according to local recommendations.

2.3.1. 1994–95

The previous crop was maize. Urea, enriched in ^{15}N at 2% (Treatments 2, 3 and 4) or 10% atom excess (Treatments 5 and 6), was applied as follows.

(1) N_0 = unfertilized control;
(2) $N_{0.5}$ = N rate equivalent to 50% of the optimum rate (60 kg N ha^{-1}, N_{60});
(3) $N_{1.0}$ = 100% of the optimum rate (120 kg N ha^{-1});
(4) $N_{1.5}$ = 150% of the optimum rate (180 kg N ha^{-1});
(5) $N_{1.5}$ = 150% of the optimum rate (180 kg N ha^{-1});
(6) $N_{1.5}$ = 150% of the optimum rate (180 kg N ha^{-1}).

2.3.2. 1995–96

The previous crop was pea. Ammonium sulphate, enriched in ^{15}N at 5.84% atom excess, was applied as follows.

(1) N_0 = unfertilized controlled;
(2) $N_{0.5}$ = N rate equivalent to 50% of the optimum rate (40 kg N ha^{-1});
(3) $N_{1.0}$ = 100% of the optimum rate (80 kg N ha^{-1});
(4) $N_{1.5}$ = 150% of the optimum rate (120 kg N ha^{-1}).

2.3.3. 1996–97

The previous plant was sunflower. Urea, enriched in ^{15}N at 5% atom excess, was applied as follows.

(1) N_0 = unfertilized control;
(2) $N_{0.5}$ = N rate equivalent to 50% of the optimum rate (60 kg N ha^{-1})
(3) $N_{1.0}$ = 100% of the optimum rate (120 kg N ha^{-1});
(4) $N_{1.5}$ = 150% of the optimum rate (180 kg N ha^{-1}).

2.3.4. 1997–98

The previous crop was pea. Urea was applied to Treatments 1 to 5 enriched in ^{15}N at 5% atom excess, and ammonium sulphate was applied to Treatment 6 enriched in N at 5.84% atom excess, as follows.

(1) N_0 = unfertilized control;
(2) $N_{0.5}$ = N rate equivalent to 50% of the optimum rate (40 kg N ha^{-1});
(3) $N_{1.0}$ = 100% of the optimum rate (80 kg N ha^{-1});
(4) $N_{1.5}$ = 150% of the optimum rate (120 kg N ha^{-1});
(5) N = N rate equivalent 100 kg N ha^{-1};
(6) N = N rate equivalent 100 kg N ha^{-1}.

2.4. Planting

Wheat seed ('Lovrin-41') was sown in rows 12.5 cm apart during the second half of October, at a rate of 280 kg ha^{-1}. A growing-season summary for wheat at Oradea Research Station is presented in Table III.

2.5. Irrigation

Irrigation, by means of a central sprinkling line system specially designed for experimental work, was applied to maintain the soil-moisture content in excess of 75% field capacity to a depth of 50 cm. The same amount of water was applied to all plots, although the quantity was based on water requirement for the optimum-N rate. Water quality is shown in Table IV.

Because of unusually high rainfall during May and June of the 1995–96 experiment, 105 and 104 mm, respectively, there was need for only two irrigations during the season. The 60-year averages for May and June are 63 and 86 mm, respectively.

TABLE III. GROWING SEASON SUMMERY FOR WHEAT GROWN AT ORADEA DURING THE 1994=1995, 1995- 1996, 1996-1997, AND 1997-1998 SEASONS

	1994-95	1995-96	1996-97	1997-98
Preceding crop	maize	pea	sunflower	hemp
Cultivar	TURDA-200	CORINA	SELECT	FIBRAMULTA 51
Planting date	15 April - 94	3 April - 95	10 April - 96	17 April - 97
Fert. N kg/ha	150	60	80	100
Harvesting date	1 Oct. - 94	20 June - 95	15 Sept - 96	24 August - 97
Wheat cultivar	LOVRIN 41	LOVRIN 41	LOVRIN 41	LOVRIN 41
Planting date	15 Oct. - 94	21 Oct. - 95	15 Oct. - 96	20 Oct - 97
Type of fertilizer	x urea, xx urea	Ammonium sulfate	urea	x urea, xx Ammo.sulf
^{15}N % excess	x-2 %, xx-10 %	5.84%	5.51	x-5 %, xx-5.84 %
Irrigation given to wheat	3, 25 May 5,27 June	26 May 14 June	15 May	27 Oct. - 97 15 May, 1 June-98
Z - 30 Sampling	3 April	20 April	17 April	9 April
Anthesis	7 June	15 June	20 June	12 June
Physiological maturity	10 July	14 July	20 July	14 July
Harvesting	17 July	23 July	25 July	27 July

TABLE IV. THE MAIN PROPERTIES OF WATER USED ON IRRIGATED FIELDS

Ca^{2+}		Mg^{2+}		Na^{+}		K^{+}		CO_3^{2-}		HCO_3^{-}	
me/l	mg/l	me/l	mg/l	me/l	mg/l	me/l	mg/l	me/l	mg/l	me/l	mg/l
3,53	70,6	1,57	19,1	0,43	10,0	0,02	1,0	0	0	4,25	259,2

Cl^{-}		CO_3^{2-}		pH	Na %	SAR	Mineral reziduu g/l	EC 10^{-6} mmhom./cm	Richards Class
me/l	mg/l	me/l	mg/l						
0,57	20,2	0,73	35,0	6,8	3,9	0,27	0,41	0,62	C.2-S.1

EC - electrical conductivity

SAR - sodium adsorbtion ratio

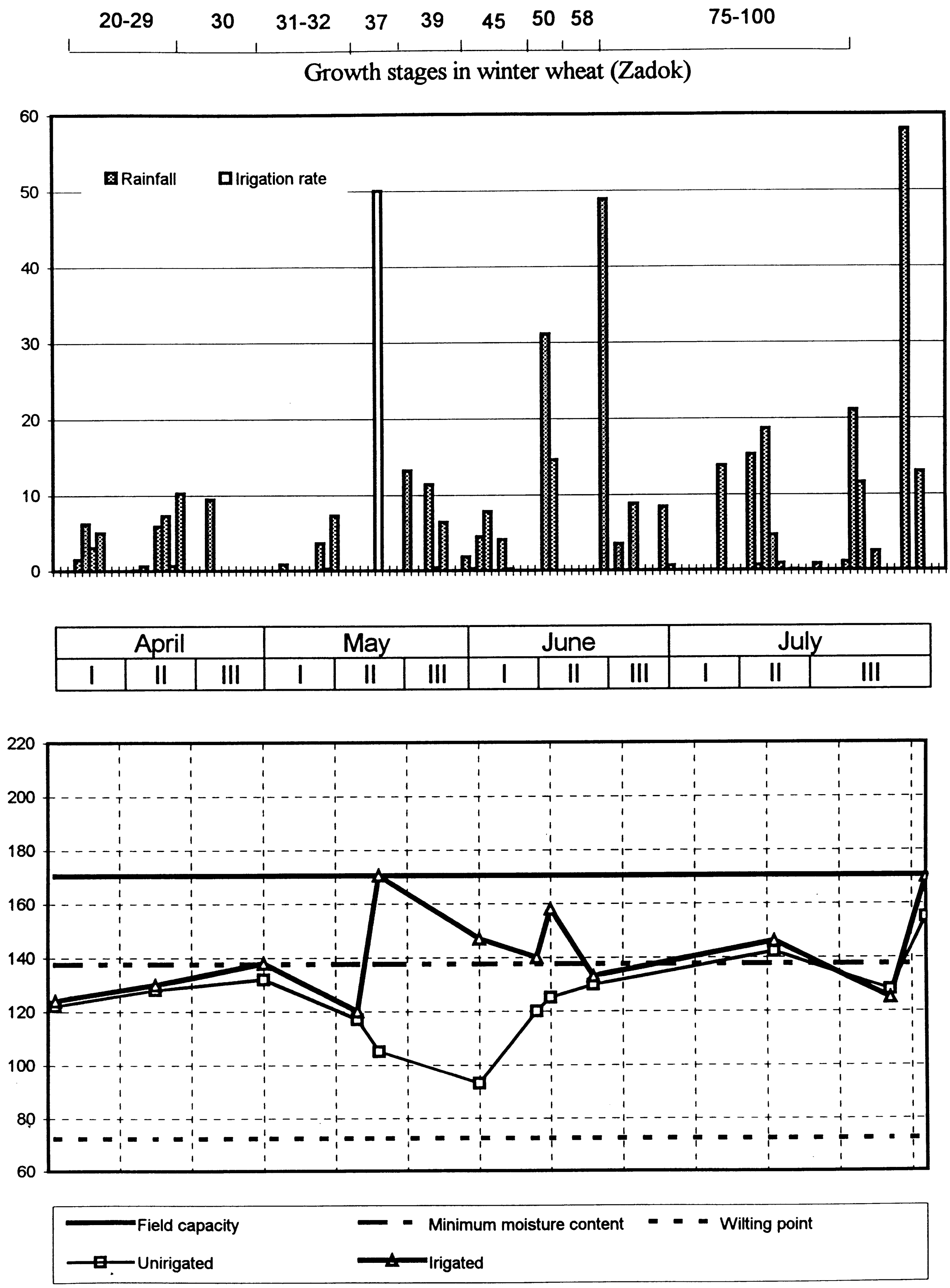

FIG. 2. Soil moisture content evolution on the 0-50 cm depth in winter wheat (1997).

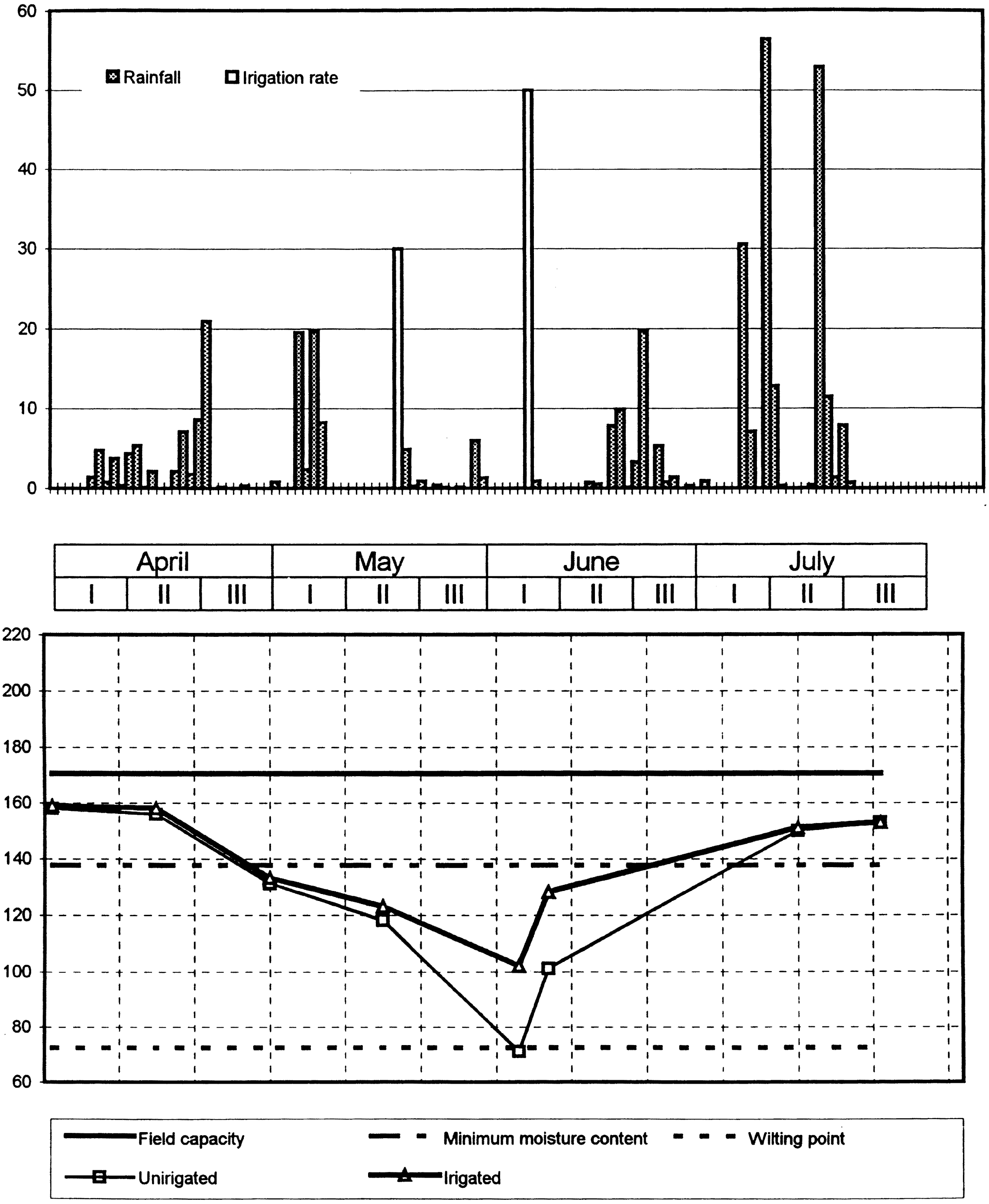

FIG. 3. Soil moisture content evolution on the 0-50 cm depth in winter wheat (1998).

During the 1996–97 season, only one irrigation was necessary, in the second half of May. In June and July, 120 and 162 mm of rain were recorded, whereas the 60-year averages are 86 and 66 mm, respectively; therefore, wheat normally responds to irrigation during this period (Fig. 2).

After planting in the autumn of 1997, rainfall was below the 60-year average, therefore 50 mm of irrigation water were applied to ensure uniform seedling emergence. Precipitation in March, April and May was below average, therefore, 30 mm irrigation were applied in May and 50 mm in the first 10 days of June (Fig. 3). Heavy rains in June and July offset the need for the usual irrigation during that period.

2.6. Analyses

Soil moisture was determined with a neutron probe, via access tubes in each plot. Calculations of soil-moisture content and determinations of timing and rate of irrigations were made using standard methods.

Soil mineral N (NH_4^+-N and NO_3^--N) determinations were made at sowing in autumn, at the second fertilizer application, at anthesis, and at final harvest.

Dry matter and %N values were determined at the end of the vegetative growth period and at maturity. Nitrogen-15 enrichment values were assayed in samples of grain and straw from plants in the micro-plots.

3. RESULTS

3.1. Soil mineral-N, 1994–98

The patterns of mineral-N content in the soil are presented in Table V, and Figs 4 and 5.

In autumn, before fertilizer application, NH_4^+-N content varied between 10 and 15 mg L^{-1}, with the lowest values in the 30- to 60-cm layer, whereas NO_3^--N content was 1.6 to 4.8 mg L^{-1} with the lowest values in the 5-to 15-cm layer. The highest amounts of mineral N of both forms were found at the foot of the profile.

The measurements taken before the second fertilization indicated increases of the NH_4^+ content in the N_{40} and N_{80} plots, whereas there was little change in NO_3^--N content. At anthesis, there were decreases in the NO_3^-- and NH_4^+-N values in the 5- to 30-cm layer in which most of the root is found; the lower NO_3^--N content can be explained in terms of plant uptake and possible leaching.

TABLE V. EVOLUTION OF NITROGEN SOIL CONTENT (ppm) DURING THE VEGETATION PERIODS FROM 1994 TO 1998

	Fertilizing rate	Depth rate	Autumn		2-nd fertilizing applic.		Anthesis		Harvest	
			NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N
1	Chec plot		15.16	1.76	16.21	1.91	5.23	0.68	7.70	1.46
		5–15	13.66	1.86	12.15	1.79	7.63	0.64	5.09	1.35
		15-30	10.72	1.92	11.3	1.95	4.69	0.65	4.40	1.73
		30-60	10.53	3.17	10.92	2.98	5.62	0.63	3.28	1.45
		60-90	15.50	3.99	15.23	3.09	6.59	0.51	4.54	0.91
2	$N_{20}+N_{40}$	0-5	15.03	1.80	24.71	1.95	15.27	1.21	11.17	2.16
		5–15	13.76	2.21	12.20	1.49	6.43	1.09	4.96	1.98
		15-30	11.88	2.66	11.95	1.79	9.46	0.81	4.35	1.29
		30-60	10.86	3.56	10.46	2.71	6.88	0.66	3.95	1.40
		60-90	15.11	4.80	13.01	3.97	7.06	0.60	4.58	0.93
3	$N_{40}+N_{80}$	0-5	15.76	1.75	16.17	2.29	9.34	1.27	7.92	3.24
		5–15	14.81	1.57	21.51	1.89	8.94	1.11	6.01	2.77
		15-30	13.15	2.42	23.08	2.56	9.88	0.77	5.72	1.66
		30-60	11.58	3.36	19.98	3.36	9.70	0.79	4.93	1.64
		60-90	14.52	3.43	21.78	3.14	8.71	0.61	4.78	1.13
4	$N_{60}+N_{120}$	0-5	15.06	1.64	27.65	2.04	14.61	1.06	3.98	1.97
		5–15	13.93	1.93	16.61	2.06	10.34	1.09	6.05	1.53
		15-30	11.49	2.73	20.26	2.20	10.06	1.05	7.12	1.43
		30-60	12.34	3.91	22.96	3.12	5.84	0.87	4.99	1.62
		60-90	14.75	4.56	30.85	5.11	8.02	0.57	5.07	1.50

TABLE VI. DRY MATTER YIELD, NITROGEN CONTENT, AND NITROGEN UPTAKE BY WHEAT PLANTS AT ANTHESIS AS INFLUENCED BY FERTILIZER-N LEVELS

Time	Treatment N level	DM yield (q/ha)		N Content (%)		N uptake (kg/ha)		
		Straw	Ears	Straw	Ears	Straw	Ears	Total
1994-95	N_0	29.0	24.0	1.67	2.88	48.43	69.12	117.55
	$N_{0.5}$	40.0	34.0	1.72	1.90	68.80	64.60	133.40
	$N_{1.0}$	46.0	39.0	1.81	2.01	83.26	78.39	161.65
	$N_{1.5}$	53.0	43.0	1.89	2.15	100.10	92.45	192.55
1995-96	N_0	28.5	23.2	1.56	2.61	44.46	60.55	105.01
	$N_{0.5}$	38.0	32.4	1.67	1.85	63.46	59.94	123.40
	$N_{1.0}$	45.2	36.3	1.75	1.92	79.10	69.69	148.79
	$N_{1.5}$	52.1	40.8	1.80	2.05	93.78	83.64	177.42
1996-97	N_0	27.3	24.1	1.11	2.32	30.30	55.91	86.21
	$N_{0.5}$	36.2	31.7	1.24	1.70	44.88	53.89	98.77
	$N_{1.0}$	46.2	38.3	1.43	1.81	66.06	69.32	135.38
	$N_{1.5}$	55.3	45.2	1.56	1.92	86.26	86.78	173.04
1997-98	N_0	34.2	25.3	1.53	2.63	52.32	66.54	118.86
	$N_{0.5}$	37.6	33.2	1.65	1.82	62.04	60.42	122.46
	$N_{1.0}$	42.0	37.2	1.72	1.86	72.24	69.19	141.43
	$N_{1.5}$	50.6	42.1	1.72	2.06	87.03	86.7	173.73

* Each value is mean of 4 replicates

TABLE VII. INFLUENCE OF FERTILIZER-N LEVELS ON WHEAT YIELD IN IRRIGATION CONDITION (1994-1998)

Treatment N level	Grain				Straw			
	Yield		Differences		Yield		Differences	
	q/ha	%	q/ha	%	q/ha	%	q/ha	%
N_0	38.15	100	-	-	42.97	100	-	-
$N_{0.5}$	49.95	131	11.80	31	58.72	137	15.75	37
$N_{1.0}$	58.42	153	20.27	53	68.12	158	25.15	58
$N_{1.5}$	64.77	170	26.62	70	77.17	179	44.01	79

LSD	Grain	Straw
5%	5.36	6.01
1%	7.21	7.58
0.10%	8.43	9.03

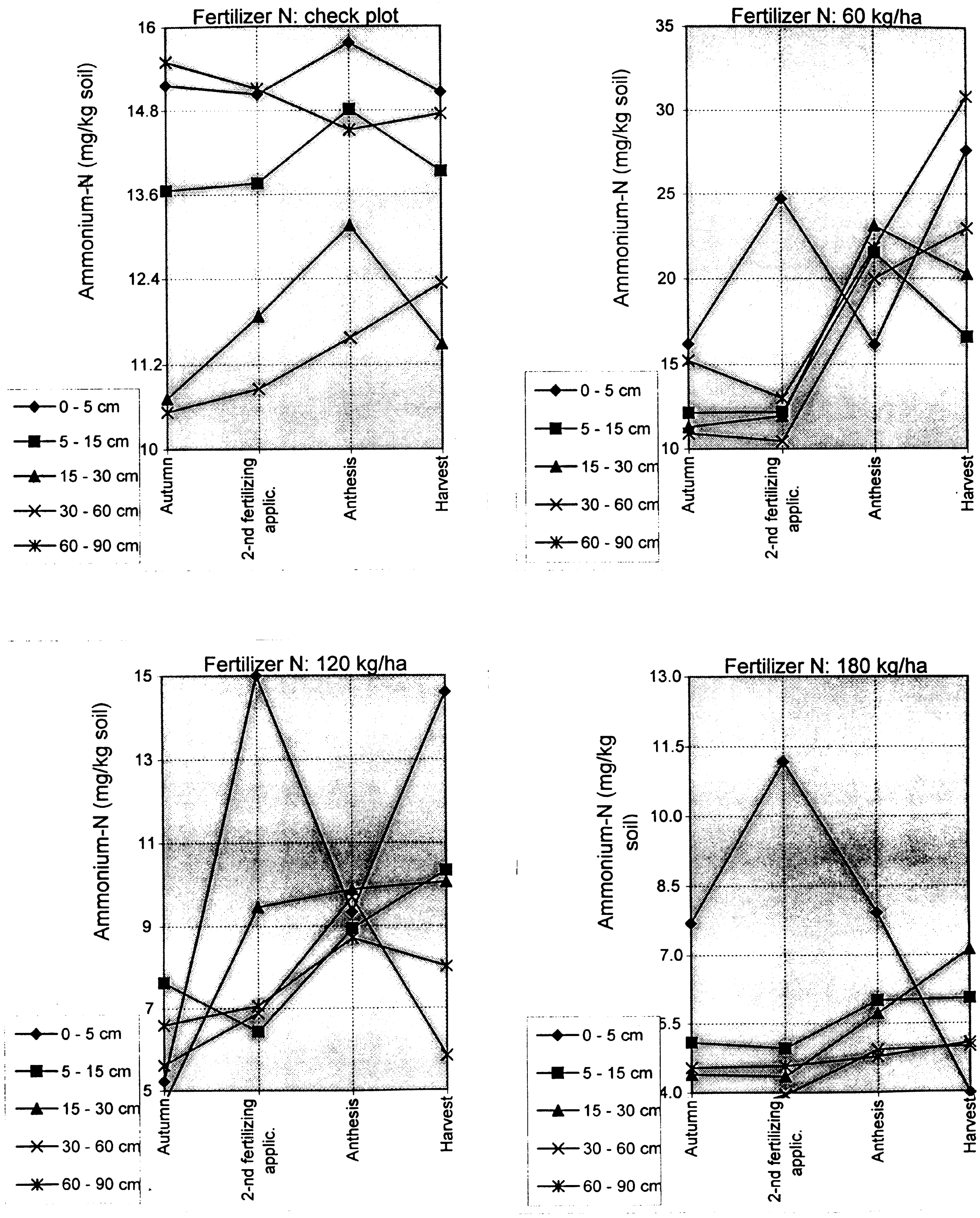

FIG. 4. Evolution of ammonium-N soil content at different depths during wheat crop growth (1994-1998).

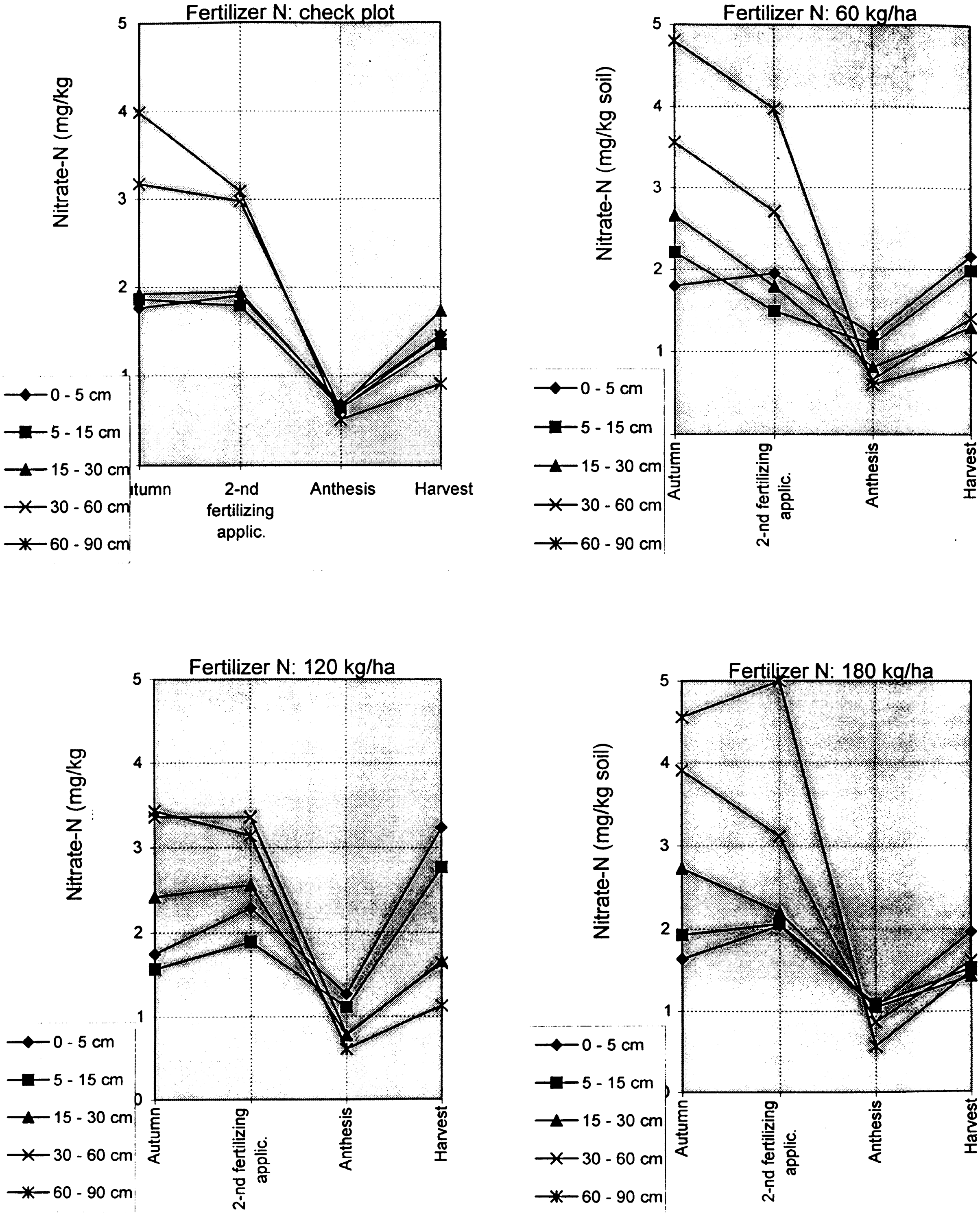

FIG. 5. Evolution of nitrate-N soil content at different depth during wheat crop growth (1994-1998).

TABLE VIII. EFFECT OF FERTILIZER-N LEVELS ON YIELD, N CONTENT, AND N UPTAKE OF WHEAT GRAIN AND STRAW AT HARVESTING

Time	Treatment N level	Yield			N Content (%)		N uptake (kg/ha)		
		Grain	Straw	Total	Grain	Straw	Grain	Straw	Total
1994-95	N_0	38.7	45.3	84.0	1.75	0.46	67.71	20.84	88.55
	$N_{0.5}$	52.3	62.4	114.7	1.95	0.47	101.98	29.33	131.31
	$N_{1.0}$	61.4	73.4	134.8	2.08	0.64	127.71	46.98	174.69
	$N_{1.5}$	67.5	81.5	149.0	2.27	0.72	153.22	58.68	211.90
1995-96	N_0	36.2	44.3	80.5	2.17	0.33	78.55	14.62	93.17
	$N_{0.5}$	51.2	61.0	112.2	2.21	0.32	113.15	19.52	132.67
	$N_{1.0}$	58.6	71.4	130.0	2.24	0.33	131.26	23.56	154.82
	$N_{1.5}$	66.2	79.5	145.7	2.51	0.35	166.16	27.82	193.98
1996-97	N_0	34.5	36.5	71.0	1.47	0.31	50.71	11.31	62.02
	$N_{0.5}$	44.6	53.5	98.1	1.86	0.36	82.96	19.26	102.22
	$N_{1.0}$	53.6	61.7	115.3	1.92	0.38	102.91	23.45	126.36
	$N_{1.5}$	61.7	72.5	134.2	2.13	0.38	131.42	27.55	158.97
1997-98	N_0	43.2	45.8	89.0	1.64	0.41	70.85	18.78	89.63
	$N_{0.5}$	51.7	58.0	109.7	1.92	0.47	99.26	27.26	126.52
	$N_{1.0}$	60.1	66.0	126.1	2.11	0.65	126.81	42.90	169.71
	$N_{1.5}$	63.7	75.2	138.9	2.24	0.70	142.68	52.64	195.32

At final harvest, lower values of NH_4^+- and NO_3^--N were recorded in the soil profile, but with an improved NH_4^+:NO_3^- ratio, as compared to the previous stage, due to nitrification and to the slowing of N consumption by the crop.

On average, the NH_4- and NO_3^--N values were lower for the 1996–97 season because of unusually high rainfall during August and September, 1996, of 142 and 172 mm, whereas the averages are 57 and 42 mm, respectively.

3.2. Dry matter and N uptake at anthesis

Dry-matter yields, %N, and total-N uptake values at anthesis, for 1994–98, are presented in Table VI. There was wide variation in the dry-matter yields. With the N_0 treatment, values ranged between 29 and 34 q ha^{-1}, 38 to 40 with $N_{0.5}$, 42 to 46 with $N_{1.0}$, and 51 to 55 q ha^{-1} with $N_{1.5}$.

Plant-N contents correlated with N rate, with relatively low values for the control-plot samples. In the first year (1994–95), the higher levels of N, 120 and 180 kg N ha^{-1} ($N_{1.0}$ and $N_{1.5}$), gave significantly higher yields and N-uptake values compared to the other N treatments.

3.3. Grain and straw yields

Highly significant grain-yield responses to N-fertilizer application were observed (Table VII). The lowest yield, 38 q ha^{-1}, was obtained in the control no-fertilizer treatment; and the highest was 65 q ha^{-1}. The largest grain-yield response was achieved with 60 kg N ha^{-1}, in comparison to the zero-N

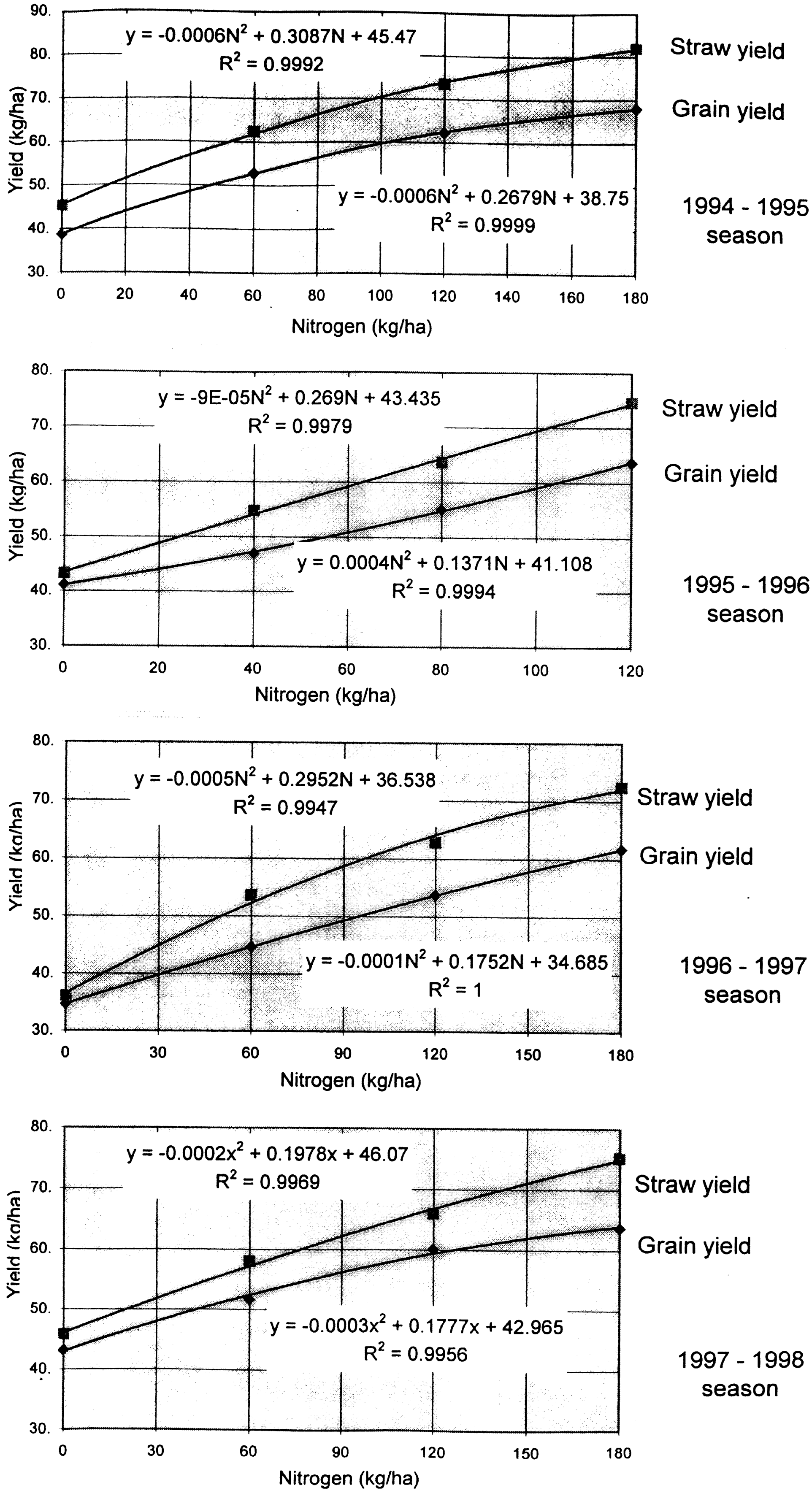

FIG. 6. Wheat grain and straw yield response curve to different rates of fertilizer application.

TABLE IX. EFFECT OF FERTILIZER-N LEVELS ON FERTILIZER N UPTAKE BY WHEAT

Time	N level kg N/ha	N uptake from fertilizer kg/ha		
		Grain	Straw	Total
1994-95	N - 60	12.0	2.8	14.8
	N - 120	32.2	9.8	42.0
	N - 180	57.6	14.9	72.5
1995-96	N - 40	10.0	1.3	11.3
	N - 80	24.7	4.4	29.1
	N - 120	36.7	6.1	42.8
1996-97	N - 60	30.8	4.8	35.6
	N -120	43.2	10.8	54.0
	N - 180	92.7	15.9	108.6
Average 1994-97	N - 0.5	17.60	2.96	20.56
	N - 1.0	33.36	8.33	41.70
	N - 1.5	62.33	12.31	74.63

TABLE X. FERTILIZER-N UPTAKE (kg/ha) BY WHEAT FROM TWO SPLIT APPLICATIONS IN THE 1994-1997 PERIOD

Time	Treatment kg N/ha		First split	Second split	Total
1994-1995	N - 60	Grain	2.7	9.3	12.0
		Straw	0.8	2.0	2.8
		Total	3.5	11.3	14.8
	N - 120	Grain	8.3	23.9	32.2
		Straw	2.3	7.5	9.8
		Total	10.6	21.4	42.0
	N - 180	Grain	13.7	43.9	57.6
		Straw	4.7	10.2	14.9
		Total	18.4	54.1	72.5
1995-1996	N - 40	Grain	2.8	7.2	10
		Straw	0.5	0.8	1.3
		Total	3.3	8.0	11.3
	N - 80	Grain	6.2	18.5	24.7
		Straw	1.6	2.8	4.4
		Total	7.8	21.3	29.1
	N - 120	Grain	13.4	23.3	36.7
		Straw	2.4	3.7	6.1
		Total	15.8	27.0	42.8
1996-1997	N - 60	Grain	7.1	23.7	30.8
		Straw	1.6	3.2	4.8
		Total	8.7	26.9	35.6
	N - 120	Grain	11.9	31.3	43.2
		Straw	3.1	7.7	10.8
		Total	15.0	39.0	54
	N - 180	Grain	16.2	76.5	92.7
		Straw	5.2	10.7	15.9
		Total	21.4	87.2	108.6

TABLE XI. FERTILIZER-N RECOVERY (%) OF WHEAT FROM SPLIT APPLICATIONS OF NITROGEN AT DIFFERENT LEVELS OF N APPLICATIONS IN THE 1994-1997 PERIOD

Time	Treatment kg N/ha		First split	Second split	Total
1994-1995	N - 60	Grain	13.50	23.25	20.00
		Straw	4.00	5.00	4.66
		Total	17.50	28.25	24.66
	N - 120	Grain	20.70	29.87	26.80
		Straw	5.75	6.25	8.16
		Total	26.45	36.12	34.96
	N - 180	Grain	22.83	36.58	32.00
		Straw	7.83	8.50	8.27
		Total	30.66	45.08	40.27
1995-1996	N - 40	Grain	21.50	26.66	25.00
		Straw	3.85	2.96	3.25
		Total	22.35	29.62	28.25
	N - 80	Grain	23.80	34.20	30.8
		Straw	6.15	5.18	5.50
		Total	29.95	39.38	36.30
	N - 120	Grain	33.50	29.12	30.56
		Straw	6.00	4.62	5.08
		Total	39.50	33.78	35.66
1996-1997	N - 60	Grain	35.5	59.25	51.33
		Straw	8.00	8.00	8.00
		Total	43.5	67.25	59.33
	N - 120	Grain	29.75	39.12	36.00
		Straw	7.75	9.62	9.00
		Total	37.50	48.74	45.00
	N - 180	Grain	27.00	63.75	51.50
		Straw	8.66	8.92	8.83
		Total	35.66	72.67	60.33

TABLE XII. THE AVERAGE OF FERTILIZER RECOVERY (%) OF WHEAT FROM SPLIT APPLICATIONS 1994–1997

N level (kg/ha)		First split	Second split	Total
N - 0.5	Grain	23.51	36.36	32.11
	Straw	5.28	5.32	5.30
	Total	28.79	41.68	37.41
N - 1.00	Grain	24.75	34.39	31.20
	Straw	6.55	7.02	7.55
	Total	31.3	41.41	38.75
N - 1.50	Grain	27.77	43.15	38.03
	Straw	7.49	7.35	7.39
	Total	35.27	50.50	45.42

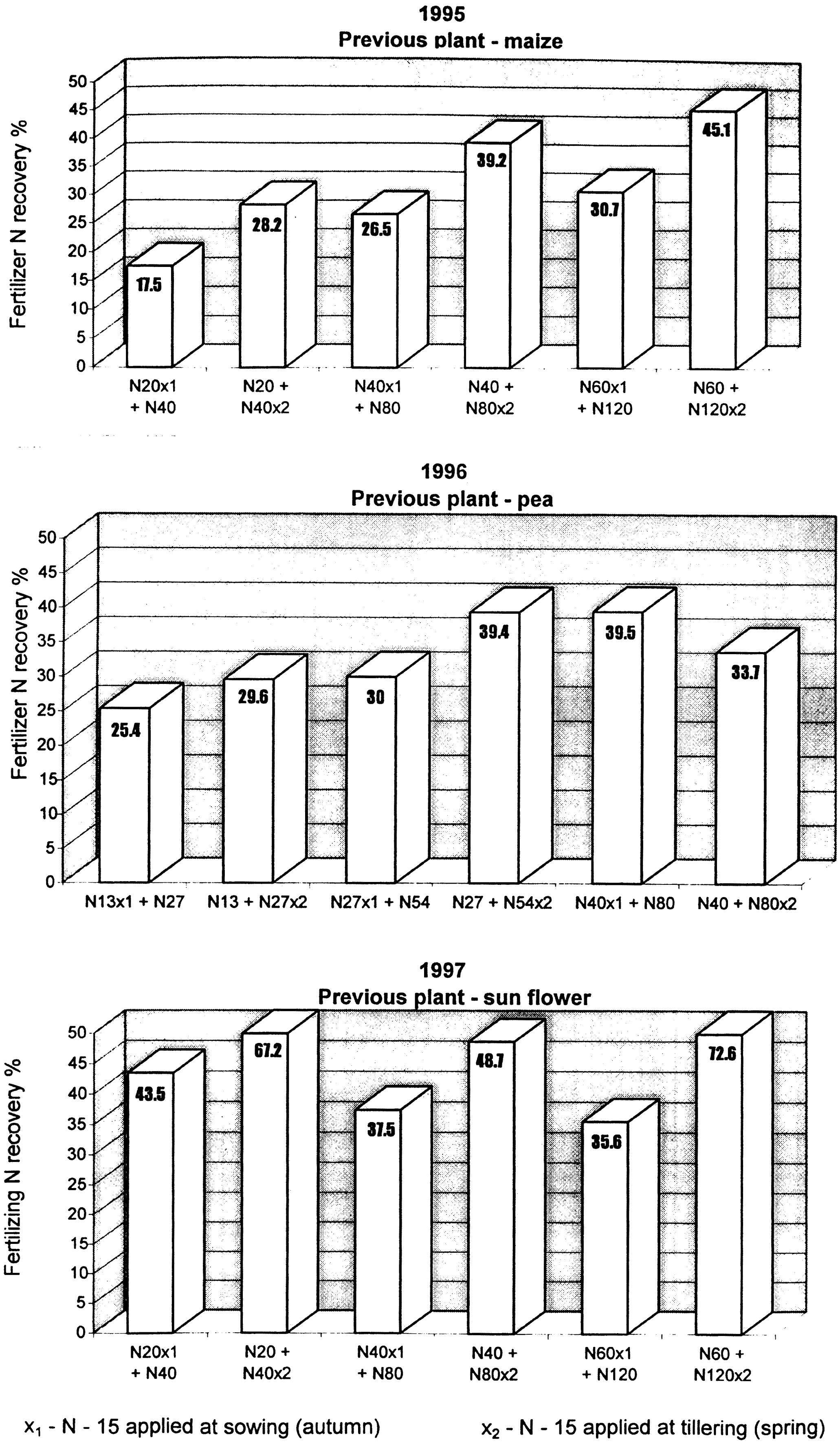

FIG. 7. The nitrogen use efficiency (%) in winter wheat as a function of rate and time of application under irrigation conditions.

TABLE XIII. CUMULATIVE EVAPOTRANSPIRATION (ET) DURING THE VEGETATION PERIODS (1994-1998)

Fertilizer rate	Cumulative evapotranspiration (ET), mm					
	15 III	1 IV	15 IV	1 V	15 VI	15 VII
N_0	28.6	68.4	93.4	118.4	240.6	356.2
N_{60}	29.3	69.5	98.9	128.3	250.2	370.2
N_{120}	29.8	70.2	100.5	130.8	266.9	386.7
N_{180}	30.2	72.5	118.6	144.6	282.0	401.8

TABLE XIV. THE EVAPOTRANSPIRATION AND ITS PROVENANCES IN N-180 TREATMENTS

Time	The surces of provenience (%)			
	ET(mm)	Soil reserve*	Rainfall(mm)	Irrigation
1995	383.8	2.3	67.5	30.2
1996	454.1	18.7	62.6	18.7
1997	341.0	3.1	82.2	14.7
1998	368.0	2.0	80.3	17.7
Average	386.7	6.5	73.2	20.3

*** Initial reserve - final reserve**

control, which suggests rates higher than 120 kg N ha^{-1} must be considered carefully in terms of higher costs and risks of environmental pollution.

Grain and straw yields, N content, total fertilizer-N uptake and N-uptake efficiency data are reported in Table VIII. The mean grain yields were 34 to 43 q ha^{-1} in check plots, 45 to 52 with $N_{0.5}$, 54 to 61 with $N_{1.0}$ and 62 to 67 q ha^{-1} with the $N_{1.5}$ treatment. Similar trends were obtained for straw yields. The highest total dry-matter production (grain and straw) was obtained with the highest N rate. No significant grain-yield responses to the higher N applications were obtained in the 1997–98 season.

Grain- and straw-yield N-response curves are shown in Fig. 6.

3.4. Nitrogen content

The application of fertilizer up 120 kg N ha^{-1} resulted in significantly higher N-content values for wheat grain and straw, in comparison with the zero-N control (Table VIII). The total-N uptake values were 62 to 93 kg N ha^{-1} for the N_0 treatment, 102 to 133 for $N_{0.5}$, 126 to 175 for $N_{1.0}$, and 159 to 212 kg N ha^{-1} with $N_{1.5}$.

The highest grain %N values, between 2.2 and 2.5%, were obtained in 1995–96, after pea; the lowest values were obtained in 1996–97 with 1.5 to 2.5% N, after sunflower. For straw, the highest %N values were obtained when the previous crop was maize and the lowest when the previous crop was pea.

The uptake of N at final harvest depended on the rate of fertilizer applied, weather conditions, and the previous crop. The highest value (212 kg N ha^{-1}) was registered with the highest N rate applied in 1994–95 season, after maize.

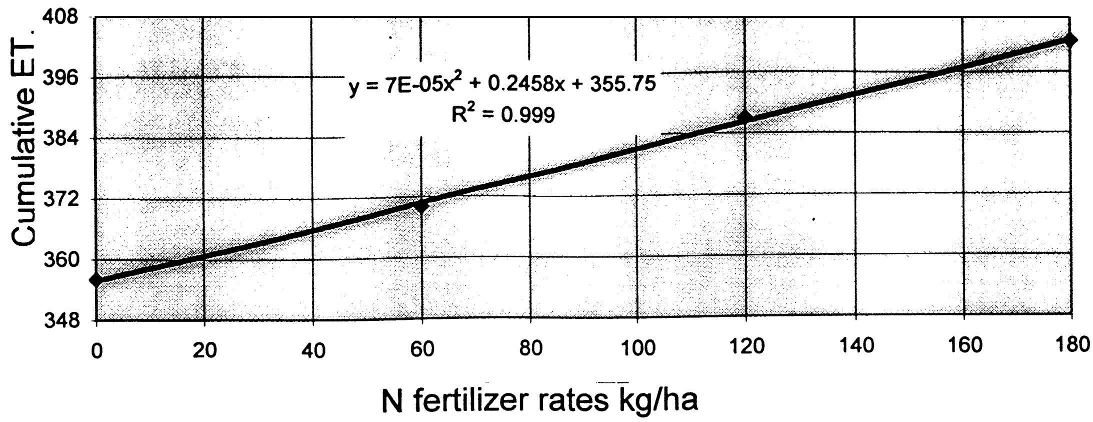

FIG. 8. Relation between ET and fertilizer rates.

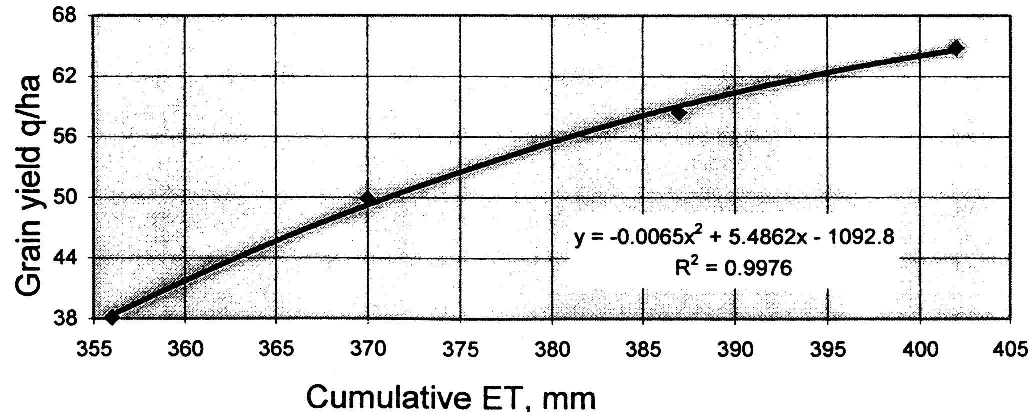

FIG. 9. Relation between cumulative evapotranspiration (mm) and grain yield (1994-1998).

3.5. Fertilizer-N uptake

Fertilizer-N uptake ranged between 14 and 72 kg N ha^{-1} in 1994–95, 11 to 43 in 1995–96, 36 to 109 in 1996–97, and averages of 21 to 75 kg N ha^{-1} were obtained for 1994–97 (Table IX). The smaller values in 1995–96 were recorded after pea.

Values for fertilizer-N-uptake are shown in Table X. Each year, greater quantities were taken up from the second split at tillering. The highest values were obtained during the 1996–97 season.

Recovery of fertilizer-N from split applications, for the 1994–97 period, depended on rate, and were higher for the second application (Table XI).

Fertilizer-N-uptake and uptake-efficiency data for 1994–97, calculated from ^{15}N enrichments, are presented in Fig. 7. With the 60 kg N ha^{-1} treatment, efficiencies for the first split of 20 kg N ranged between 17 and 43% and, for the second dose, 28 to 67%. With 120 kg N ha^{-1}, use-efficiency values ranged between 26 and 37% and between 39 and 49%, for the first and second splits, respectively. Overall, the fertilizer-N-uptake efficiency values for wheat for N_{60} and N_{120} were 59 and 45%, respectively. With N_{180}, although there were significant increases in fertilizer-N uptake both in grain and straw, use-efficiency values ranged between 40 and 60%.

Fertilizer-N recoveries with the $N_{0.5}$ treatment was 37%, 39% with $N_{1.0}$, and 45% with $N_{1.5}$ (Table XII). Higher values were obtained with applications made at tillering.

3.6. Crop-water consumption

Crop-water consumption (ET) through the season increased with rate of N applied, from 336 to 390 mm for the zero-N control and the highest N rate (180 kg N ha^{-1}), respectively. The results imply that N fertilization promotes higher water usage and, thereby, higher grain yield (Tables XIII and XIV).

The connection between cumulative evapotranspiration and N-fertilizer rate is shown in Fig. 8, and the relation between ET and wheat-grain yield is in Fig. 9.

3.7 Residual N

The figures show that in both timing treatments (sowing and tillering application) the residual fertilizer N in soil after wheat harvest could be traced to a depth of 90 cm, the bulk of which was present to 60 cm. When 120 kg N ha^{-1} was applied at tillering, fertilizer N could be found even to a depth of 90 cm. With tillering application of 80 and 120 kg N ha^{-1}, fertilizer N was detectable at lower soil depths after grain harvest.

4. CONCLUSIONS

- To improve fertilizer-N-use efficiency in irrigated wheat, it is necessary to take into account location, soil type, and seasonal variations in climate,
- By utilizing the neutron probe to determine soil-moisture trends, it is possible to quickly and correctly establish the amount and time for the application of necessary irrigation,
- The use of ^{15}N labelled fertilizer allows the determination of the contribution of the fertilizer to yield as well as the efficiency of use of fertilizer N as influenced by time of application and rate,
- The amounts of N derived from fertilizer in straw and grain were higher when applied in spring at tillering, with values commensurate with rate of application,
- Fertilizer-N-use efficiency ranged from 25 to 35%, the highest value being recorded with N applied at 54 kg ha^{-1} at tillering, after pea,
- Total dry matter, grain-yield responses, and the mineralization of soil organic matter were influenced by climatic conditions and the previous crop; wheat benefited more from fertilizer-N applied at early tillering than at planting.

For the period 1994–97:

- With half of the optimal N rate (i.e. 60 kg ha^{-1}) applied at sowing, fertilizer-N recovery was 29% and, when applied at tillering, 42%. For the whole quantity, both splits, the value was 37%.
- With the optimal rate (120 kg N ha^{-1}) applied at sowing, fertilizer-N recovery was 31%, and at tillering it was 41%. For the whole quantity, both splits, the value was 39%,
- There were no significant differences in terms of fertilizer-N recovery between the 60 and 120 kg N ha^{-1} treatments,
- The highest fertilizer-N-recovery values were obtained with 180 kg ha^{-1}: 28% when applied at sowing, 50% when applied at tillering, and 45% for both splits,
- Irrigation increased the recovery of fertilizer N applied at tillering.

WHEAT-YIELD RESPONSES TO IRRIGATION AND NITROGEN

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Abstract

Wheat-yield responses to the application of different rates of N fertilizer, under irrigated and rainfed conditions, were evaluated over four growing seasons. Nitrogen applied at tillering was utilized more effectively with proportionately less residual in the soil compared to that applied at planting. Subsequent crops of maize or cotton were positively affected by residual fertilizer N. Volatilization and leaching losses of applied N were small. Crop-water consumption showed strong positive associations with N rate. No wheat-grain-yield benefits accrued from irrigation, although straw yields were increased. Tiller production increased with N-fertilizer usage, however, tiller survival decreased at high N and was highest at 160 kg N ha^{-1}. Higher N rates produced higher stomatal conductance, increased rates of CO_2 assimilation and higher water-use efficiency. The CERES-Wheat growth-simulation model predicted rather closely the progress of dry-matter production, leaf area index, seasonal evapotranspiration, phenological development and of many other plant-growth attributes. The data indicated that the rate of 160 kg N ha^{-1}, which is commonly used by the farmers of the region, is acceptable, not only for optimum grain yields but also to minimize the risks of leaching NO_3^- to groundwater.

1. INTRODUCTION

Next century, the biggest challenge of will be to meet food and fiber needs of the world's expanding population. Therefore, increasing the production of cereals is strategically important to ensure food self-sufficiency [1]. Wheat is second only to rice in terms of planted area, 707 Mha, and total production, 1.95 Gt; its average yield is 2.76 Mg ha^{-1} [2].

In Turkey, wheat ranks first in terms of total area and production [3]. Although, the area has not recently increased significantly, total production has risen substantially due to expanding fertilizer use. With the introduction of high-yielding varieties, average N-fertilizer rates increased from 120 to 160 kg N ha^{-1} in the 1970s [4, 5] to 350 to 400 kg N ha^{-1} currently. However, these high levels of N do not insure superior yields and quality of grain, and may result in lodging and increased loss of unused N to the environment, by various means. Therefore, there has been extensive research on timing of N application to match plant uptake and utilization during various stages of growth. The effects of split applications of N, e.g. in the fall (at planting) and again in the spring (anthesis), on fertilizer-uptake efficiency [6–8], on N-harvest index [9, 10] and on N losses [8, 10], have been studied in detail; the evidence is persuasive that this strategy is beneficial under a wide range of conditions.

Wheat production in Turkey increased from 6.5 Mt in the 1950s to 18 Mt in the 1990s [11]. Some 2 Mt of this increase was due to area expansion, and the remaining 10 Mt was due to the combined effects of improved genotypes, increased fertilizer inputs, and good agronomic practices. Because Turkey is in a semi-arid/arid region, wheat production depends strongly on the amount of annual rainfall and its seasonal distribution. In the largest area planted to wheat, the highlands of central Anatolia, irrigation is not available and the main yield-constraint is erratic precipitation. Yields in coastal areas are somewhat higher because of greater rainfall with a relatively more uniform seasonal distribution. However, even in these areas, if irrigation is not available, wheat yields show large seasonal fluctuations depending on rainfall [12]. In coastal areas where spring precipitation is low and irrigation not practised, wheat yields are low.

The objectives of our research were to:

– Measure and compare N recoveries from two split applications of fertilizer to wheat, at planting near full emergence and at early tillering, Zadoks growth stage 25–30 (Z-25–30),
– Establish yield-response curves to N-fertilizer applications and to assess interactions with supplementary irrigation,

– Monitor the fate of applied fertilizer using ^{15}N, i.e. taken up by the wheat, residual within the soil profile, and recovery by a subsequent crop,
– Use our results to calibrate and refine various relationships in the CERES-Wheat growth-simulation model for the Mediterranean coastal region of Turkey.

2. MATERIALS AND METHODS

2.1. Site

The experimental site was in the research fields of the Faculty of Agriculture, Çukurova University, on a soil containing significant amounts of smectite clay, classified as a Palaxerollic chromoxeret with heavy clay texture. Additional information is given in Table I.

2.2. Climate

Table II gives scheduled activities and dates of occurrence of characteristic growth stages during the 4 years of study, 1994–95 to 1997–98. The field was deep-ploughed in September, then disc-harrowed and chisel-ploughed as further preparation for planting. A combined drill facilitated the concurrent application of fertilizer and seed. Planting was between mid-November and mid-December, depending on rainfall. Seeds of a bread variety (*Triticum aestivum* L. 'Seri 82'), popular in the region, were planted at 230 kg ha^{-1}, 5 cm deep, with a 17-cm row spacing. Specifically bred for the Çukurova region, this cultivar responds well to N with a potential yield of 9.1 Mg ha^{-1}, but is sensitive to weather conditions and planting time.

2.3. Fertilizer and irrigation

The plots received 80 $kg{\cdot}ha^{-1}$ of triple superphosphate and potassium sulphate at planting. One third of the N fertilizer was applied at full emergence, 10 to 15 days after planting (DAP), and the rest was applied during tillering, at Z-20.4–20.9. Potassium and P fertilizers were applied directly along the seed bed with the seed drilling machine. Nitrogen fertilizer, however, was broadcast.

TABLE I. DESCRIPTION OF THE EXPERIMENTAL SOIL

Depth cm	Sand %	Silt %	Clay %	OC %	TN %	PWP	FC	S	pH	BD	RGF
5	24	21	55	0.87	0.080	0.25	0.37	0.47	7.8	1.19	0.90
15	24	21	55	0.85	0.075	0.27	0.41	0.50	7.8	1.19	1.00
30	21	22	57	0.65	0.060	0.26	0.40	0.50	7.8	1.19	1.00
60	21	22	57	0.55	0.045	0.26	0.40	0.50	7.7	1.16	0.82
90	21	22	57	0.30	0.025	0.28	0.41	0.50	7.7	1.16	0.82
120	21	22	57	0.06	0.004	0.28	0.41	0.50	8.0	1.25	0.00

OC : Organic carbon
TN : Total Nitrogen
PWP: Permanent wilting point, $cm^3.\ cm^{-3}$
FC : Field capacity, $cm^3.\ cm^{-3}$
S : Saturation water content, $cm^3.cm^{-3}$
pH : pH in water
BD : Bulk density, $g.cm^{-3}$
RGF : Root growth factor (0= no roots, 1.00=many roots)

The experiment was laid out using a single-line source irrigation system [13] that allowed a gradual variation in applied water, if and when needed, from excess to none (i.e. rainfed) perpendicular to the source (Fig. 1). However, either because of high rainfall or its relatively uniform distribution, irrigation was applied during the 1995–96 and 1997–98 seasons only (Fig. 2). Therefore, experimental objectives had to be modified to de-emphasize the irrigation effects initially envisaged.

The experimental design had a zero-N control (N_o) and three rates of N fertilizer as urea, 80 (N_1), 160 (N_2) and 240 (N_3) kg N ha^{-1}, arranged as a randomized block with four replicates (Fig. 1). Three of the four replicates (i.e. blocks) had neutron-probe access tubes installed, and two replicates had four sets of tensiometers at depths of 45, 60, 75 and 90 cm. Additionally, soil-water suction cups were installed at 60 and 90 cm, in the two replicates with tensiometers in the 160 (N_2) and 240 (N_3) kg N ha^{-1} treatments, to assess NO_3^--N leaching below the rooting zone (i.e. at 90 cm).

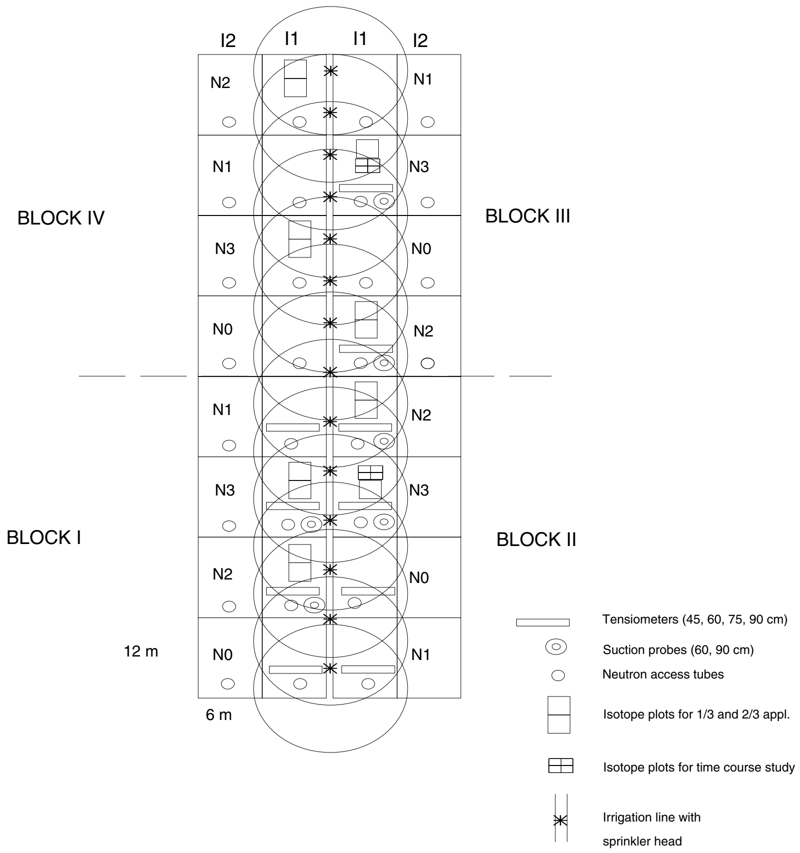


FIG.1. Field experimental design and arrangement of treatments, showing the sites of tensiometers, neutron access tubes, water suction probes and of isotope plots.

Micro-plots, receiving ^{15}N-enriched urea, were established on the 160 and 240 kg N ha^{-1} treatments (Fig. 1). Each accommodated six rows of wheat at a spacing of 15 cm, 1.5 m long, i.e. 1.15 m^2. During the 1995–96 and 1997–98 growing seasons, time-course studies assessed plant uptake of fertilizer N, and N residual within the soil profile (Fig. 1). Furthermore, during the first 2 years, crops of maize and cotton were grown after the 1994–95 and 1995–96 seasons to evaluate benefits from residual fertilizer N.

2.4. Crop-water consumption

Crop-water consumption (ET) was estimated using the water-balance equation [14–16]:

$$ET = I + P \pm \Delta S - D$$

where

ET is evapotranspiration (mm),
I is irrigation (mm),
P precipitation (mm),
D is deep percolation, i.e. drainage, (mm), and

ΔS	is change of soil-water storage in a given time period Δt (days) within the rooting zone.

Deep percolation, D, if it exists during the period Δt, was estimated:

$$D = \int_0^{\Delta t} q\,dt$$

where

q	is Darcy's water flux, field measured with the equation

$$q = -K(\theta)\nabla H$$

where

∇H	is the hydraulic gradient,
K(θ)	is unsaturated hydraulic conductivity (LT^{-1}, cm day^{-1}) assessed through use of internal drainage test [17, 18],

where

L	is plant rooting depth (cm).

The hydraulic gradient, ∇H, at a rooting depth of 90 cm was measured with tensiometers installed at 75, 90 and 105 cm. Soil water storage was assessed with a neutron probe [19] to a depth of 120 cm at 7–10-day intervals.

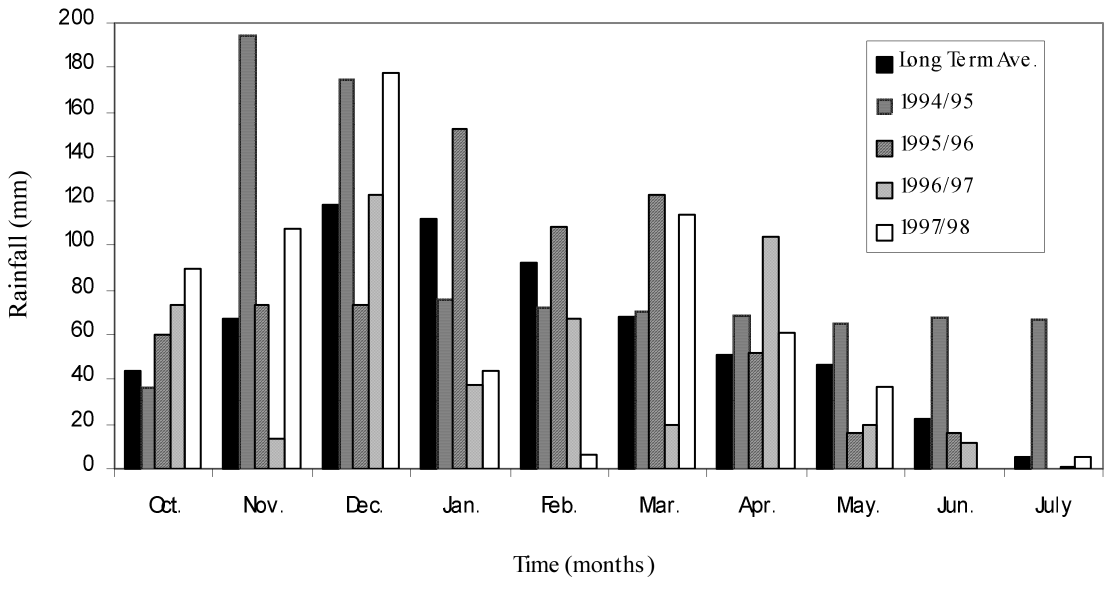


FIG.2. Comparison of monthly average rainfall during the four years period from 1994/95 till 1997/98 seasons with long term (62 years) average.

2.5. Yield and growth attributes

The dates of phenological growth stages were recorded through the four growing seasons of 156 to 200 days, depending on planting date (Table II). To determine time variance for dry-matter production, plant samples were collected at 7–10 day intervals, from 0.25-m row lengths. Starting at about 50% anthesis, four rows of plants were cut weekly, and separated into spikes and straw. Spikes were counted and dry weight determined; straw dry weight was also measured to assess time variance of total dry-weight production and of spike-weight increase. Leaf area index (LAI) measurements were made on fresh leaves using the optical transmittance technique described by Beadle [20]. The samples were dried at 68°C to constant weight [21, 22] to determine progress of dry-matter production.

Wheat is usually harvested when the leaves are chlorotic and grain-moisture content is less than 30%. Kün [23] has suggested delaying until grain moisture is below 15%, therefore, harvests were made in late May or early June at Z-91, when grain moisture was about 13%. Plot size for the yield determination was 8 m^2.

2.6. Soil water

Suction cups [24] were used to sample soil water to monitor leaching of NO_3^--N below the rooting zone. These probes were installed in two replicates of the 160 and 240 kg N ha^{-1} treatments, at 60 and 90 cm. The sampling program was arranged based on cumulative rainfall from the date of first split application of N. Sampling interval was based on total rainfall between the sampling dates, i.e. after 18 to 20 mm cumulative rainfall. Breakthrough curves for NO_3-N were constructed for 60 and 90 cm.

2.7. Soil mineral N

Before planting and during the growing season, soil samples were collected to monitor NO_3^--N and NH_4^+-N concentrations. Samples were collected in plastic bags, treated with a few drops of toluene to stop microbial activity, and deep frozen pending analysis by the semi-micro Kjeldahl method described by Bremner [25].

2.8. Photosynthetic gas exchange

Gas-exchange characteristics of individual leaves were measured with an LCA-3 portable infrared gas analyzer system (ADC BioScientific Ltd., Hoddesdon, UK). Four readings were taken in each plot with the leaf chamber held perpendicular to the sun's rays to maximize light intensity. For each measurement, the abaxial leaf surface was uppermost. Gas exchange was measured on fully emerged 6^{th}, 7^{th} and on the flag leaf (8^{th}) of the main stem. Measurements were taken on clear days when solar radiation at leaf level was 750 µmol m^{-2} s^{-1} (6^{th} leaf) or 1,000 and 1,400 µmol m^{-2} s^{-1} light intensity in the 1996–97 and 1997–98 growing seasons, respectively.

2.9. Simulation model

Field-determined data consisting of plant-growth attributes and soil measurements were used for site calibration of the CERES-Wheat V.3 crop-growth simulation model. The following data were collected to test the model:

(1) Weather data:
- Daily maximum/minimum temperature
- Rainfall
- Total solar radiation;

(2) Plant-growth attributes:
- Total dry matter production
- Leaf area index
- Yield and yield attributes
- Thousand-grain weight
- Grain number per unit area
- Phenological growth stages for flower setting
- Days to anthesis

– Days to physiological maturity;

(3) Soil measurements:

– Physical and chemical characteristics – Moisture status

– NO_3^-- and NH_4^+-N contents – pH.

Data on time variance of plant-growth attributes, i.e. dry-weight production, spike-weight increase and LAI, were compared with predictions of the CERES-Wheat growth model.

3. RESULTS AND DISCUSSION

3.1. Yield

Harvest index (HI) and grain yields are shown in Table III. As expected, the lowest yield was recorded without fertilizer N. There was a statistically significant ($P \leq 0.01$) yield increase beyond 80 kg N ha^{-1} only in 1997–98. Increased N application tended to decrease HI values.

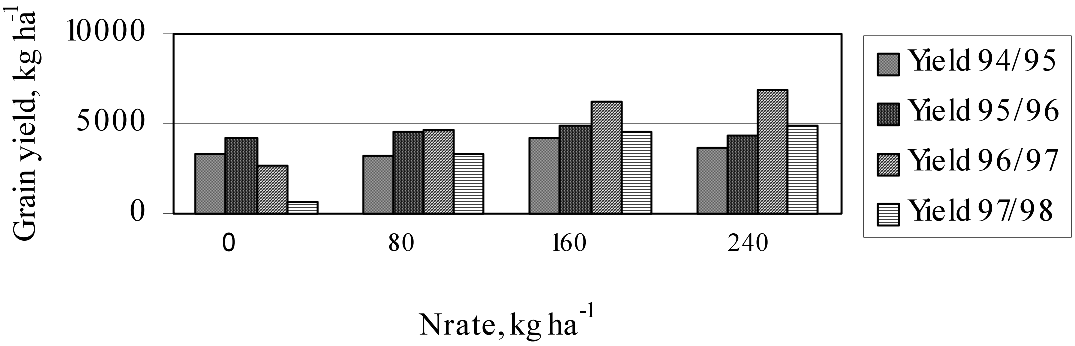


FIG. 3. Wheat grain yield response to different rates of N fertiliser application in four growing seasons.

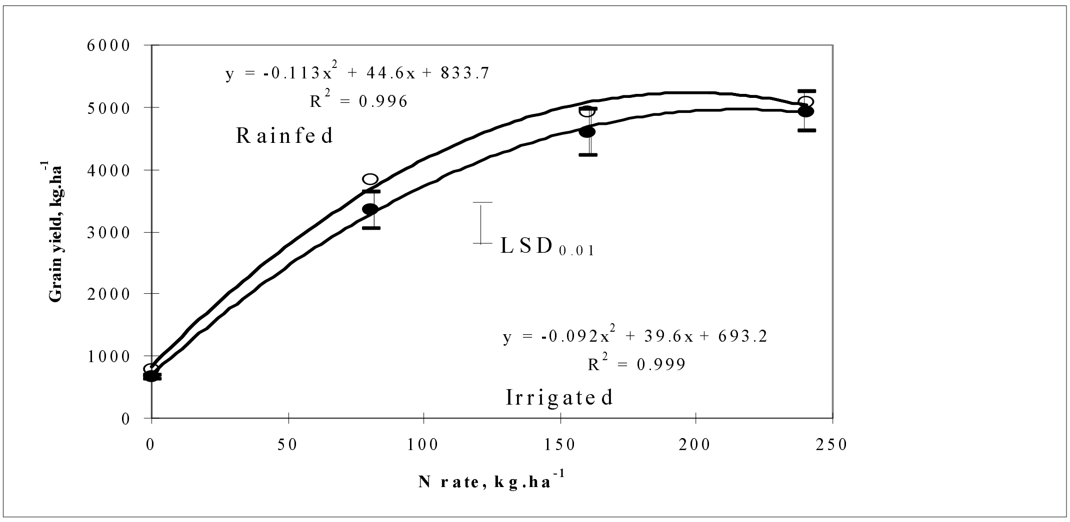


FIG. 4. Wheat grain yield response to different rates of N fertiliser applications, under rainfed and supplementary irrigated conditions.

TABLE II. SCHEDULE OF ACTIVITIES FROM FALL 1994 UNTIL SUMMER 1998

	Schedule of activities, dates of occurrence of characteristic wheat growth stages						
Growing season	Planting	Full emergence	2^{nd} Fert.	Anthesis	Physiological maturity	Harvest	Growing season, days
1994/95	11/11/94	2/12/94	9/3/95	27/3/1995	4/5/95	31/5/95	200
1995/96	5/12/95	18/12/95	25/3/96	8/4/96	16/5/96	7/6/96	182
1996/97	13/11/96	9/12/96	9/1/97	27/4/97	17/5/97	3/6/97	200
1997/98	28/12/97	15/01/98	27/2/98	26/4/98	20/5/98	4/6/98	156

TABLE III. GRAIN YIELD ANDs HARVEST INDEX AS INFLUENCED BY DIFFERENT RATES OF N FERTILISER APPLICATIONS

N fertiliser rates	Growing season							
	1994/95		1995/96		1996/97		1997/98	
	Y, $Mg.ha^{-1}$	HI[b]	Y, $Mg.ha^{-1}$	HI	Y, $Mg.ha^{-1}$	HI	Y, $Mg.ha^{-1}$	HI
N_o 0 kg $N \cdot ha^{-1}$	3.34 B[a]	0.28	4.18 B	0.25	2.71 B	0.31	0.67 C	0.34 B
N_1 80 kg $N \cdot ha^{-1}$	3.18 AB	0.26	4.60 A	0.24	4.72 AB	0.32	3.35 B	0.39 A
N_2 160 kg $N \cdot ha^{-1}$	4.25 A	0.25	4.93 A	0.18	6.23 A	0.34	4.60 A	0.37 AB
N_3 240 kg $N \cdot ha^{-1}$	3.67 A	0.22	4.28 B	0.16	6.87 A	0.34	4.94 A	0.33 B
Average	3.61	0.25	4.50	0.21	5.13	0.33	3.39	0.36

[a]Values in columns followed by different letters are significantly different ($P \leq 0.01$) as determined with Duncan's multiple range test.
[b]Harvest index was defined as $HI = Grain/(Straw + Grain)$.

Yield responses to similar N rates were highly variable from year to year, possibly due to weather differences and to varying soil mineral-N levels at planting. This differential character of yield response is shown in Fig. 3. Nevertheless, the largest grain-yield increases (i.e. highest slope of the curve) were consistently achieved within the zero to 160 kg N ha^{-1} range, suggesting that the use of higher rates must carefully be analyzed in view of higher fertilizer costs.

TABLE IV. EQUATIONS OF THE SECOND DEGREE POLYNOMIALS FOR THE GRAIN YIELD RESPONSE (Y, $kg.ha^{-1}$) TO NITROGEN FERTILISER RATES (X, kg N·ha^{-1})

Growing season	Equation	R^2
1994/95	$Y = -0.0465 X^2 + 15.644 X + 2736.5$	0.823
1995/96	$Y = -0.0418 X^2 + 10819 X + 4135.5$	0.885
1996/97	$Y = -0.0535 X^2 + 30.331 X + 2691.5$	0.999
1997/98	$Y = -0.0917 X^2 + 39.592 X + 693.2$	0.999

The data did not conclusively show that irrigation produced significant yield benefits. Applied in only two of the four growing seasons, irrigation promoted plant growth but reduced tiller survival, resulting in insignificant losses in grain yield compared with rainfed conditions (Fig. 4).

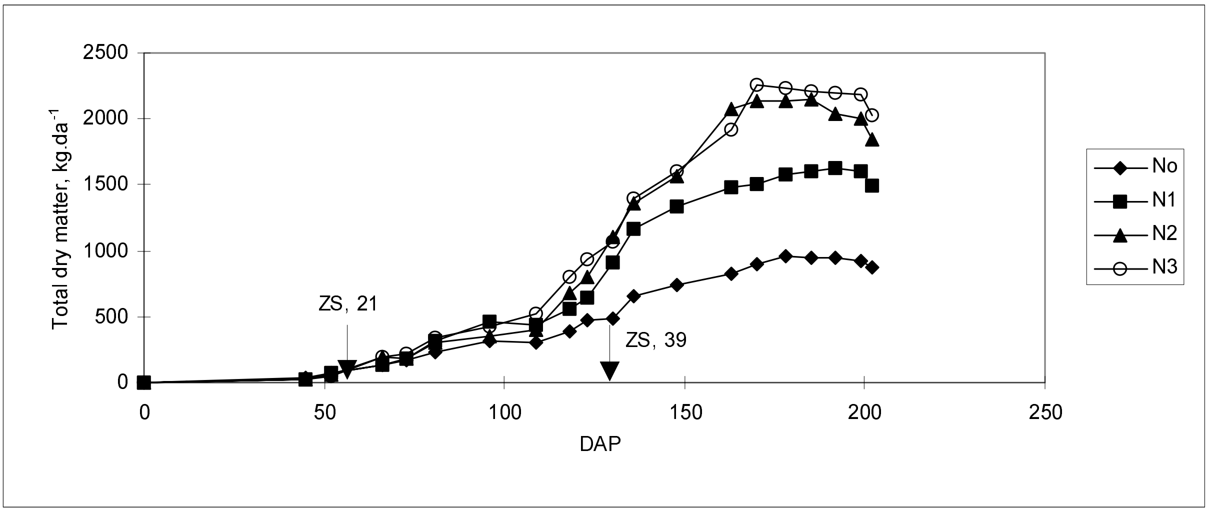


FIG. 5. Total dry matter production under different N fertiliser rates during the growing season of 1996/97.

3.2. Time variance

Time variance of dry-matter production under different rates of N fertilizer is shown for 1996–97 in Fig. 5. The largest dry-matter production was obtained with the highest N rate (240 kg N ha^{-1}), and, as expected, the least production occurred without fertilizer N. Dry-matter production was enhanced significantly after the second N-fertilizer application at 57 DAP, Z-21 (Fig. 5), suggesting that N assimilation accelerates after that growth stage. Data from other years (not shown) confirm this finding. A similar trend was obtained with spike-weight increase (Fig. 6), with no differences observed at fertilizer rates higher than 160 kg N ha^{-1}.

Plant samples collected at 7- to 10-day intervals to monitor time variance of biomass production were also used to measure LAI. Time variances of LAI under different N-fertilizer treatments are shown in Fig. 7; the highest index, 7.5, was observed with the highest N rate, and the index with the control treatment was the lowest, 3.5. Maximum LAI values were reached with each N treatment just before anthesis, at Z-52, and progressively decreased toward the milking and ripening stages [6] at Z-70 and 90. Leaf area index showed a strong association with N rate, confirming that

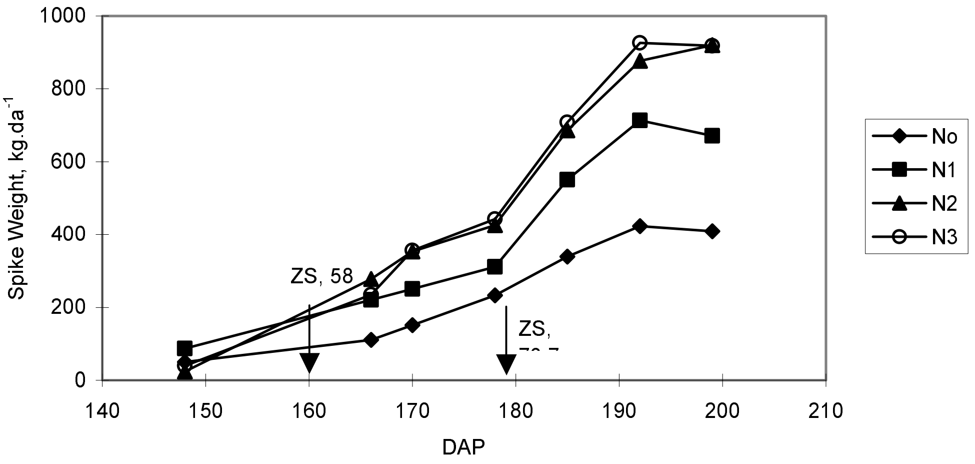


FIG. 6. Cumulative spike weights during the growing season under different rates of N fertilisers application.

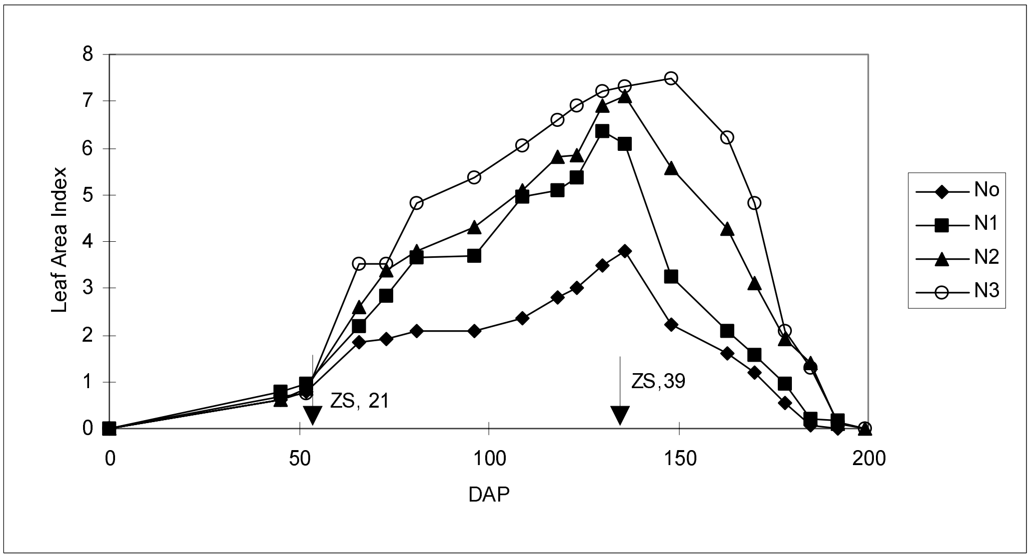


FIG. 7. Measured leaf area index (LAI) as influenced by different rates of N fertilisers application during 1996 /97 growing season.

fertilizer is essential to promote canopy development and thereby to ensure good yields. However, excessive use must be prevented to minimize environmental pollution through leaching and gaseous losses.

3.3. Crop-water consumption

Crop-water consumption (ET) increased proportionately with rate of N fertilizer, as shown by data from the 1997–98 growing season (Fig. 8) and from earlier years (not shown). Cooper *et. al.* [26] found a similar trend with barley. During early growth, crop-water consumption rates were similar irrespective of N rate, but increased after mid-season commensurately with fertilizer rate (Fig. 9). It is noteworthy that higher rates of N fertilizer prevented excess drainage; seasonal drainage values (D, mm) during the 1997–98 growing season were lower in the fertilized plots (Fig. 9), possibly due to increased root density in response to fertilizer application [27].

3.4. Fertilizer-N recovery

Fertilizer-N uptake was two- to three-fold greater from the second fertilization, at tillering, than when applied at planting (Table V). Percent N derived from fertilizer (%Ndff) was less influenced by the rate of fertilizer than by application time, i.e. 14.5 to 21% of N applied at planting, and 40 to 39% of N applied at Z-25, for 160 and 240 kg N ha^{-1}, respectively (Table V). The 3-year results from 1994–95 and 1996–97 therefore suggest that, in the coastal areas of the Mediterranean region where it rains from November until February or March, wheat benefits more from fertilizer applied at tillering as compared with application near planting.

TABLE V. N FERTILISER UTILISATION OF WHEAT DURING IN 1994–95, 1995–96 , 1996–97 AND 1997–98 GROWING SEASONS

N Treatment (1)	TDM (2)	N yield (3)	% ^{15}N a.e (4)	% N dff (5)	Partial % NFR, (6)	Total %NFR, (7)
			1994–95 Growing season			
160 kg N·ha^{-1},1/3	1420	19.6	0.727	14.5 B	53.0 AB	17.7 B
2/3			1.010	40.1 A	72.7 A	48.5 A
240 kg N.ha^{-1}, 1/3	1554	21.7	1.046	20.8 B	49.4 B	14.1 B
2/3			0.978	38.8 A	54.4 AB	38.5 A
			1995–96 Growing season			
160 kg N·ha^{-1},1/3	1894	24.0	0.659	13.2 B	59.4	19.8 B
2/3			1.091	21.9 A	44.3	29.3 A
240 kg N·ha^{-1}, 1/3	2162	24.9	0.843	17.0 B	45.6 B	15.1 B
2/3			0.934	37.5 A	60.6 A	40.4 A
			1996–97 Growing season			
160 kg N·ha^{-1},1/3	1844	20.5	0.574	11.5 A	46.1 B	15.0 B
2/3			1.119	44.9 B	81.5 A	54.3 A
240 kg N·ha^{-1}, 1/3	2031	26.7	0.621	12.4 A	43.1 B	19.6 B
2/3			1.073	43.1 B	65.4 A	48.0 A
			1997–98 Growing season			
160 kg N·ha^{-1},1/3	1263	13.5	0.671	13.4 B	33.9 B	11.3 B
2/3			1.415	56.9 A	61.2 A	40.8 A
240 kg N·ha^{-1}, 1/3	1492	18.7	0.850	16.9 B	38.0 B	19.0 B
2/3			1.333	55.4 A	53.9 A	36.0 A

(1) 1/3 and 2/3 designate split application of N fertilizer at planting and tillering, respectively; (2) Above ground total dry matter yield g m-2; (3) N yield g N m^{-2}; (4) %^{15}N atom excess; (5) %N derived from fertilizer N; (6) Partial N fertilizer recovery (%); (7) Total N fertilizer recovery (%). Means which are not significantly different are followed by the same letter ($P\leq 0.01$)

There have been numerous studies on pre-plant versus split applications of N to winter wheat. Mahler *et al* [6] reported that, in the 480 to 650 mm precipitation zone, wheat grain yields and N-fertilizer recoveries were greater with split applications, and as little as 25% of the N should be applied at planting, reserving the remainder for spring application. Similarly, Wuest and Cassman [7], pointing out the significance of later N applications, found N recoveries of 30 to 55% and 55 to 80% for applications at planting and at anthesis, respectively. They further found that post-anthesis N uptake was not increased with greater pre-plant N applications. Another advantage of split-N application is the lowered risk of N losses from leaves by volatilization and from leaching between anthesis and maturity [10].

3.5. Residual N

Soil samples, from only one replicate, were collected from the isotope plots of the highest N application (i.e. 240 kg N·ha^{-1}) and analysed for ^{15}N enrichment in 1995–96 and 1997–98 to assess depletion of fertilizer N within the soil profile through plant uptake. Figure 10 shows that N applied near planting was depleted more slowly than that applied at tillering.

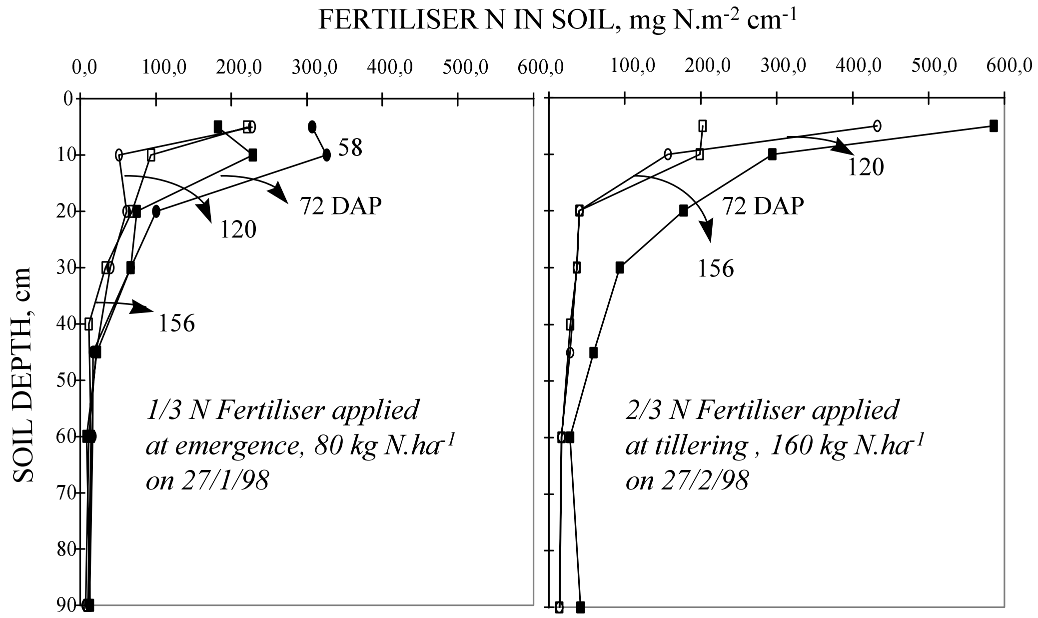


FIG. 10 Depletion profiles of fertiliser N under the progress of wheat growth during 1997/98 season.

Although N applied at tillering was twice the amount of that applied at planting, residues within the soil profile at harvest (156 DAP) were similar, which suggests that fertilizer applied at tillering was utilized more effectively. With both application modes, one third near planting and two thirds at tillering, the N remained mainly within 40 cm of the surface. Only trace values ($\leq$ 20 mg N m^{-2} cm^{-1}) were deeper than 60 cm (Fig. 11), therefore significant leaching of fertilizer N more deeply was unlikely. Data for other years (not shown) showed similar trends. It was concluded that leaching risks of N fertilizer applied to wheat at rates even as high as 240 kg N·ha^{-1}, are low in our conditions. Nitrate concentrations of the leachates collected at 90 cm soil depths did not show significant increases in concert with split N-fertilizer applications to the soil surface in 1997–98 (Fig. 12), under farmers' general practice of 160 kg N ha^{-1}. Similar trends in earlier years (not shown) confirm that leaching of N fertilizer during wheat growth was unlikely. Further work is needed, however, to examine transformations, immobilization and mineralization, of residual N within the soil profile that might be leached in subsequent years.

3.6. Succeeding crop

Fertilizer applied to a crop may remain in the soil as residue after grain harvest. For example, under the highest N application (N_3, 240 kg N ha^{-1}), 47 to 65% was recovered by the wheat, and the rest remained in the soil profile (Fig. 11 and Table VI). Cotton, planted in the summer of 1996 after wheat, showed positive responses to the preceding N applications, clearly indicating significant benefit from residual fertilizer [28] (Fig. 13). In the summer of 1995, maize gave similar yield responses (data not shown) [29] to preceding N treatments to wheat. Residual-N fertilizer recovered by the succeeding crops was 10 to 25% of the total applied, depending on the species and the rate (Table VII). Therefore, with fertilizer rates no greater than 160 kg N ha^{-1} for wheat, leaching losses would be expected to be insignificant if another crop is subsequently planted.

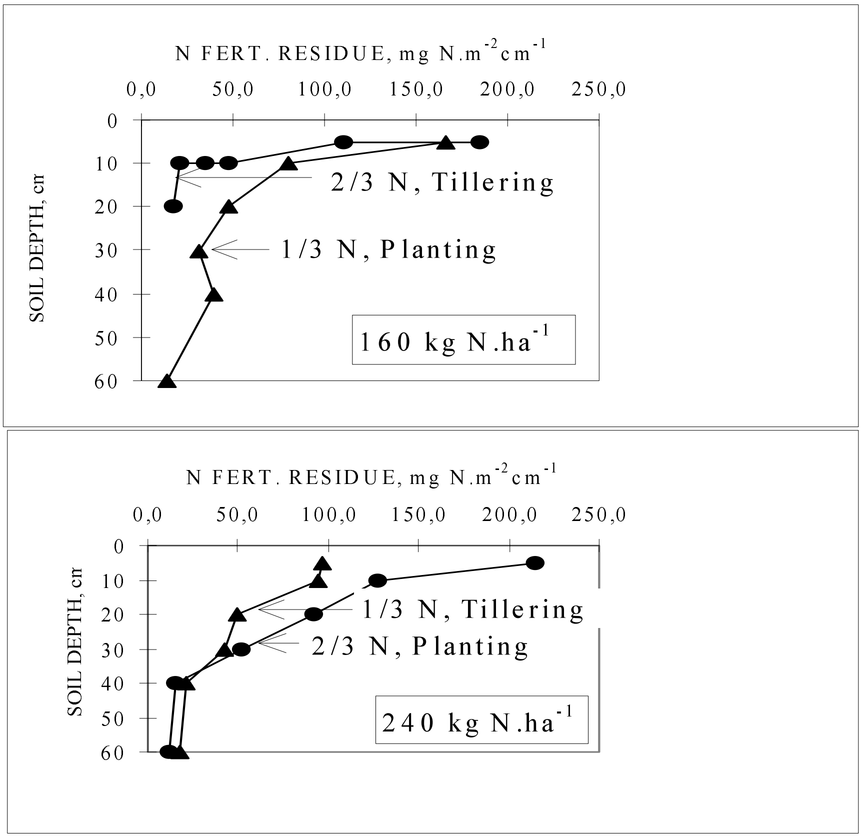


FIG. 11. Fertiliser N residue remained in the soil after the harvest of wheat crop in 1996/97 growing season.

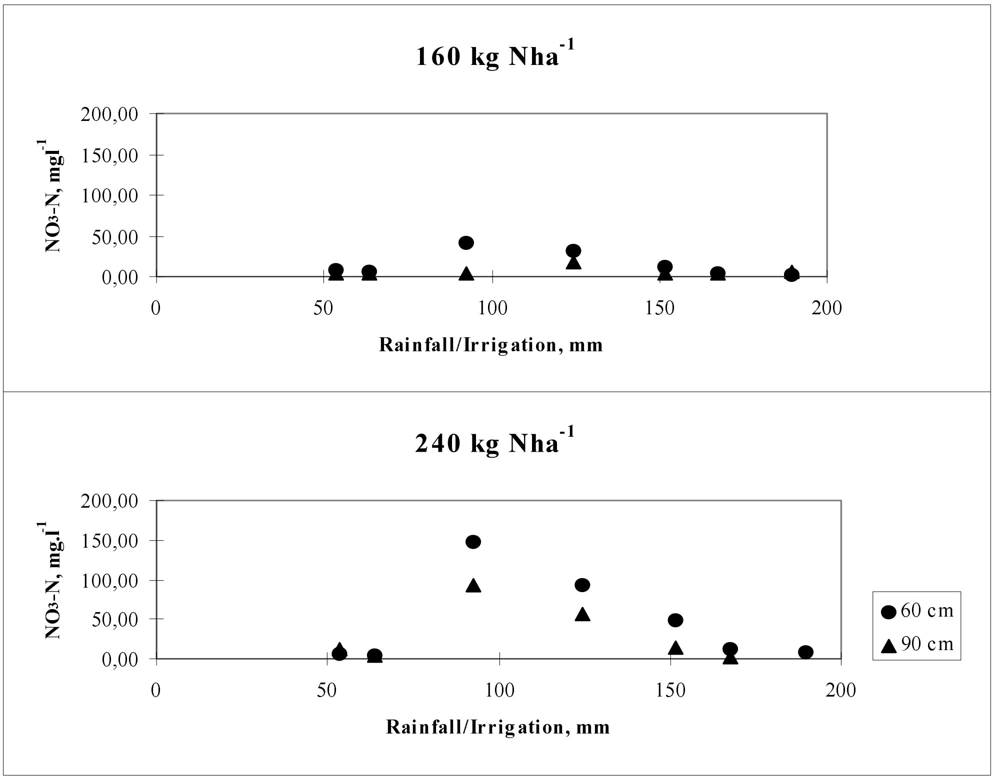


FIG. 12. Changes of NO_3-N concentrations of soil water samples extracted at 60 and 90 cm soil depths under two rates of N fertiliser applications. Note that rainfall/irrigation is cumulative values after the date of first split application of N fertiliser.

TABLE VI. PLANT RECOVERY AND SOIL RESIDUE OF N FERTILISER, APPLIED TO WHEAT CROP AT A RATE OF 240 kg N ha^{-1}

N application	Plant uptake (kg N ha^{-1})	Residue in soil[1] (kg N ha^{-1})	Unaccounted fertiliser , %
	1994–95 Growing season		
1/3, 80 kg N.ha^{-1}	42.8	37.2 (35.3)	2.5
2/3, 160 kg N·ha^{-1}	88.0	72.0 (81.8)	-
	1995–96 Growing season		
1/3, 80 kg N·ha^{-1}	37.7	42.3 (32.2)	12.6
2/3, 160 kg N·ha^{-1}	103.7	56.7 (14.1)	26.6
	1996–97 Growing season		
1/3, 80 kg N·ha^{-1}	47.0	33.0 (24.3)	10.8
2/3, 160 kg N·ha^{-1}	115.2	44.8 (46.8)	-
	1997–98 Growing season		
1/3, 80 kg N·ha^{-1}	31.6	48.4 (50.1)	1.7
2/3, 160 kg N·ha^{-1}	86.4	73.6 (61.2)	12.4

[1]N residue in parenthesis is calculated based on N fertiliser residue distribution profiles, measured through soil sampling, right after the harvest of wheat crop.

3.7. Crop development

Developmental stages were identified through surveys of all the treatments. Dates to attain prescribed Zadoks growth stages were recorded to evaluate influence of N fertilizer on rate of development. Procedures used to evaluate crop growth and development were as described by Bell and Fischer [30].

3.7.1. Plant establishment

From 23 g seed planted per m^2, stands of 600 and 563 plants m^2 (80% establishment) were obtained in 1996–97 and 1997–98, respectively. No significant variation was observed among the N treatments, confirming that fertilization is unlikely to influence germination and seedling establishment, except when supra-optimal levels cause salt toxicity.

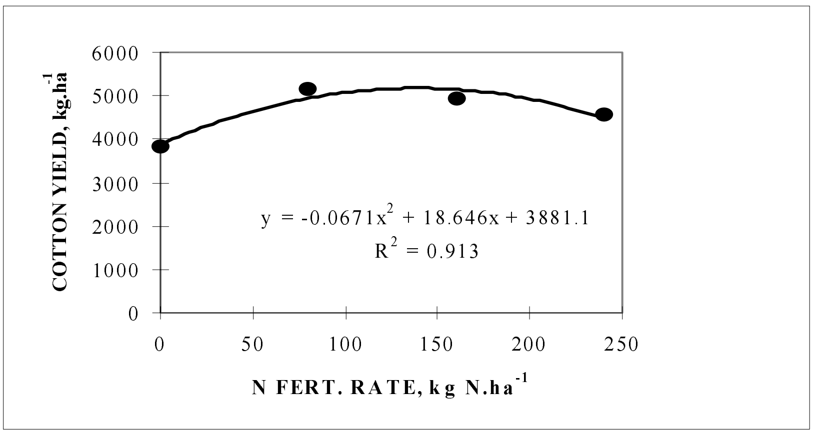


FIG. 13. Yield response of second crop cotton to soil N fertiliser residue after a wheat crop, which received different rates of N fertiliser.

TABLE VII. RECOVERY OF RESIDUAL N BY SECOND CROPS, MAIZE AND COTTON, SUCCEEDING WHEAT

	N treatments for the preceding crop		
	N_1, 80 kg N·ha^{-1}	N_2, 160 kg N·ha^{-1}	N_3, 240 kg N·ha^{-1}
	Second crop maize, Summer 1995		
Kernel, kg N·ha^{-1}	5.2	12.5	21.7
Vegetative parts, kg N·ha^{-1}	4.0	7.8	14.5
Total, kg N·ha^{-1}	9.2	20.3	36.2
% of Total N applied	11.5	12.7	15
% of Residual N	-	24.9	33.9
	Second crop cotton, Summer 1996		
Total, kg N·ha^{-1}	22.0	35.2	68.0
% of Total N applied	27.5	22.0	28.3
% of Residual N	-	27.0	26.3

The numbers of leaves on the main stem were counted once or twice weekly until full emergence of the flag leaf. There was a highly significant positive linear relationship between leaf number with DAP (Table VIII); the regression slope depended on planting date, which varied from year to year. In 1996–97, the slope was 0.0757; whereas for the late-sowing 1997–98 season (Table II) it increased to 0.0987, suggesting that delayed planting increased the rate of leaf emergence [31, 32]. The slopes for 1996–97 fell within the narrow range of 0.0724 to 0.0780, whereas the slope for the no-N treatment in 1997–98 was significantly lower than those for the higher N rates, demonstrating a beneficial effect of N on leaf emergence [33].

The intercepts of the regression equations differed between the 1996–97 and 1997–98 growing seasons, attributable to planting date [34] and divergent cumulative degree days [35].

Although it varied from year to year depending on the initial N status of the soil, main-stem development (Z-30–70) responses to applied N occurred as early as flag-leaf development stage (Z-40), and was delayed with earlier anthesis in the absence of fertilizer N (Fig. 14). The grain-development stage (Z-70–90) was more responsive to soil and weather conditions. With either no or a low rate of N, grain development started earlier (Fig. 14).

TABLE VIII. REGRESSION EQUATIONS DESCRIBING EFFECTS OF N RATES ON THE NUMBER OF LEAVES (N) DEVELOPING ON THE MAIN STEM OF WHEAT CULTIVAR SERI-82 AS A FUNCTION OF TIME, EXPRESSED AS DAYS AFTER PLANTING (DAP)

Year	N rate, kg N·ha^{-1}	Equation	R^2
1996/97	0	N=0.0771DAP+0.4656	0.970**
	80	N=0.0724DAP+0.9482	0.924**
	160	N=0.0780DAP+0.6336	0.940**
	240	N=0.0754DAP+0.7376	0.945**
1997/98	0	N=0.0773DAP-0.5851	0.970**
	80	N=0.1035DAP-1.4657	0.990**
	160	N=0.0780DAP-1.5381	0.990**
	240	N=0.0754DAP-1.6096	0.990**

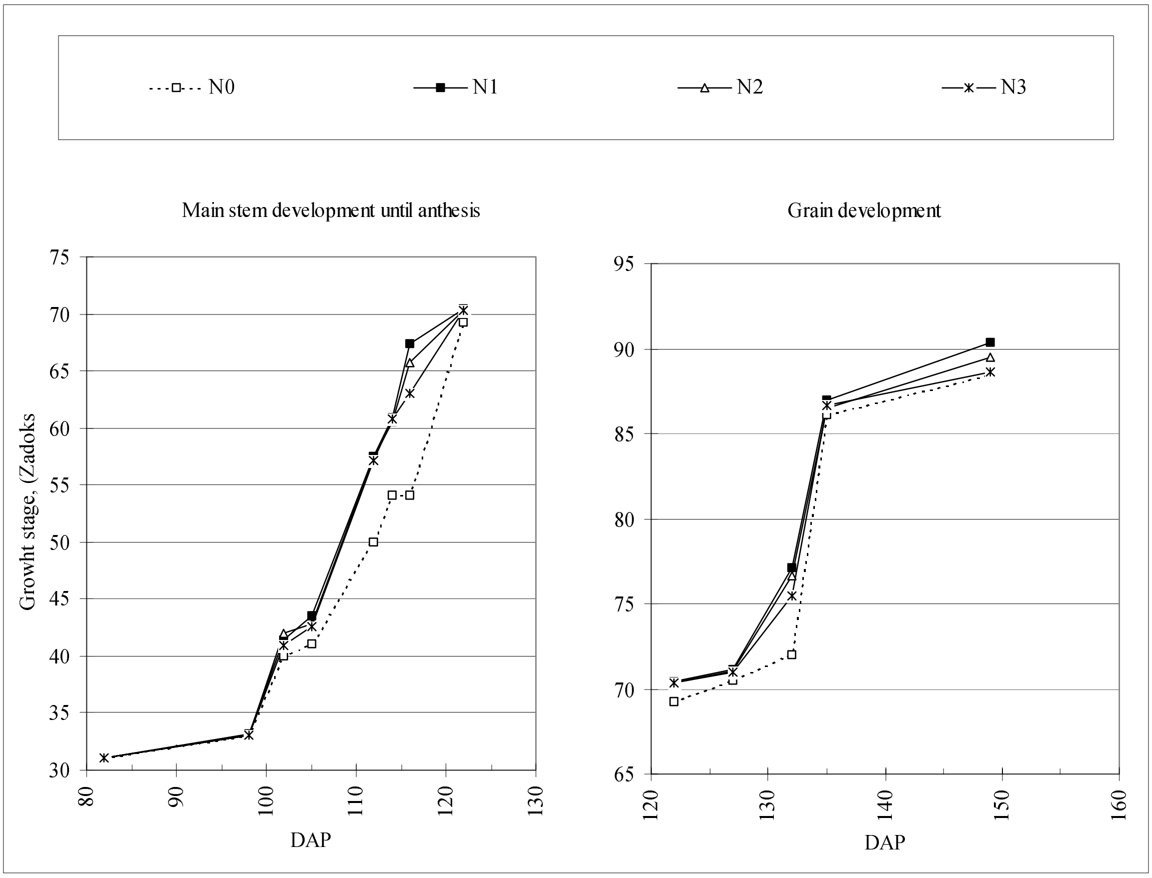


FIG. 14. Effects of N fertilisation on main stem and grain development stages in 1997/98.

There were insufficient data to reach conclusions on the effects of irrigation on the rate of grain development. Results for 1997–98 (Table IX) and earlier experiments (data not shown) indicate that a 10 to 15% deficit in ET increased rate of grain development (Table IX) if excess rainfall was received after mid-season. Effects of irrigation, therefore, were influenced by local rainfall characteristics, the amount and seasonal distribution.

TABLE IX. AVERAGE GRAIN DEVELOPMENT STAGES (ZS) IN 1997/98 SEASON

	DAP			
Irrigation	127	132	146	149
Irrigated, I_1	70.82 B	75.06 B	86.63	89.13
Deficit Irr., I_2	71.07 A	75.56 A	86.50	89.38
$LSD_{0.05}$	0.181	0.324	NS	NS

3.7.2. Tiller production and survival

Tiller production and survival were monitored from emergence until senescence (Z-90) to evaluate N-fertilizer and irrigation effects. Fertilizer application promoted tiller production (Fig. 15). Although irrigation effects were not significant, the benefits of N fertilization were enhanced, and tiller development was more vigorous. However, in contrast with previous results [36–38], neither irrigation nor N fertilizer benefitted tiller survival. Although full irrigation increased the number of tillers initially, more fertile stems survived under deficient irrigation (Fig. 15).

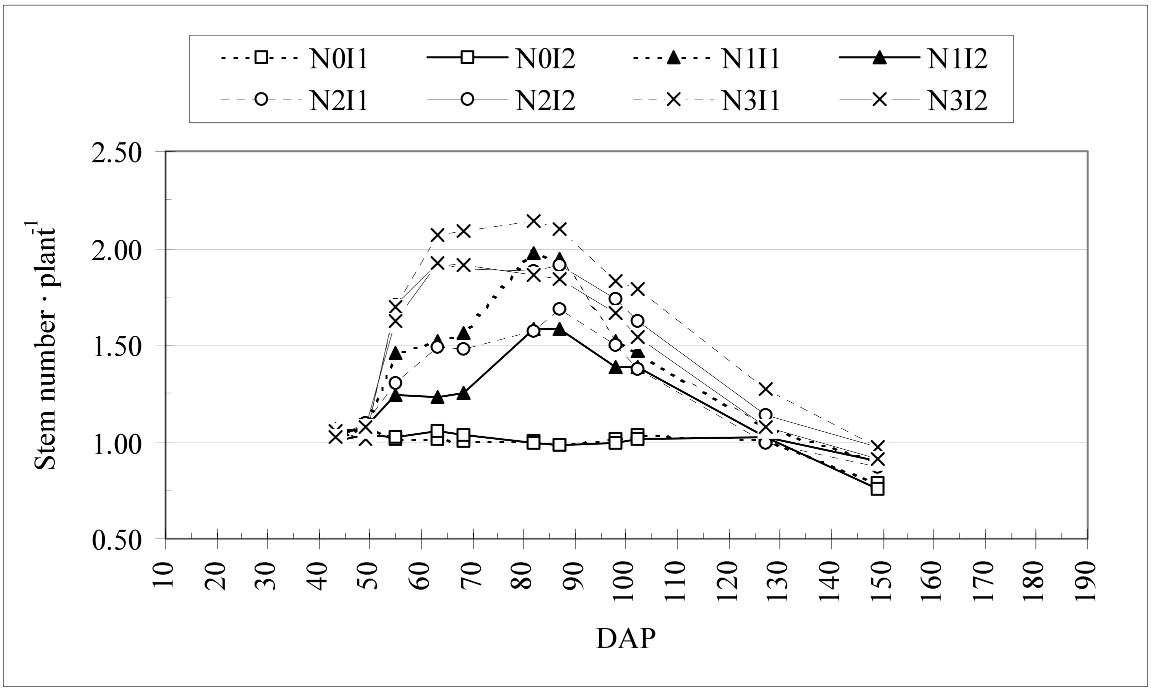


FIG. 15. Effects of irrigation and N fertiliser application on tiller production in 1997/98.

TABLE X. EFFECTS OF APPLIED NITROGEN FERTILIZER ON THE PHOTO-SYNTHETIC GAS EXCHANGE CHARACTERISTICS OF FULLY EXPANDED 6th AND 7th YOUNG LEAVES OF WINTER WHEAT CULTIVAR SERI-82 UNDER MEDITERRANEAN COASTAL CONDITION IN 1996/97 GROWING SEASON

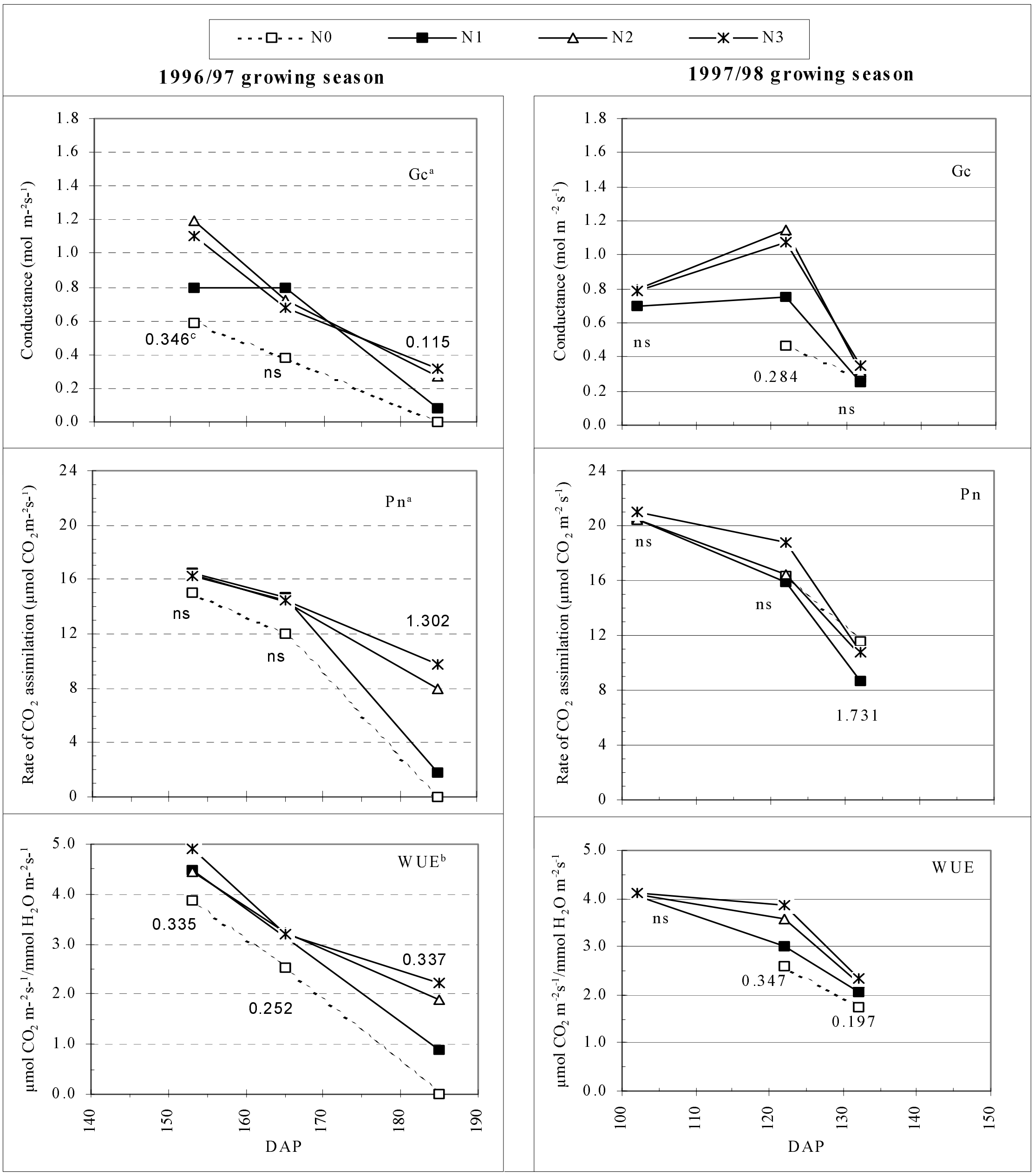
	6th. Leaf			**7th. Leaf**		
Treatments	Gc[a]	Pn[a]	WUE[b]	Gc	Pn	WUE
N_0	0.396	15.98	5.60	0.142	9.40	3.88
N_1	0.480	17.91	5.60	0.205	12.37	4.41
N_2	0.525	17.85	5.63	0.395	14.95	4.59
N_3	0.496	16.73	5.49	0.250	11.60	4.11
Average	0.474	17.12	5.58	0.248	12.08	4.25
$LSD_{0.05}$	0.0715	NS	NS	0.0715	1.475	0.5655

[a]Gc and Pn, represent stomatal conductance to CO_2 and rate of net photosynthesis, respectively.
[b]WUE determined by dividing the millimolar net photosynthesis rate by molar transpiration rate

3.8. Photosynthetic gas exchange

3.8.1. Sixth and 7th leaves

All the measured gas-exchange characteristics showed higher values with the 6th leaf than with the 7th leaf, although solar radiation was lower during the measurements on the former (Table X). Stomatal conductance of these leaves was lower in unfertilized than in fertilized plants. The net photosynthetic rate and water-use-efficiency (WUE) values showed similar trends, with significant effects obtained with the 7th leaf.



[a]Gc and Pn, represent stomatal conductance to CO_2, and rate of net photosynthesis, respectively.
[b]WUE, water use efficiency determined by dividing µmolar net photosynthesis rate by molar transpiration rate.
[c]LSD (0.05); ns, not significant.

FIG. 16. Effects of applied N fertiliser on the changes of stomatal conductance to CO_2 (Gc), rate of net photosynthesis (Pn) and of water use efficiency (WUE) on flag leaves from ear emergence through senescence.

3.8.2. Flag leaf

Main-stem flag-leaf stomatal conductance (Gc), net CO_2 assimilation rate (Pn) and WUE declined from maximum values at spikelet emergence (153 DAP, 8 days pre-anthesis) in 1996–97, and at booting stage in 1997–98, to low or zero values (Fig. 16). Net photosynthesis at the onset of ear emergence was not significantly changed by N supply (average 17.1 µmol CO_2 m^{-2} s^{-1}). However, N application slowed the rate of decline of photosynthesis with senescence, i.e. photosynthesis remained higher longer with increasing N, as the plants aged.

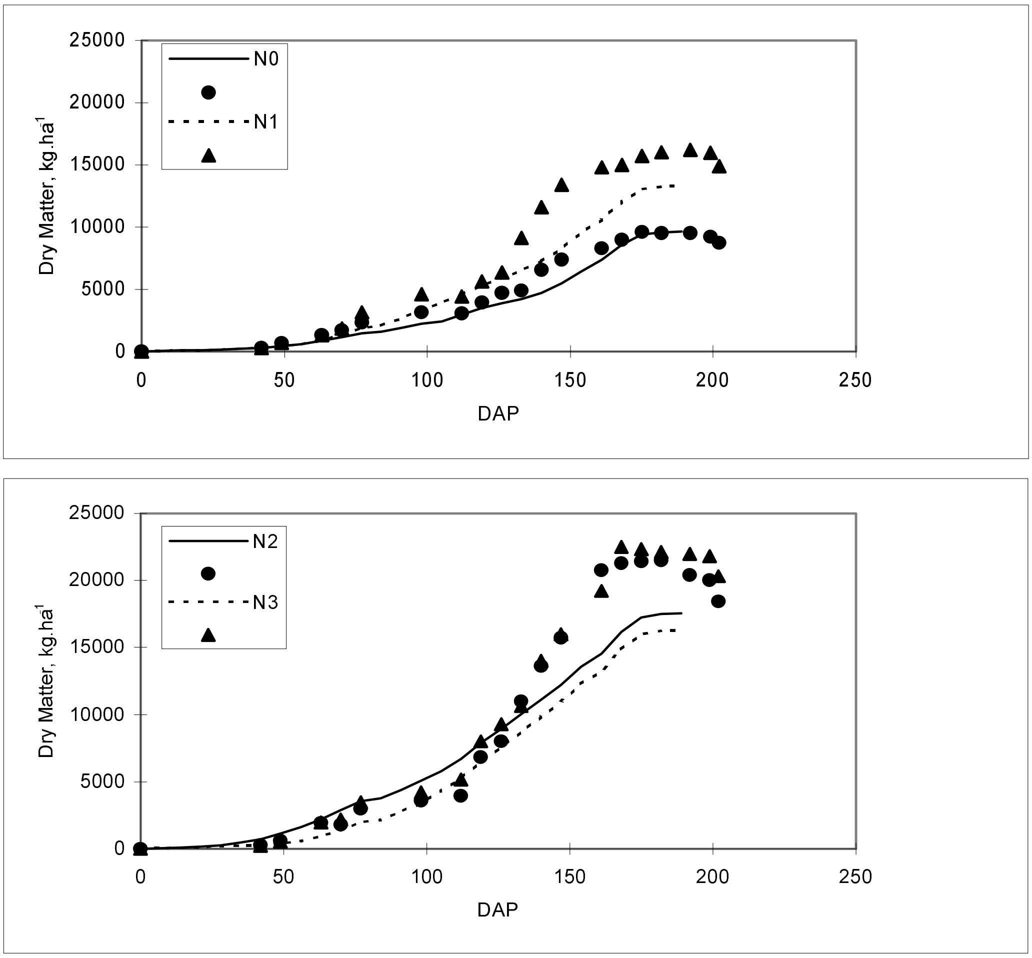


FIG. 17. Comparison of measured and predicted dry matter production with CERES-Wheat (V.3) growth model in 1996/97 growing season. The lines show predicted trend while the points are the measured data.

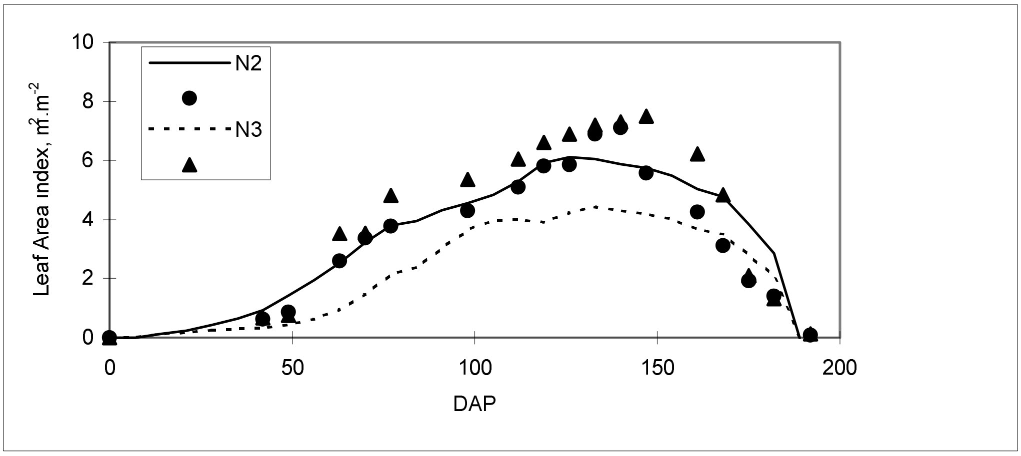


FIG. 18. Comparison of measured and predicted LAI with CERES-Wheat (V.3) growth model in 1996/97 growing season. The lines show predicted trend while the points are the measured data.

TABLE XI. ACTUAL AND PREDICTED GROWTH ATTRIBUTES IN 1996/97

Variable	(N_0) 0 kgha^{-1}		(N_1) 80 kgha^{-1}		(N_2) 160 kgha^{-1}		(N_3) 240 kgha^{-1}	
	Predicted	**Measured**	**Predicted**	**Measured**	**Predicted**	**Measured**	**Predicted**	**Measured**
Flowering date (DAP)	155	156	155	156	155	156	155	156
Physiology maturity (DAP)	187	183	187	183	187	183	187	183
Grain yield (kg.ha^{-1})	4278	2710	5215	4720	5827	6230	5900	6870
Weight per grain (g)	0.0399	0.0307	0.0358	0.0351	0.0327	0.0320	0.0327	0.0349
Grain number (grain·m^{-2})	10731	8827	14579	13477	17831	19848	18020	19684
Grain number per Spike	22.4	28.0	27.6	30.0	37.6	40.0	40.0	44.0
Maximum LAI (m^2·m^{-2})	2.89	3.80	4.43	6.30	6.07	7.10	5.48	7.50
Harvest index	0.44	0.31	0.39	0.32	0.33	0.34	0.36	0.34
Total evapotranspiration (mm)	371	412	371	426	378	446	370	457
Biomass at harvest (kg·ha^{-1})	9639	8750	13330	14880	17539	18440	16310	20310

Flag-leaf Gc values obtained with unfertilized plants were lower than those from N-treated plants. Flag-leaf WUE also showed lower values in N-deficient plants and the differences were enhanced with the onset of senescence (Fig. 16). The WUE values increased with rate of N, and decreased Pn as the plants aged. The positive effects N fertilization on Pn were significant during early grain filling (Z-71) [39]. However, the Pn rates decreased rapidly with onset of grain filling in all N treatments [39, 40].

3.9. Simulation model

Measured plant-growth attributes throughout the 4-year experiment were compared with those predicted with the CERES-Wheat (V.3) growth-simulation model (Table XI). There were no differences between measured and predicted dates of flowering or of physiological maturity. However, the model over-estimated grain yields with the N_0 check and the N_1 treatment (80 kg N ha^{-1}), whereas it under-estimated grain yield at the higher rates of fertilizer (N_2, N_3). Similar trends were observed regarding measured and predicted LAI values, dry-matter production, HI, thousand-grain weight and grain number per unit area. The predicted ET values under different treatments were considerably lower than those measured, which showed no statistical differences among treatments.

The model rather closely predicted the progress of dry-matter production until 120 to 130 DAP, but values predicted later were considerably lower than actual (Fig. 16). The predictions were better for LAI, but deviations from predicted values occurred with the higher N applications (Fig. 17).

4. CONCLUSIONS

Nitrogen-fertilizer practices for wheat production in the Mediterranean coastal regions of Turkey require thorough evaluation, in terms of amounts applied and timing. The rate of 160 kg N ha^{-1}, commonly used by farmers of the region, appears to be acceptable not only for optimum grain yields, but also to minimize the risks of leaching NO_3^- from fertilizer to groundwater. Of the split applications, N applied at tillering was utilized more effectively with proportionately less residual in the soil compared to that applied at planting. Recovery of the recommended N rate ranged from 49 to 68%. Subsequent crops of maize or cotton showed good responses to residual fertilizer N, with recoveries of 10 to 15%, and 22 to 28%, respectively, depending on the rate applied to the preceding wheat. Recovery of fertilizer N by the wheat plus that residual in the soil after the harvest accounted for nearly 100% of what was applied, suggesting that volatilization and leaching were essentially nil.

Crop-water consumption (ET) showed a strong positive association with N rate. The seasonal ET extremes were 389 for the control (zero N applied) to 613 mm for the highest rate used (240 kg N ha^{-1}). Seasonal drainage was only 5 to 10% of ET, and it was confined to the mid-season. No wheat-grain-yield benefits accrued from irrigation; applied as 10 to 15% of seasonal ET, only straw yields were increased.

Tiller production increased with N-fertilizer usage. However, tiller survival decreased at high N; best tiller survival occurred with 160 kg N ha^{-1}. Grain development was influenced by both irrigation and N-fertilizer rate. Although leaf development on the main stem was not influenced by N, higher rates extended the grain-filling period. Increased N rates produced higher stomatal conductance, increase rates of CO_2 assimilation and water-use efficiency.

The CERES-Wheat growth-simulation model rather closely predicted the progress of dry-matter production, leaf area index, seasonal ET, phenological development and of many other plant growth attributes. In general, deviations of the model from the predicted values were largest under high rates of N fertilizer.

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NITRATE MOVEMENT IN SOIL UNDER IRRIGATED WHEAT

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Abstract

In field experiments on wheat from 1994 to 1998, grain yields and yield-contributing components increased with the amount of fertilizer N; however, differences with 120 and 180 kg N ha^{-1} were not statistically significant. Grain yields ranged between 1.22 to 5.25 Mg ha^{-1} over the four growing seasons. Water-use efficiency values increased with amount of fertilizer N applied. Total-N uptake was always highest with the 180 kg N ha^{-1} treatment, i.e. with 50% more fertilizer applied than the locally recommended 120 kg N ha^{-1}. The use of ^{15}N revealed that percent N derived from fertilizer from the first split application at planting, 40 or 60 kg N ha^{-1}, was lower than that applied as a second split of 80 and 120 kg N ha^{-1}, respectively, at growth stage Z-30; this trend prevailed in all the cropping seasons. Fertilizer-N uptake was highest with 180 kg N ha^{-1} and varied from 16 to 50% of that applied. Nitrogen applied to the wheat had positive residual effects on subsequently grown rice in comparison with the zero-N checks. The downward flux of water measured in a nearby plot increased with depth, but showed a decreasing trend with wheat growth; the fertilizer-N fraction was relatively lower with depth. A minor fraction of applied N moved down to 120 cm, indicating little likelihood of pollution of groundwater by NO_3^- from fertilizer.

1. INTRODUCTION

Nitrogen is the mineral element required in the greatest quantity by cereal crops, and is the nutrient most often deficient. As a result of its critical role and often low supply, the management of N resources is an important aspect of crop production [1]. Demand for food in developing countries is growing more rapidly than current potential to increase production. Irrigation is applied to about 40% of wheat, but efficiency of use of nutrients is thought to be low by international standards. Yield responses to N, which accounts for about two thirds of all fertilizers used, are larger than to other nutrients in intensively cropped tropical areas, as in Bangladesh [2]. Moreover, there has been a dramatic increase in N-fertilizer applied to irrigated wheat. However, improper application of fertilizer has resulted in substantial losses of N due to volatilization, denitrification, and leaching that is responsible for contaminating ground and surface waters [3].

In Bangladesh, the area planted to wheat is increasing and currently is close to 1 Mha [4]. The increase is due mainly to adverse climatic conditions during wetland rice cultivation, e.g. heavy rainfall, severe flooding, and cyclones. The recent unprecedented floods in Bangladesh will result in increased cultivation of wheat. Wheat is grown mostly under rainfed conditions in Bangladesh, and irrigation has been found to double productivity. However, inefficient use of N under irrigated wheat threatens the environment through groundwater pollution and volatilization to the atmosphere.

Nitrogen-15 provides a unique tool for the study of the fate of fertilizer N applied to soil. In addition, the neutron probe and tensiometer allows quantification of movement of N through the soil profile and potential contribution to groundwater.

The objectives of this work were:

- To investigate various aspects of N-uptake efficiency by wheat under irrigation,
- To use ^{15}N and the neutron-probe moisture gauge to determine the fate of fertilizer N and organic N in relation to water movement in the soil, and increase nutrient- and water-use efficiencies in our wheat-cropping system,
- To use the generated data to further develop and refine the CERES-Wheat computer simulation model,
- To develop a N-recommendation system for refining specific management strategies with respect to fertilizer applications, expected yields and other components of the production system.

TABLE I. SURFACE SOIL CHARACTERISTICS (0–60 cm DEPTH)

Soil depth, cm	Soil texture (%)				Soil Bulk density (g cm^{-3})	Hydraulic conductivity at saturation (cm day^{-1})	Field capacity moisture (cm^3 cm^{-3})
	Sand	Silt	Clay	Textural class			
0–15	57.6	32.0	10.4	Sandy loam	1.36	0.19–2.1	0.314
15–30	55.6	26.0	18.4	Sandy loam	1.41	2.0– 2.4	0.331
30–45	49.6	24.0	26.4	Loam	1.44	3.5– 6.7	0.331
45–60	49.6	24.0	26.4	Loam	1.35	3.0–10.8	0.308

Soil depth, cm	Permanent wilting point, cm^3 cm^{-3}	pH soil:water 1:2.5	Soil organic matter %	Total N %	CEC meq	EC, dS m^{-1}	SAR
0–15	0.127	5.7	1.35	0.12	12.0	0.17	1.09
15–30	0.128	5.5	0.81	0.09	14.6	0.04	1.06
30–45	0.143	5.5	0.64	0.07	13.7	0.03	1.01
45–60	0.142	5.1	0.46	0.06	12.8	0.04	1.01

TABLE II. AGRO-METEOROLOGICAL DATA DURING THE GROWTH PERIOD OF WHEAT

Month	Sunshine hours day^{-1}	Air temperature(°c)		Evaporation mm. day^{-1}	Wind at 2m. ht. km $hour^{-1}$	Rainfall cm
		Max.	Min.			
1994–95						
November	6.5	29.2	15.1	2.4	1.6	0.0
December	3.7	25.3	8.8	2.0	1.8	0.0
January	5.3	22.9	8.8	2.2	2.0	0.2
February	7.9	26.5	11.9	2.7	2.53	0.9
March	7.7	31.5	16.0	3.4	3.9	0.3
1995–96						
November	7.2	28.9	18.0	3.3	2.0	0.97
December	4.7	25.2	14.2	2.4	2.1	0.39
January	5.0	23.2	15.6	3.0	5.1	0.67
February	7.8	27.3	18.9	2.8	2.3	0.0
March	8.7	32.3	22.6	5.0	3.8	0.0
1996–97						
November	8.9	29.4	23.4	3.4	2.8	0.00
December	5.3	27.2	14.9	2.7	3.5	0.66
January	4.5	23.7	12.3	2.2	1.3	0.63
February	6.6	24.9	11.4	3.4	2.7	0.71
March	9.3	31.8	16.9	4.9	4.4	0.00
1997–98						
November	6.4	29.5	16.5	3.4	1.6	0.00
December	4.2	23.7	11.3	2.0	2.7	1.77
January	4.6	20.5	9.0	2.4	2.4	0.00
February	6.5	27.3	11.8	3.4	2.1	0.54
March	8.5	29.3	15.5	4.2	4.7	0.00

TABLE III. DATE OF DIFFERENT GROWTH STAGES OF WHEAT DURING STUDY PERIOD

Year	Sowing	Z-30, GS-1	Flag leaf ligule, GS-2	Anthesis, GS-3	8 days after anthesis, GS-4	Physiological maturity, GS-5	Harvest GS-6
1994–95	28-11-94	2-1-95 (35 days)	19-1-95 (52 days)	9-2-95 (72 days)	17-2-95 (80 days)	22-3-95 (113 days)	5-4-95 (127 days)
1995–96	24-11-95	24-12-95 (30 days)	15-1-96 (52 days)	4-2-96 (72 days)	12-2-96 (80 days)	10-3-96 (106 days)	23.3.96 (119 days)
1996–97	26-11-96	30-12-96 (34 days)	21-1-97 (52 days)	12-2-97 (78 days)	20-2-97 (86 days)	20-3-97 (114 days)	31-3-97 (125 days)
1997–98	24-11-97	26-12-97 (32 days)	16-1-98 (53 days)	6-2-98 (74 days)	14-2-98 (82 days)	14-3-98 (110 days)	26-3-98 (122 days)

TABLE IV. TDM AND N UPTAKE BY WHEAT AT Z-30 STAGE (GS-1)

Treatments	TDM kg ha^{-1}	N uptake kg ha^{-1}	TDM kg ha^{-1}	N uptake kg ha^{-1}
1994–95			**1995–96**	
N-O	751	17.1	585	15.7
N-60	785	19.4	642	19.1
N-120	898	23.0	793	24.4
N-180	1007	27.4	835	27.3
LSD(P=0.05)	121	NS	138	5.1
1996–97			**1997–98**	
N-O	518	13.8	231	4.2
N-60	614	14.8	312	5.6
N-120	824	22.4	353	6.1
N-180	824	24.1	386	5.9
LSD(P=0.05)	56	5.0	78	NS

2. MATERIALS AND METHODS

Field experiments on irrigated wheat were carried out over four consecutive years from 1994–95 at the experimental farm of the Wheat Research Centre, Bangladesh Agricultural Research Institute in Dinajpur, 25°38'N 88°41'E. The Tista Meander Floodplain soil is a non-calcareous Typic Haplquepts of the Birganj series; its physical and chemical properties, and agro-meteorological data, are presented in Tables I and II, respectively.

The experiments had a randomized complete-block design with three urea treatments and a zero-N (N_0) check, and four replications. The treatments were: N_1 – 60 kg N ha^{-1}, N_2 – 120 kg N ha^{-1} and N_3 – 180 kg N ha^{-1}. Each treatment plot of 8×6 m was divided longitudinally into halves for yield and sampling, respectively. There were two isotope (^{15}N 10% a.e.) sub-plots (1×1 m) in one half of the sampling plots of the N_2 and N_3 treatments. All the treatments received a basal application of (ha^{-1}) 45 kg P, 50 kg K, 20 kg S, 5 kg Zn and 2 kg B, and one third of the urea treatment at final land preparation. The remainder of the urea, ^{15}N enriched and non-enriched, was applied at Zadok's 30 (Z-30) growth stage (GS) as top dressing. The critical growth stages of wheat were identified as Z-30 (GS-1), flag leaf ligule emergence (GS-2), anthesis (GS-3), 8 days after anthesis (GS-4), physiological maturity (GS-5) and final harvest (GS-6). The growth stages were defined as follows:

– Z-30, 10% of the main stem have nodes detectable at ground level,
– Anthesis, 50% of the spikes have at least one anther,
– Physiological maturity, 50% of the glumes have no green colour.

The growth stages, as observed in the field during the 4-year study, are shown in Table III.

The wheat (*Triticum aestivum* L. cv. Kanchan, a widely used high-yielding genotype) was sown on 28/11/94, 24/11/95, 26/11/96 and 24/11/97. Total dry matter (TDM) values were recorded at various growth stages. The crops were irrigated at 50% soil-water depletion (SWD) of maximum water-holding capacity to a depth of 45 cm. Soil moisture was monitored with a neutron probe (Troxler Model 3320) periodically from sowing to final harvest.

Unsaturated hydraulic conductivity and downward fluxes were determined in situ in a nearby plot by the internal drainage method. Soil-water contents of the profile, initially and at harvest, were determined for all 4 years to calculate SWD values that were used to calculate the total water use (TWU) and water use efficiency (WUE) of the wheat. Mineral-N contents (NH_4^+-N and NO_3^--N) in the soil profile (0–120 cm) were estimated in soil samples. Total-N content and ^{15}N-enrichments in the soil profile after final harvest were also determined.

Rice was grown on the plots after the wheat harvest to study the residual effects of fertilizer N.

3. RESULTS

3.1. Total dry matter and N uptake

3.1.1. At Z-30

There was wide variation in TDM production recorded at Z-30 in the different N treatments, 751 to 1,007 kg ha^{-1} in 1994–95, 585 to 835 kg ha^{-1} in 1995–96, 518 to 824 kg ha^{-1} in 1996–97 and 231 to 386 kg ha^{-1} in 1997–98 (Table IV). The low TDM values in 1997–98 resulted from stunted growth due to a cold period immediately after germination.

Total-N uptake was consistently higher in the N-fertilized plots, but with no significant differences among N-treatments in 1994–95 and 1997–98. In unfertilized check plots, the N uptake was lower and relatively uniform. In the 1997–98 growing season, N uptake was low in all the treatments, concomitant with poor TDM production.

3.1.2. At other growth stages

The TDM values at various growth stages increased proportionately with applied-N levels in all the growing seasons (Tables V–VIII). During ligule emergence, (GS-2), TDM and N-uptake values were similar in all the growing seasons and increased with the amount of N applied. Similar trends were recorded at other growth stages up to physiological maturity (GS-5) in all the years. At physiological maturity, TDM production varied from 4,063 in 1997–98 to 11,447 kg ha^{-1} in 1995–96. Correspondingly, N uptake ranged between 26.5 and 146 kg ha^{-1} in 1997–98 and 1994–95, respectively. It is noteworthy that, although TDM and N uptake were highest with N_3 (180 kg N ha^{-1}), those obtained with 120 kg N ha^{-1} were not significantly inferior, except for 1997–98. In all growing seasons, TDM values for all N treatments decreased prior to final harvest. Total-N values also decreased with dry-matter losses and N leaks [5, 6]. Rapid rises in temperature cause losses in N from leaves [7].

TABLE V. TDM AND N UPTAKE BY WHEAT AT FLAG LEAF LIGULE EMERGENCE STAGE (GS-2)

Treatments	TDM kg ha^{-1}	N uptake kg ha^{-1}	TDM kg ha^{-1}	N uptake kg ha^{-1}
1994–95			**1995–96**	
N-O	1012	15.9	824	15.9
N-60	1220	27.0	1220	28.8
N-120	1410	39.1	1436	38.9
N-180	1485	40.2	1441	40.2
LSD(P=0.05)	136	7.81	148	8.3
1996–97			**1997–98**	
N-O	695	11.8	855	13.5
N-60	1122	20.2	1686	28.9
N-120	1463	25.2	1892	35.2
N-180	1501	28.7	2348	42.6
LSD(P=0.05)	190	7.72	213	15.7

TABLE VI. TDM AND N UPTAKE BY WHEAT AT ANTHESIS (GS-3)

Treatment	TDM kg ha^{-1}	N uptake kg ha^{-1}	TDM kg ha^{-1}	N uptake kg ha^{-1}
1994–95			**1995–96**	
N-O	3152	43.6	3212	34.7
N-60	3725	50.3	3353	43.3
N-120	4005	60.5	3362	58.8
N-180	4015	71.5	3951	73.5
LSD(P=0.05)	285	14.7	571	15.6
1996–97			**1997–98**	
N-O	2525	16.9	1946	18.6
N-60	3366	23.9	3278	44.1
N-120	3440	37.5	3644	61.4
N-180	4501	58.1	4662	70.8
LSD(P=0.05)	476	12.3	564	17.1

TABLE VII. TDM AND N UPTAKE BY WHEAT AT EIGHT DAYS AFTER ANTHESIS (GS-4)

Treatment	TDM kg ha^{-1}	N uptake kg ha^{-1}	TDM kg ha^{-1}	N uptake kg ha^{-1}
1994–95			**1995–96**	
N-O	3750	43.9	3456	34.9
N-60	4550	63.7	4487	49.9
N-120	5605	86.1	5215	64.1
N-180	5750	98.8	5745	77.0
LSD(P=0.05)	675	15.9	817	16.3
1996–97			**1997–98**	
N-O	3036	23.7	3150	25.4
N-60	4525	33.9	4320	43.6
N-120	5715	55.4	5458	48.1
N-180	5668	61.8	5708	62.1
LSD(P=0.05)	709	159	415	14.6

TABLE VIII. TDM AND N UPTAKE BY WHEAT AT PHYSIOLOGICAL MATURITY STAGE (GS-5)

Treatment	TDM kg ha^{-1}	N uptake kg ha^{-1}	TDM kg ha^{-1}	N uptake kg ha^{-1}
	1994–95		**1995–96**	
N-O	4975	43.6	4950	44.6
N-60	7752	75.5	8116	72.2
N-120	10255	128.6	10289	119.4
N-180	10521	146.5	11447	144.2
LSD(P=0.05)	1015	24.5	1080	28.9
	1996–97		**1997–98**	
N-O	4223	28.3	4063	26.5
N-60	7836	50.2	8445	45.5
N-120	11928	95.0	10615	55.3
N-180	11417	101.9	11060	70.3
LSD(P=0.05)	1263	26.7	879	9.4

TABLE IX. YIELD AND YIELD CONTRIBUTING CHARACTERS OF WHEAT AS INFLUENCED BY N LEVELS

Treatments	Grain yield, Mg ha^{-1}	Straw yield, Mg ha^{-1}	Harvest index %	Plant height cm	Spike length cm	1000 grain weight g
			1994–95			
N-O	1.86	3.21	36.7	75.6	7.48	42.5
N-60	2.94	4.25	40.9	82.1	8.39	43.9
N-120	3.77	5.19	42.1	89.7	8.35	44.7
N-180	4.19	5.50	45.2	91.0	8.84	45.7
LSD(P=0.05)	0.339	0.402	NS	4.52	0.83	1.03
			1995–96			
N-O	1.67	2.17	43.5	77.6	7.50	45.7
N-60	2.87	3.64	44.1	89.8	8.62	45.8
N-120	3.93	5.21	43.0	92.9	8.83	46.4
N-180	3.82	5.12	42.7	93.2	8.91	47.5
LSD(P=0.05)	0.32	0.52	NS	71.0	NS	NS
			1996–97			
N-O	1.22	1.59	43.4	78.4	6.85	48.1
N-60	2.93	3.78	43.7	91.4	8.52	48.3
N-120	3.94	4.67	45.8	97.9	8.93	47.5
N-180	4.13	5.05	45.0	96.2	9.15	46.4
LSD(P=0.05)	0.41	0.43	NS	7.6	0.78	NS
			1997–98			
N-O	1.25	2.35	34.7	76.4	7.69	47.3
N-60	3.00	5.00	37.5	101.3	9.92	47.6
N-120	4.38	7.92	35.6	96.9	10.4	48.1
N-180	5.25	8.61	37.9	108.3	10.5	47.8
LSD(P=0.05)	0.963	1.366	NS	13.68	0.503	NS

TABLE X. TDM AT HARVEST, TOTAL AND FERTILIZER N YIELD, NDFF AND N RECOVERY BY WHEAT

Treatments	TDM kg ha^{-1}	Total N yield kg ha^{-1}	Fert. N yield kg ha^{-1}	Ndff %	Fert. N recovery %
		1994–95			
N-0	5071	31.7	-	-	-
N-60	7192	56.3	24.6*	43.7*	41.0*
N-120(1/3 ^{15}N)	8961	89.3	11.4	12.9	28.5
N-120 (1/3+2/3 ^{15}N)	**8961**	**89.2**	**46.6**	**52.1**	**38.84**
N-180 (1/3 ^{15}N)	9693	117.3	24.6	21.0	40.87
N-180 (1/3+2/3 ^{15}N)	**9693**	**119.0**	**68.6**	**57.8**	**38.14**
LSD (P=0.05)for 1/3 ^{15}N	914	14.3	10.4	12.2	9.8
LSD (P=0.05) for 1/3+2/3 ^{15}N	914	6.4	8.2	10.9	10.3
		1995–96			
N-0	3844	28.2	-	-	-
N-60	6513	43.9	15.7*	35.8*	26.2*
N-120(1/3 ^{15}N)	9143	97.6	20.5	20.9	51.3
N-120 (1/3+2/3 ^{15}N)	**9143**	**97.6**	**50.7**	**51.8**	**42.3**
N-180 (1/3 ^{15}N)	8941	108.6	20.7	18.8	34.5
N-180 (1/3+2/3 ^{15}N)	**8941**	**108.2**	**62.5**	**57.8**	**34.7**
LSD (P=0.05)for 1/3 ^{15}N	980	13.6	9.5	13.5	8.8
LSD (P=0.05) for 1/3+2/3 ^{15}N	980	6.7	7.9	10.6	9.6
		1996–1997			
N-0	2812	20.8	-	-	-
N-60	6713	48.1	27.4*	57.0*	45.6*
N-120(1/3 ^{15}N)	8611	78.1	6.3	8.0	15.7
N-120(1/3+2/3 ^{15}N)	**8611**	**82.5**	**21.2**	**25.4**	**17.6**
N-180 (1/3 ^{15}N)	9184	108.1	13.2	12.5	22.0
N-180 (1/3+2/3 ^{15}N)	**9184**	**114.5**	**37.0**	**32.3**	**20.6**
LSD (P=0.05) for 1/3 ^{15}N	1163	18.9	13.5	18.2	13.7
LSD (P=0.05) for 1/3+2/3 ^{15}N	1163	20.2	10.6	16.8	12.5
		1997–1998			
N-0	3603	16.4	-	-	-
N-60	8004	46.3	29.9*	64.6*	49.8*
N-120(1/3 ^{15}N)	12301	101.9	11.4	11.9	28.5
N-120 (1/3+2/3 ^{15}N)	**12301**	**104.3**	**25.0**	**23.9**	**20.8**
N-180 (1/3 ^{15}N)	13862	147.9	19.5	12.3	32.5
N-180 (1/3+2/3 ^{15}N)	**13862**	**141.2**	**55.3**	**39.2**	**30.7**
LSD (P=0.05) for 1/3 ^{15}N	1365	24.1	19.1	14.1	11.7
LSD (P=0.05) for 1/3+2/3 ^{15}N	1365	17.4	12.3	12.4	8.5

* Predicted values of fertilizer N for N-60 treatment were calculated by subtracting the total N of N-0 from that of N-60 treatment.

TABLE XI. NH_4-N AND NO_3-N (kg N ha^{-1}) IN SOIL AT Z-30 STAGE

Soil depth cm	1994-95		1995-96		1996-97		1997-98	
	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N
N control								
0–15	14.4	10.2	18.7	16.4	19.7	17.2	20.4	14.0
15–30	13.0	10.1	19.0	15.8	18.6	16.9	20.6	15.1
30–45	12.8	10.8	18.2	13.1	17.7	15.2	20.3	15.9
45–60	12.0	10.0	17.4	12.2	17.9	14.1	22.9	12.2
60–75	11.4	9.2	14.6	10.1	16.4	10.5	19.3	12.8
75–90	11.4	8.4	12.7	9.3	15.1	8.9	18.7	9.2
90–105	11.0	8.6	10.2	7.4	15.2	6.8	16.6	6.9
105–120	10.0	8.0	11.6	7.0	14.9	6.9	14.4	8.8
60 kg N ha^{-1}								
0–15	23.0	18.4	22.9	18.3	22.4	18.6	24.6	16.2
15–30	21.4	17.4	23.0	18.0	22.0	18.0	24.6	14.0
30–45	21.8	17.0	22.0	16.0	23.4	20.2	24.6	14.6
45–60	20.4	16.4	20.2	15.5	21.6	21.0	21.8	12.6
60–75	19.4	16.8	21.7	14.9	20.4	19.6	20.4	11.0
75–90	18.4	15.6	18.6	11.3	19.8	19.0	17.6	10.8
90–105	17.0	14.8	17.2	10.9	21.4	17.8	22.6	11.2
105–120	16.0	13.8	15.6	9.5	17.0	17.2	16.8	10.4
120 kg N ha^{-1}								
0–15	20.2	20.4	21.1	17.8	21.0	18.4	22.0	14.0
15–30	15.0	20.6	22.0	18.5	20.4	16.6	24.8	15.6
30–45	16.4	19.6	21.0	16.6	19.4	16.4	22.4	98.4
45–60	15.0	15.8	19.2	16.0	18.8	14.8	22.0	13.0
60–75	14.4	15.0	14.6	13.7	19.6	19.8	20.0	7.4
75–90	15.0	14.4	13.7	12.0	17.4	14.4	17.2	8.8
90–105	13.8	10.6	11.8	9.7	17.8	14.8	14.8	8.4
105–120	12.2	10.8	10.2	9.0	15.0	14.4	14.8	7.4
180 kg N ha^{-1}								
0–15	17.8	20.4	23.4	19.2	22.0	21.0	23.8	13.4
15–30	15.2	18.8	24.0	18.9	21.0	18.8	22.0	12.0
30–45	10.4	14.6	23.5	17.0	20.0	17.4	23.8	13.0
45–60	9.8	12.8	21.2	15.8	22.4	15.6	21.0	10.8
60–75	9.2	12.4	22.3	14.7	18.8	15.0	18.2	9.2
75–90	8.4	15.0	21.0	10.3	18.4	16.0	15.0	6.4
90–105	8.0	10.2	17.3	9.7	16.6	15.8	17.2	6.0
105–120	6.4	6.0	16.8	7.8	14.4	14.8	16.8	5.4

3.2. Grain yield

Grain yield and yield-contributing characters of the wheat varied significantly among the treatments (Table IX). Over the 4-year study, the mean grain yields were 1.22 to 1.86 Mg ha^{-1} in unfertilized check plots, 2.87 to 3.0 Mg ha^{-1} with treatment N_1, 3.77 to 4.38 Mg ha^{-1} with N_2, and 3.82 to 5.25 Mg ha^{-1} with N_3. Similar trends prevailed for straw and other yield components. The effects of N_3 on yield and yield-contributing characters were marginal compared with N_2, although the highest grain yield, 5.25 Mg ha^{-1}, was recorded at N_3 in the 1997–98 growing season. Increased rates of N fertilizer promoted harvest-index values. The low harvest index during 1997–98 was attributable to the production of higher straw yield compared to other years.

3.3. Nitrogen uptake

Total-N uptake by the wheat in check plots was significantly lower in all the four growing seasons (Table IX) and varied from 16.5 kg N ha^{-1} in 1997–98 to 31.7 kg N ha^{-1} in 1994–95. Over the 4-year study, total-N values varied from 43.9 to 56.3 kg ha^{-1} with N_1, 78.1 to 104 kg ha^{-1} with N_2 and 108 to 148 kg ha^{-1} with N_3.

Fertilizer-N assimilation, as revealed by ^{15}N-enrichment data, was highest with N_3 during 1994–95. During the 4 years, applied-N uptake varied from 21.2 to 46.6 kg ha^{-1} with N_2, and from 37.0 to 68.6 kg ha^{-1} with N_3; the contribution of the application at planting was considerably lower that of that made at Z-30.

The percent N derived from fertilizer (%Ndff) was highest with N_3, ranging from 32 to 58% over the four growing seasons. The %Ndff values with N_2 varied from 24 to 52%.

Fertilizer-N recoveries with N_2 and N_3 were similar from year to year except in 1996–97 when lower values were recorded, attributable to less rainfall and higher evaporation rates.

It is noteworthy that fertilizer-N recovery, calculated indirectly by the difference method (Total N with N_1 – Total N at $N_{0)}$), gave an over-estimate when compared to the isotope method.

3.4. Soil mineral N

During all 4 years of the experiment, soil NH_4^+-N content in check plots, to a depth of 120 cm, declined, whereas, in N-treated plots values were maintained except in the surface 15 cm which showed increases after the basal and Z-30 applications, followed by declines (Table XI).

Ammonium-N values at Z-30 were similar with all the levels of N; the values decreased with depth by final harvest (Table XII). The NO_3^--N content at Z-30 in different soil layers did not significantly change by grain harvest. There were considerably higher amounts of NO_3^--N in all soil layers of the N-treated plots. Although the trends in NH_4^+-N and NO_3^--N levels of different soil layers at Z-30 and final harvest stage were similar in all 4 years, their magnitudes differed considerably with soil depth. At final harvest, the amounts of NH_4^+-N and NO_3^--N decreased with depth and were less than those recorded at sowing, indicating considerable losses of mineral N during the growing season due to leaching or due to gaseous losses to atmosphere.

3.5. Residual N

Nitrogen residual in the soil after the wheat harvest decreased with depth and was proportional to the rate applied (Table XIII). Nitrogen-15 was traced only to a depth of 75 cm with N_2, and with N_3 to 45 cm in 1996–97 and to 90 cm in 1997–98.

3.6. Soil water

Changes in soil-water content were mainly in the upper 60 cm in the N-treated plots (Table XIV). Decreases in moisture content in the 0 to 15 cm layer in all the treatments were rapid probably due to higher evapotranspiration demand.

3.6.1. SWD and WUE

Soil water depletion patterns from the surface to 90 cm were similar for all treatments during the 4-year study (Table XV). Total water use varied with the amount of irrigation applied in different growing seasons, and there was considerable variation in WUE. The WUE values increased with N level, the highest being recorded with N_3 followed by N_2, related to higher yields of wheat; they varied from 67.6 to 106 with N_0, 158 to 169 at N_1, 218 to 234 at N_2 and 246 to 276 kg ha^{-1} cm^{-1} at N_3, over the four growing seasons.

TABLE XII. MINERAL NITROGEN (kg ha^{-1}) IN SOIL AT HARVEST DURING THE STUDY PERIOD

Soil depth	1994–95		1995–96		1996–97		1997–98	
cm	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N
N control								
0–15	11.8	10.4	14.3	9.8	15.4	9.4	17.0	11.2
15–30	12.4	8.6	11.6	9.2	12.4	10.28.6	16.4	11.4
30–45	11.4	9.2	11.7	9.4	12.2	10.0	15.8	8.6
45–60	11.6	8.2	11.2	8.7	11.8	9.2	16.0	9.4
60–75	9.8	7.8	10.6	8.2	12.8	9.6	15.2	10.0
75–90	10.4	7.6	10.4	7.2	11.4	10.2	14.8	9.4
90–105	9.0	8.4	10.2	8.1	12.6	9.4	12.2	8.2
105–120	8.4	7.4	9.8	7.9	11.8	7.8	10.6	7.8
60 kg N ha^{-1}								
0–15	19.4	16.4	21.2	17.2	20.4	15.0	15.4	17.0
15–30	19.0	14.0	21.4	14.8	20.6	14.8	18.8	16.2
30–45	19.0	14.0	18.7	15.0	18.8	14.4	15.2	16.4
45–60	17.4	12.6	18.8	14.2	10.4	14.0	11.8	13.6
60–75	17.8	12.4	17.4	12.8	9.8	12.6	12.2	10.2
75–90	15.6	11.8	16.0	11.6	8.4	12.0	16.4	10.0
90–105	15.8	10.6	14.2	10.7	7.4	8.0	8.4	8.4
105–120	12.4	9.4	14.0	9.2	9.0	6.4	7.2	8.0
120 kg N ha^{-1}								
0–15	20.4	16.6	23.2	15.4	21.4	16.4	16.8	16.6
15–30	19.4	14.4	22.8	14.2	18.6	15.0	14.6	16.1
30–45	18.6	14.0	18.7	12.0	17.4	12.4	16.4	14.2
45–60	18.4	12.4	16.2	11.8	16.4	12.0	14.6	14.0
60–75	16.4	11.8	16.8	10.2	14.4	12.6	14.0	14.2
75–90	14.6	10.0	16.4	9.8	13.8	11.4	8.6	8.2
90–105	13.0	8.6	14.8	8.2	12.4	9.8	8.8	8.0
105–120	14.2	8.2	14.0	7.6	12.0	9.4	6.6	7.2
180 kg N ha^{-1}								
0–15	19.6	13.4	23.9	16.2	20.4	13.4	24.8	12.2
15–30	18.4	12.6	23.8	14.8	19.4	12.2	21.2	14.2
30–45	17.0	11.8	20.0	13.2	17.0	10.4	22.6	14.4
45–60	15.8	12.4	18.4	12.8	14.4	12.0	18.2	12.8
60–75	16.4	11.4	17.2	10.4	18.4	10.4	18.0	10.0
75–90	15.4	10.8	17.6	10.8	17.4	12.6	16.2	12.0
90–105	13.8	9.8	15.7	10.6	14.4	10.8	14.2	8.0
105–120	12.2	8.4	14.2	10.0	11.8	8.0	10.2	8.2

3.6.2. Percolation

Soil-water percolation measured in the nearby plot using the internal drainage method showed that the downward flux of water increased with depth but decreased with time [8]. After 25 days of drainage, the water flux in the soil was 6.2 mm day^{-1} at 15 cm depth and 34 mm day^{-1} at 120 cm.

Fertilizer-N movement in the soil was proportionately lower, indicating that little NO_3^- percolated to groundwater. The experimental field was located in a region of highly variable temperature. Sudden rises in temperature in daytime cause higher evapotranspirational losses of soil water. As a result, volatilization of fertilizer N may be higher than leaching losses.

TABLE XIII. TOTAL N AND N-15 A.E. CONTENT IN SOIL PROFILE AFTER HARVEST OF WHEAT

Treatment	Soil Depth cm	1995–96		1996–97		1997–98	
		% N	% N-15	% N	% N-15	% N	% N-15
N-120 (1/3+2/3)	0–15	0.05	0.108	0.07	0.104	0.08	0.145
	15–30	0.05	0.032	0.05	0.084	0.06	0.036
	30–45	0.04	0.025	0.05	0.066	0.05	0.013
	45–60	0.03	*	0.03	0.033	0.04	0.005
	60–75	0.03	*	0.03	0.082	0.03	0.003
	75–90	0.03	*	0.02	*	0.02	0.005
N-180 (1/3+2/3)	0–15	0.06	0.179	0.06	0.194	0.08	0.274
	15–30	0.04	0.118	0.04	0.080	0.06	0.067
	30–45	0.03	*	0.03	0.081	0.04	0.039
	45–60	0.02	*	0.02	*	0.04	0.023
	60–75	0.02	*	0.02	*	0.03	0.026
	75–90	0.01	*	0.02	*	0.02	0.009

* below detectible limit.

TABLE XIV. SOIL WATER CONTENT AT SOWING AND AT HARVEST OF WHEAT IN DIFFERENT DEPTHS

Soil depth (cm)	Soil water content, $cm^3 cm^{-3}$				
	At sowing	At harvest			
		N-0	N-60	N-120	N180
1994–95					
0–15	0.261	0.172	0.152	0.142	0.142
15–30	0.374	0.233	0.281	0.211	0.283
30–45	0.392	0.311	0.303	0.273	0.303
45–60	0.381	0.292	0.314	0.294	0.341
60–75	0.343	0.241	0.272	0.292	0.321
75–90	0.324	0.204	0.221	0.291	0.312
1995–96					
0–15	0.274	0.104	0.123	0.083	0.133
15–30	0.373	0.322	0.254	0.322	0.312
30–45	0.391	0.353	0.331	0.404	0.364
45–60	0.402	0.374	0.323	0.411	0.391
60–75	0.421	0.392	0.334	0.412	0.402
75–90	0.354	0.401	0.392	0.391	0.343
1996–97					
0–15	0.264	0.113	0.121	0.122	0.094
15–30	0.370	0.234	0.233	0.312	0.223
30–45	0.380	0.233	0.324	0.374	0.314
45–60	0.401	0.342	0.341	0.353	0.331
60–75	0.393	0.334	0.353	0.320	0.350
75–90	0.381	0.351	0.342	0.371	0.342
1997–98					
0–15	0.221	0.162	0.124	0.133	0.114
15–30	0.291	0.214	0.231	0.214	0.223
30–45	0.320	0.270	0.274	0.253	0.282
45–60	0.373	0.312	0.321	0.301	0.311
60–75	0.364	0.314	0.302	0.312	0.340
75–90	0.373	0.323	0.320	0.340	0.331

TABLE XV. SOIL WATER DEPLETION (SWD) AND WATER USE EFFICIENCY (WUE) OF WHEAT AS INFLUENCED BY N LEVELS

Treatments	Soil water content (0–90 cm) cm		SWD cm	Total water use cm	WUE kg ha^{-1} cm^{-1}
	At sowing	At harvest			
1994–95* Includes irrigation of 7.5 cm and effective rainfall of 1.4 cm during growth period.					
N-0	30.5	21.8	8.7	17.6	105.7
N-60	31.6	23.1	8.5	17.4	169.0
N-120	30.1	21.7	8.4	17.3	217.9
N-180	30.3	22.4	7.9	16.8	249.4
LSD(p=0.05	-	-	NS	NS	23.3
1995–96* Includes irrigation of 7.5 cm and effective rainfall to 2.1cm. during growth period.					
N-0	29.1	20.5	8.6	18.2	91.6
N-60	30.0	21.3	8.7	18.3	158.0
N-120	29.6	22.4	7.2	16.8	233.6
N-180	30.2	23.8	6.4	16.0	238.7
LSD(p=0.05	-	-	NS	NS	18.7
1996–97* Includes irrigation of 7.5 cm and effective rainfall of 2.0 cm during growth period.					
N-0	27.8	19.6	8.2	17.7	68.8
N-60	28.6	20.3	8.3	17.8	164.8
N-120	29.1	21.1	8.0	17.5	225.1
N-180	30.1	22.8	7.3	16.8	245.9
LSD(p=0.05	-	-	NS	NS	16.6
1997–98* Includes irrigation of 7.5 cm and effective rainfall of 2.3 cm during growth period.					
N-0	29.0	20.3	8.7	18.5	67.6
N-60	29.2	20.1	9.1	18.9	158.7
N-120	30.1	21.2	8.9	18.7	234.2
N-180	30.2	21.0	9.2	19.0	276.3
LSD(P=0.05	-	-	NS	NS	25.6

TABLE XVI. RICE YIELD (Mg ha^{-1}) AFTER WHEAT DURING THE STUDY PERIOD

Treatment	1995		1996		1997		1998	
	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw
N-0	2.6	4.6	2.5	4.7	2.8	4.7		
N-60	3.7	4.4	3.7	4.7	3.8	4.3		
N-120	3.9	5.5	3.8	4.8	3.8	5.5		
N-180	3.1	5.8	3.7	5.1	3.9	5.2		
LSD(P=0.05)	0.73	NS	0.79	NS	0.83	NS		

3.7. Residual effects on rice

There were significant differences in rice grain and straw yields between the unfertilized check plots and the N-treatment plots, however, no significant differences in yield emerged among the N treatments. (Table XVII). Grain yields of rice varied from 2.5 to 2.8 Mg ha^{-1} at N_0 and 3.1 to 3.9 Mg ha^{-1} with N previously applied to wheat. Straw yields ranged between 4.3 and 5.5 Mg ha^{-1}.

4. CONCLUSIONS

- Applied N had significant positive effects on yield and WUE of wheat. Total dry matter showed a downward trend between physiological maturity and ripening,
- The highest grain yield was recorded with 180 kg N ha^{-1} followed by the 120 kg N application. There were, however, no significant differences between these treatments during the 4-year study. Harvest indices also were similar with these two levels of N. Therefore, application of 120 kg N ha^{-1} is recommended for economic yield for wheat cultivation in the study area,
- The maximum rate of N uptake occurred after anthesis and the amount peaked at physiological maturity,
- Nitrogen-15-aided studies revealed that Ndff and fertilizer-N recovery varied over the four cropping season, the highest values being recorded with N_3,
- Application of two thirds of the N fertilizer at Z-30 increased the fertilizer-N uptake in both N_2 and N_3 treatments,
- Soil N and fertilizer N decreased with depth. Total N left in the soil after wheat harvest was proportional to the amount applied,
- Both NH_4^+-N and NO_3^--N in soil decreased with depth.
- The downward flux of water increased with depth but decreased with time, indicating higher evapotranspirational losses and higher volatilization of applied N,
- Because mineral-N levels were lower with soil depth, there was no immediate threat of NO_3^- pollution of ground water,
- Rice yields increased significantly with the application of N fertilizer to the previous crop of wheat, but there was no significant variation among the three N levels.

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FATE OF FERTILIZER N ON IRRIGATED WHEAT AND ITS POLLUTION POTENTIAL

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Abstract

Irrigated field experiments with wheat over four seasons, 1994–98, compared the regionally recommended application of 120 kg N ha^{-1} with rates of 50% and 150% of this value. The application of 180 kg N ha^{-1} increased grain and dry-matter yields significantly. The highest fractional uptake of N was obtained at the 100%-N level, and additional fertilizer was utilized less efficiently. The first one third split application of basal N was less efficiently assimilated than a second two thirds split application at growth stage Z-30. The higher N application (150%) resulted in three- to five-fold more fertilizer-derived NO_3^--N in the soil solution below the root zone (120 cm depth). The soil water was depleted mostly from the upper 60 cm, below which moisture content remained unchanged during crop growth and was in excess of the upper limit of drainage.

1. INTRODUCTION

In India, wheat is grown in tropical and sub-tropical areas. The total production in 1965 was 12.3 Mt. Since then, with the introduction of semi-dwarf cultivars and expanded use of irrigation and fertilizers, production increased to 68.7 Mt in 1996, due largely to improved productivity per unit area. At present, wheat is cultivated on 25.4 Mha, of which more than 70% is irrigated, albeit not necessarily with optimum amounts of water. Yields on farmers' fields range from 650 to 4500 kg ha^{-1}, depending on region and fertilizer use, which varies from 5 to 160 kg N ha^{-1} [1]. Demand for wheat and other cereals is increasing rapidly with the expanding population, and by the year 2000 the requirement for wheat is likely to be 75 Mt [2] and to exceed 100 Mt by 2025. Future increases in wheat yields would obviously require greater N uptake and water use. Because more inputs may not always be economical as well as environmentally sound, it is necessary to optimize their use efficiencies by adapting management practices.

The majority of soils in the northwestern wheat belt of India are low in organic C and N. For wheat production, N is the most common limiting nutrient. Despite past gains through increases in fertilizers and irrigation, research has demonstrated that applied N is not efficiently assimilated and is prone to losses [3, 4]. With concern over environmental issues, the problem of high NO_3^- concentration in surface waters and aquifers in relation to excessive fertilizer N use is increasingly receiving attention. In the Punjab, monitoring of shallow wells showed that elevated NO_3^- which tended to reach the water table during the rainy season in rice-wheat rotations [5]. In the future, with increasing fertilizer-N-application rates the possibility of NO_3^- pollution of groundwater will be strongly linked with N-uptake efficiency [6]. Optimum assimilation of applied N will be possible only through appropriate management practices [4].

This paper summarizes the results of 4 years of experiments on irrigated wheat using ^{15}N-enriched urea at the recommended level and 50 to 100% more on a typical sandy loam soil, with particular emphasis the fate of applied N.

2. MATERIALS AND METHODS

Field experiments were conducted during four winter seasons at the Indian Agricultural Research Institute farm. The soil is an alluvial sandy loam of the Mehrauli series and has been classified as a coarse loamy non-acid hypothermic typic Ustochrept. The soil profile description is given in Table I.

TABLE I. SOIL PROFILE DESCRIPTION

Soil ID	:	Mehrauli Sandy Loam
Soil classification	:	Coarse loamy non-acid hypothermic typic Ustochrepts (Non-calcareous light alluvium)
Soil description by layer :		

Depth	Sand	Silt	Clay	OC	TN	LLW	ULD	ULS	pH
	%					cm^3/cm^3			
0- 15	76.4	11.8	11.8	0.44	0.050	0.101	0.260	0.391	7.8
15- 30	74.4	10.8	14.8	0.38	0.036	0.097	0.259	0.389	7.8
30- 60	77.4	9.8	12.8	0.32	0.033	0.103	0.263	0.394	8.0
60- 90	72.4	11.8	15.8	0.30	0.031	0.105	0.259	0.390	8.2
90-120	68.6	13.6	17.8	0.27	0.029	0.119	0.272	0.411	8.3
120-150	63.4	11.8	24.8	0.25	0.021	0.121	0.272	0.417	8.5

The fertilizer-N treatments in 1994–95 and 1995–96 were $N_{0.5}$ – 50% of the recommended application (60 kg N ha^{-1}), $N_{1.0}$ – the recommended application (120 kg N ha^{-1}), and $N_{1.5}$ (180 kg N ha^{-1}), with N_0 – a zero-N check. In the third year, 1996–97, two additional N treatments were included, $N_{1.75}$ (210 kg N ha^{-1}) and $N_{2.0}$ (240 kg N ha^{-1}). In the fourth year, the additional treatments tested were $N_{1.0}$ and $N_{1.5}$ at a higher plant density.

All four experiments had a randomized block design with four replications. The main plot size was 10.0×6.0 m in the first year and subsequently was 8.0 × 8.0 m. In treatments $N_{1.0}$, $N_{1.5}$, $N_{1.75}$ and $N_{2.0}$, two micro-plots of 1.0 × 1.0 m were installed on each main plot for application of ^{15}N-enriched urea (10.032 atom % excess ^{15}N in the first year, 10.016 atom % excess ^{15}N in second year and 5.021 atom % excess ^{15}N in the third and fourth years).

A crop of maize (*Zea mays* L. cv. Ganga Safed-2) was grown, July to October, prior to each wheat crop, with uniform application of 120 kg N ha^{-1} as urea, 60 kg P_2O_5 ha^{-1} as single superphosphate and 60 kg K_2O ha^{-1} as muriate of potash. The urea was applied in three equal splits of 40 kg N ha^{-1} at planting, knee high and tasselling.

After the maize harvest, the land was prepared and, before sowing wheat, profile soil samples were collected from each replication from six locations. The samples were drawn from depths of 0 to 15 cm, 15 to 30, 30 to 60, 60 to 90, and 90 to 120 cm. The growing summary for wheat for the duration of the experiment is provided in Table II. Initial soil-moisture contents and concentrations of NH_4^+-N and NO_3^--N are shown in Tables III and IV.

In each plot of the $N_{1.0}$ and $N_{1.5}$ treatments, a neutron moisture meter access tube was installed to a depth of 180 cm to record soil moisture status at various stages of crop growth. Also, tensiometers were installed in all four $N_{1.0}$ and $N_{1.5}$ plots at depths of 30, 60, 90 and 120 cm. Soil-solution samplers (Soil Moisture Equipment Co., USA) were installed at depths of 60, 90 and 120 cm in one of the micro-plots in the $N_{1.0}$ and $N_{1.5}$ treatments receiving one third and two thirds ^{15}N-labelled urea at planting and at Z-30, respectively,

A pre-sowing irrigation of 60 mm was given each year and the wheat (*Triticum aestivum* L. cv. HD-2285 in 1994–95 and HD-2329 for 1995–98) was sown with uniform application of 60 kg P_2O_5 ha^{-1} and 60 kg K_2O ha^{-1} as single superphosphate and muriate of potash, respectively. Also, a one third dose of N was applied according to the treatments. In all micro-plots, ^{15}N-enriched urea was applied. The fertilizers were broadcast and incorporated to a depth of 15 cm. The wheat seed (100 kg ha^{-1}) was sown

TABLE II. GROWING SEASON SUMMARY FOR IRRIGATED WHEAT GROWN AT IARI RESEARCH FARM DURING 1994–95, 1995–96, 1996–97 AND 1997–98 WINTER SEASONS

	1994–95	**1995–96**	**1996–97**	**1997–98**
Preceding crop	Maize	Maize	Maize	Maize
Cultivar	Ganga Safed 2	Ganga Safed 2	Ganga Safed 2	Ganga Safed 2
Planting date	05 July	08 July	06 July	07 July
Fertilizer N (kg/ha)	120	120	120	120
Harvesting date	14 October	18 October	13 October	15 October
Pre-sowing irrigation	09 November	05 November	10 November	13 November
Wheat cultivar	HD 2285	HD 2329	HD 2329	HD 2329
Planting date	19 November	13 November	19 November	23 November
N Treatments	N_0 $N_{0.5}$ $N_{1.0}$ $N_{1.5}$	N_0 $N_{0.5}$ $N_{1.0}$ $N_{1.5}$	N_0 $N_{0.5}$ $N_{1.0}$ $N_{1.5}$ $N_{1.75}$ $N_{2.0}$	N_0 $N_{0.5}$ $N_{1.0}$ $N_{1.5}$ $N_{1.0}$ (D)* $N_{1.5}$ (D)*
Irrigation given to wheat	26 Dec. 1994 31 Jan. 1995 06 March 1995 20 March 1995	21 Dec. 1995 24 Jan. 1996 22 Feb. 1996 12 March 1996	21 Dec. 1996 15 Jan. 1997 25 Feb. 1997 15 March 1997	30 Dec. 1997 27 Jan. 1998 03 March 1998 25 March 1998
Z-30 sampling	31 Dec. 1994	23 Dec. 1995	26 Dec. 1996	04 Jan. 1998
Anthesis + 7 days sampling	01 March 1995	23 Feb. 1996	28 Feb 1997	06 March 1998
Physiological maturity	02 April 1995	25 March 1996	31 March 1997	05 April 1997
Harvesting date	14 April 1995	08 April 1996	15 April 1997	16 April 1998

* Row to row spacing of 15 cm.

with a drill at a row spacing of 22.5 cm. In the micro-plots the sowing was by hand. In the fourth year (1997–98), for the additional $N_{1.0}$ and $N_{1.5}$ treatments, the row spacing was 15 cm with a planting of 150 kg seed ha^{-1}.

The first irrigation was just before growth-stage Z-30 (29 to 37 days after germination) when the two thirds applications of N were made, immediately after plant samples were collected. Also, soil samples from each plot were taken with a Viehmeyer tube at depth intervals of 0 to 15, 15 to 30, 30 to 60, 60 to 90 and 90 to 120 cm. The plant samples were dried (70^{o}C), weights recorded, then analyzed for total N.

The chlorophyll content of the growing wheat crop was monitored in situ using a Minolta SPAD chlorophyll meter. At each recording, thirty measurements were made in each plot on the upper three leaf blades of selected plants.

The plant and soil samples were collected each year at 7 days after 50% anthesis and at physiological maturity. Dry-matter yields were calculated separately for straw and eared portions and were analyzed for N.

The soil sampling to 120 cm was carried out at 14-day intervals and samples so collected were extracted with 2 *N* KCl and analyzed colourimetrically for NH_4^+- and NO_3^--N by auto-analyzer.

TABLE III. PROFILE SOIL MOISTURE CONTENT (cm^3/cm^3) BEFORE WHEAT SOWING

depth (cm)	1994–95	1995–96	1996–97	1997–98
0–15	0.249±0.009	0.237±0.008	0.252±0.007	0.255±0.010
15–30	0.269±0.008	0.268±0.007	0.277±0.006	0.266±0.008
30–60	0.302±0.005	0.296±0.009	0.297±0.009	0.295±0.009
60–90	0.362±0.004	0.347±0.004	0.352±0.004	0.350±0.005
90–120	0.371±0.006	0.354±0.006	0.359±0.007	0.348±0.008
120–150	0.380±0.004	0.364±0.008	0.370±0.005	0.366±0.006

TABLE IV. MINERAL NITROGEN IN SOIL (mg/kg) BEFORE WHEAT SOWING

Depth (cm)	1994–95		1995–96		1996–97		1997–98	
	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N
0–15	10.57	6.80	11.29	6.56	9.67	6.71	6.38	5.61
15–30	9.57	7.28	9.57	6.84	9.26	7.02	5.85	4.43
30–60	9.37	5.48	9.37	5.46	8.97	5.46	5.39	4.07
60–90	8.11	4.41	8.61	4.20	8.32	4.88	5.11	3.68
90–120	9.16	6.70	8.45	6.85	7.82	7.49	5.47	4.05

Soil-solution samples from ^{15}N micro-plots in the $N_{1.0}$ and $N_{1.5}$ treatments in the first and second years were collected at approximately 14-day intervals by applying suction. In the third year, soil-solution samples were collected from the $N_{1.0}$, $N_{1.5}$, $N_{1.75}$ and $N_{2.0}$ treatments. In the fourth year, they were collected from both the normal and higher-plant densities, from the ^{15}N micro-plots in the $N_{1.0}$ and $N_{1.5}$ treatments. These soil solutions were analyzed for NH_4^+- and NO_3^--N, and for ^{15}N enrichment of the NO_3^- fraction only.

The crops were harvested at maturity for grain and straw yields. From the micro-plots, plant samples were collected only from the central 0.5 × 0.5 m, from which soil samples were also collected from depths of 0 to 15, 15 to 30, 30 to 60, 60 to 90 cm, 90 to 120 cm, 120 to 150, and 150 to 180 cm from two locations, mixed and sub-samples taken. These were analyzed for total N, NH_4^+-N and NO_3^--N, and for ^{15}N enrichment for assessment of residual fertilizer N.

The crops was surface irrigated four times; a total of about 27 cm of water were applied each year. The climate data (T_{Max}, T_{Min}, rainfall and sunshine hours) were obtained from the IARI observatory located about 300 m from the experimental site in the farm area. The soil-moisture profile data for $N_{1.0}$ and $N_{1.5}$ treatments to a depth of 150 cm was recorded periodically by neutron moisture meter (Troxler model 4300).

3. RESULTS AND DISCUSSION

3.1. Dry matter yield and N uptake

3.1.1. At Z-30

There were large differences among replications in dry-matter yield at the Z-30 sampling (Table V). Values ranged between 370 and 474 kg ha^{-1} in the N_0 check, 438 to 516 kg ha^{-1} at N_1, 579 to 639 kg ha^{-1} at N_2, and at N_3 from 649 to 716 kg ha^{-1}. Plants in N-fertilized plots had similar N-contents that were higher than those for plants in check plots. In the third year, 1996–97, the higher levels of N, 210 and 240 kg ha^{-1} ($N_{1.75}$ and $N_{2.0}$), gave significantly greater dry-matter yields and N-uptake values.

3.1.2. At 7 days post-anthesis

At 50% anthesis, some 70 to 85% of the final-harvest total N was accounted for in the straw and ear portions (Table VI).

TABLE V. DRY MATTER YIELD, NITROGEN CONTENT AND NITROGEN UPTAKE BY WHEAT PLANTS AT Z-30 STAGE AS INFLUENCED BY FERTILIZER N LEVELS

N levels (kg/ha)	Dry matter yield* (kg/ha)	N content* (%)	N uptake* (kg/ha)
	1994–95		
0	439	3.41	14.92
60	456	4.21	19.20
120	621	4.20	26.06
180	667	4.20	28.36
	1995–96		
0	474	3.54	16.79
60	506	4.36	22.07
120	639	4.37	27.88
180	710	4.42	31.38
	1996–97		
0	426	3.37	14.34
60	516	4.26	21.93
120	636	4.21	26.80
180	716	4.39	31.44
210	759	4.52	34.35
240	766	4.56	34.99
	1997–98		
0	370	3.33	12.30
60	438	4.25	18.63
120	579	4.46	25.83
180	649	4.41	28.64
120 D**	650	4.18	27.17
180 D**	737	4.43	32.65

* Each value is mean of 4 replicates ** Row to row spacing of 15 cm.

3.2. Grain and straw yields

Mean grain yields ranged from 1.78 to 2.23 Mg ha^{-1} in the check plots, 2.97 to 3.79 Mg ha^{-1} with $N_{0.5}$, 4.51 to 5.38 Mg ha^{-1} with N_1, and 4.84 to 6.09 Mg ha^{-1} with $N_{1.5}$ (Table VII). A similar trend prevailed for straw yields. There was no significant grain-yield response to higher fertilizer-N application in 1996–97, and the increase in straw yield was marginal. The grain-yield response to N was linear and, at $N_{1.5}$, about 600 kg ha^{-1} more grain was obtained, an economically beneficial response. Similar yield increases have been obtained by farmers in the northwestern plains of India by applying higher fertilizer doses [7].

In the fourth year, 1997–98, there was a general decline in grain yields; with N_1 only 4.51 Mg ha^{-1} were obtained, and, with $N_{1.5}$ it was 4.84 Mg ha^{-1} compared to >5.0 Mg ha^{-1} over the previous 3 years. This was a result of poor early growth due to unusually cloudy weather with little or no sunshine for the month of December, 1997. Also, in the $N_{1.0}$ treatment, the increased plant population caused a further grain-yield decline, whereas with $N_{1.5}$ the higher population gave a significant increase in grain yield. Harvest index also decreased in the fourth year.

3.3. Nitrogen uptake

Grain and straw from check plots had significantly lower N contents (Table VII). The values for total N assimilated were 35.7 to 41.6 kg ha^{-1} at N_0, 69.6 to 88.5 kg ha^{-1} with $N_{0.5}$, 117 to 136 kg ha^{-1} with $N_{1.0}$, and 141 to 172 kg ha^{-1} with $N_{1.5}$. In the third year, fertilizer N at 175% and 200% showed higher total-N values by about 10 kg ha^{-1}, similar to that obtained with 150% N in the first 2 years. In the fourth year, there were declines in total N uptake at all levels or N.

TABLE VI. DRY MATTER YIELD, N CONTENT AND TOTAL N UPTAKE BY WHEAT AT ANTHESIS + 7 DAYS STAGE AS INFLUENCED BY N LEVELS

N levels (kg/ha)	Dry matter yield* (kg/ha)		N content* (%)		N uptake* (kg/ha)		
	Straw	Ears	Straw	Ears	Straw	Ears	Total
			1994–95				
0	2157	1361	0.816	0.999	17.61	13.58	31.19
60	4161	2319	1.000	1.335	41.41	30.97	72.38
120	5316	3679	1.158	1.595	61.32	58.81	120.13
180	5863	4239	1.354	1.816	79.39	77.08	156.47
			1995–96				
0	2288	1299	0.780	0.996	17.67	12.93	30.60
60	3973	2275	1.113	1.279	44.12	29.10	73.22
120	5482	3623	1.164	1.546	63.74	55.92	119.66
180	5775	3833	1.297	1.807	74.82	69.23	144.05
			1996–97				
0	2056	1474	0.812	1.022	16.68	15.03	31.71
60	3894	2284	1.021	1.292	39.74	29.46	69.20
120	5784	3526	1.104	1.590	63.85	56.11	119.96
180	5950	4152	1.114	1.691	66.27	70.22	136.49
210	5880	3942	1.116	1.789	65.56	70.42	135.98
240	5985	4200	1.273	1.754	76.14	73.68	149.82
			1997–98				
0	1890	1326	0.760	0.923	14.36	12.23	26.59
60	3351	2122	0.891	1.094	29.85	23.21	53.06
120	5031	3019	0.994	1.304	50.01	39.37	89.38
180	5355	3697	1.059	1.429	56.73	52.81	109.54
120 D	5679	3378	0.934	1.402	52.99	47.38	100.36
180 D	6068	3863	1.098	1.523	66.61	58.34	125.44

3.4. Nitrogen uptake efficiency

With the $N_{1.0}$ treatment, the fertilizer-N-uptake efficiency from the first split of 40 kg N ha^{-1} was 28 to 31% and from the second split at Z-30 stage was 62 to 64% (Tables VIII and IX). With $N_{1.5}$, it ranged between 25 to 26% and 50 to 51%, respectively. The overall uptake-efficiency values with $N_{1.0}$ and $N_{1.5}$ were 52% and 42%, respectively. Although there were significant increases in fertilizer-N uptake in grain and straw with 210 and 240 kg N ha^{-1}, the efficiencies were lower at 40 and 35%, respectively. In the 1997–98 season, the fertilizer-N uptake and, consequently, per cent N recovery by the crop decreased significantly. With $N_{1.0}$ it was only 42% compared to about 50% in the previous 3 years.

3.5. Soil mineral N

During all 4 years of experimentation, the soil NH_4^+-N content declined in the check-plots to a depth of 120 cm, whereas in N-treated plots, except in the surface layer (0 to 15 cm), more or less steady values were maintained (Fig. 1). In the surface layer, it first increased with the basal N application and again increased with the second application at Z-30, but, thereafter, continuously decreased and by 50% anthesis reached a steady value similar to that before planting. The NO_3^--N content in the various soil layers increased after the Z-30 fertilizer application and showed maximum values in each layer (Fig. 2). There were considerably higher concentrations of NO_3^--N in all the soil layers with $N_{1.5}$. Although the

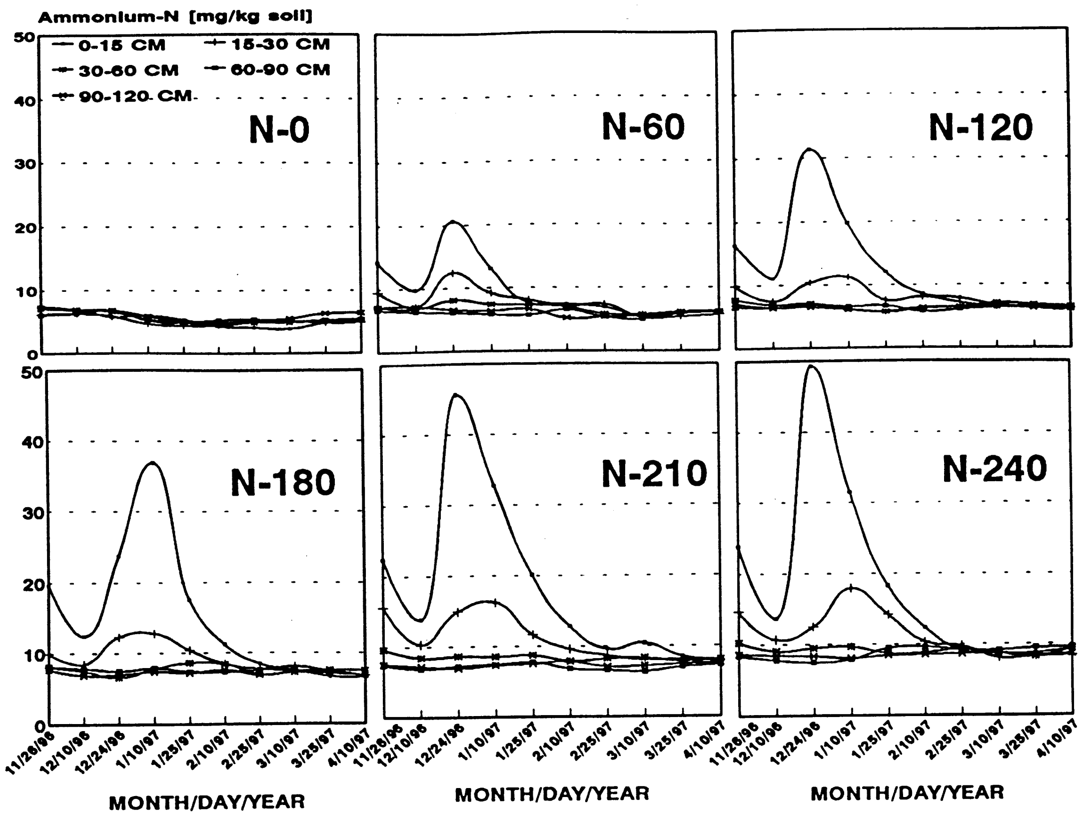

Fig. 1. Ammonium N in soil at different depths during wheat growth (1996–1997).

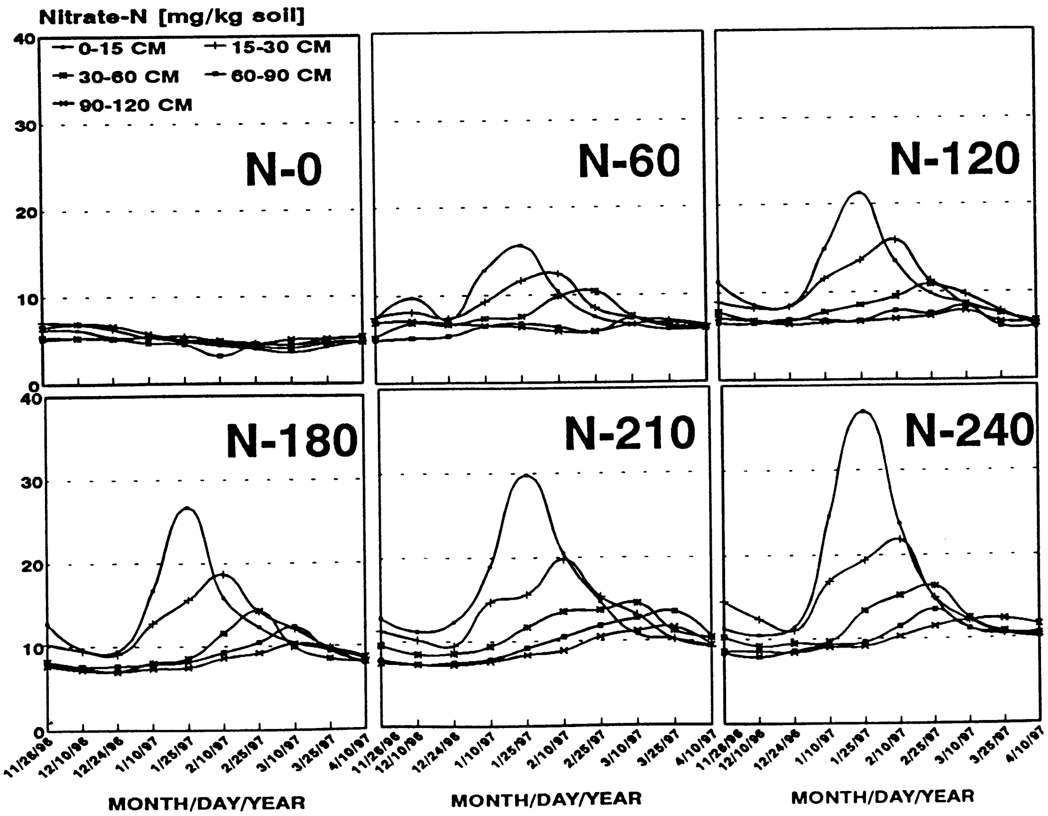

Fig. 2. Nitrate N in soil at different depths during wheat growth (1996–1997).

TABLE VII. GRAIN, STRAW AND TOTAL BIOMASS YIELD, N CONTENT AND UPTAKE BY WHEAT GRAIN AND STRAW AS INFLUENCED BY N LEVELS DURING THE FOUR SEASONS.

N levels (kg/ha)	Wheat yield* (kg/ha)			N content* (%)		Total N uptake* (kg/ha)		
	Grain	Straw	Total	Grain	Straw	Grain	Straw	Total
				1994–95				
0	2022	1959	3981	1.464	0.313	29.60	6.14	35.74
60	3498	4725	8223	1.946	0.396	68.09	18.68	86.76
120	5110	5997	11 107	2.118	0.446	108.20	26.76	134.95
180	5703	7128	12 830	2.406	0.494	137.17	35.19	172.35
				1995–96				
0	2313	2721	5033	1.430	0.314	33.06	8.54	41.60
60	3785	4167	7951	1.895	0.402	71.74	16.75	88.49
120	5378	5302	106.81	2.104	0.440	113.17	23.32	136.49
180	6090	6354	12 444	2.297	0.487	139.90	30.94	170.84
				1996–97				
0	2191	2597	4788	1.408	0.334	30.85	8.67	39.52
60	3642	4080	7722	1.829	0.405	66.64	16.53	83.17
120	5253	5257	10 510	2.101	0.444	110.35	23.33	133.68
180	5872	6260	12 132	2.236	0.474	131.26	29.69	160.94
210	6003	6444	12 448	2.310	0.479	138.65	30.89	169.54
240	5910	6674	12 583	2.355	0.472	139.24	31.49	170.73
				1997–98				
0	1781	2924	4705	1.474	0.339	26.23	9.90	36.13
60	2972	4521	7493	1.707	0.417	50.73	18.83	69.55
120	4507	5722	10 229	2.031	0.446	91.57	25.50	117.06
180	4837	7281	12 118	2.186	0.480	105.70	34.98	140.69
120 D**	4340	6160	10 500	2.047	0.471	88.88	28.99	117.86
180 D**	5542	7097	12 639	2.260	0.488	125.20	36.60	159.80

trends in NH_4^+-N and NO_3^--N contents of the different soil layers were similar during for all four years, the magnitudes differed.

3.6. Mineral N in soil solution

Soil-solution samples collected from the $N_{1.0}$ and $N_{1.5}$ micro-plots at depths of 60, 90, and 120 cm depths, contained little NH_4^+-N in comparison with soil extracted with 2 *N* KCl at similar depths. However, NO_3^--N content of soil solution at 60 cm showed initial increases that were later seen at 90 cm and 120 cm depths (Fig. 3). The concentrations of NO_3^--N with 180 kg N ha^{-1}, at all three depths, were two- to three-fold higher than those with 120 kg N ha^{-1}. The fertilizer-derived NO_3^--N in soil-solution showed similar trends, but with three to four times more with the $N_{1.5}$ treatment than with $N_{1.0}$ (Fig. 4). In the third year, with the higher applications, 210 kg and 240 kg N ha^{-1}, both total and fertilizer-derived NO_3^- fractions in soil solution were much higher, with peak values around anthesis. Fertilizer-derived NO_3^--N at 90- and 120-cm depths was 60 to 70% of the total in the soil solution, indicating a strong potential for NO_3^- leaching because the deeper soil layers were always close to the water-holding limit. Although the application of higher levels of N was economically beneficial in terms of approximately 0.6 Mg ha^{-1} more grain yield, the additional N supply was prone to leaching and likely to result in environmental pollution in the long run.

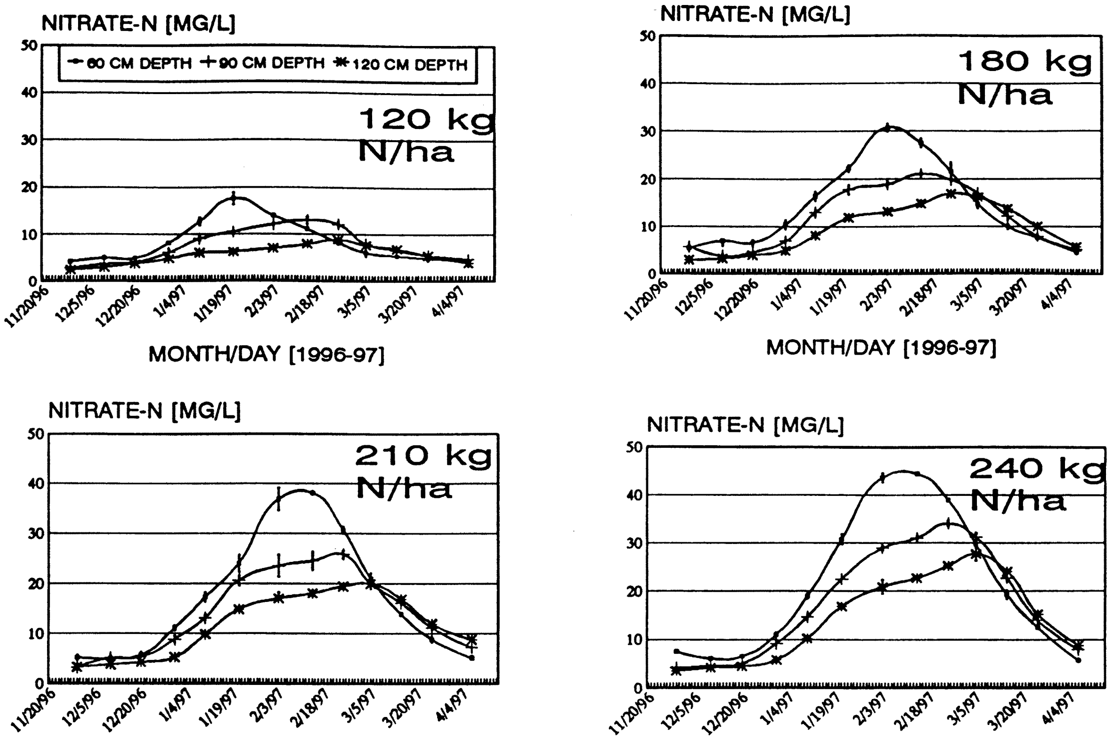

Fig. 3. Effect of fertilizer N levels on Nitrate-N in soil solution at different depths during 1996–1997.

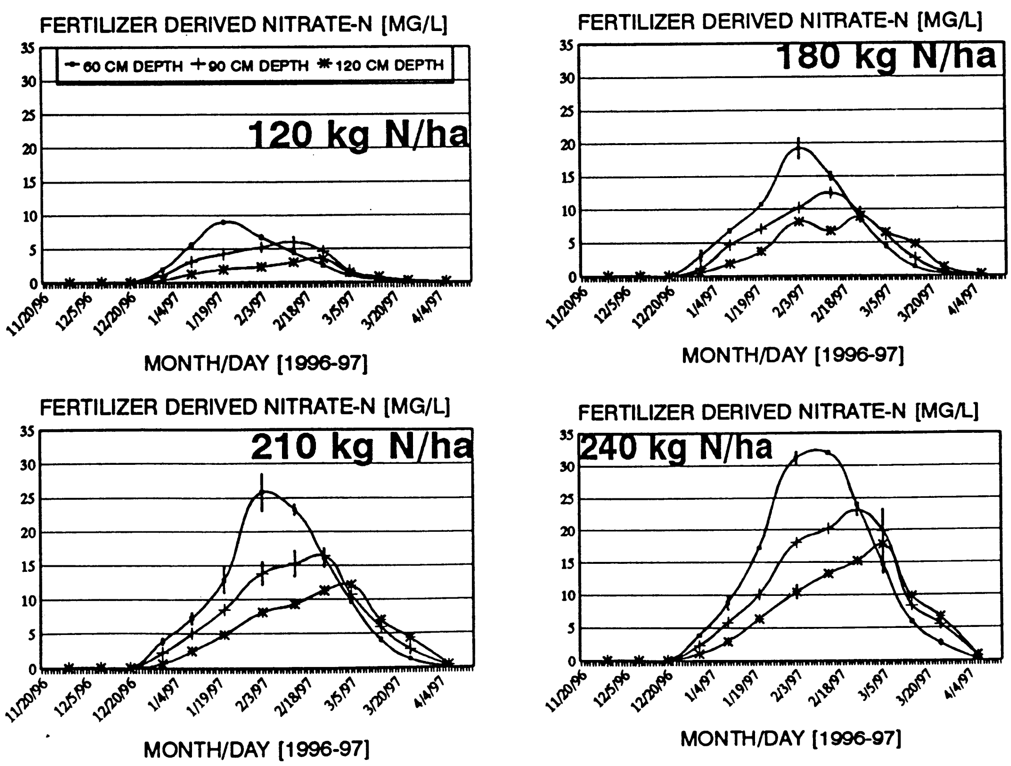

Fig. 4. Effect of fertilizer N levels on fertilizer derived Nitrate-N in soil solution at different depths during 1996–1997.

TABLE VIII. EFFECT OF FERTILIZER N LEVELS ON FERTILIZER N UPTAKE AND USE EFFICIENCY BY WHEAT DURING FOUR SEASONS

N level (kg/ha)	Fertilizer N uptake (kg/ha) Grain	Straw	Total	N use efficiency (%)
		1994–95		
120	49.85	12.45	62.30	51.92
180	59.67	15.00	74.67	41.48
		1995–96		
120	52.15	10.73	62.88	52.40
180	63.58	13.38	76.96	42.76
		1996–97		
120	51.41	10.60	62.01	51.68
180	63.08	13.77	76.85	42.70
210	68.53	15.55	84.08	40.04
240	68.14	16.21	84.35	35.15
		1997–98		
120	38.54	11.56	50.09	41.74
180	49.72	16.72	66.43	36.91
120 D**	41.26	13.48	54.74	45.61
180 D**	61.67	17.09	78.76	43.75

3.7. Chlorophyll content

In all three years, lower chlorophyll-index values were obtained from plants on the check plots than on the N-fertilized plots (Fig. 5). Compared to $N_{1.0}$, the recommended fertilizer level for wheat in the region, plants with the $N_{0.5}$ treatment consistently gave SPAD readings that were lower than those with $N_{1.5}$. The index values decreased in all treatments after the initiation of grain development. In wheat, if the SPAD reading at maximum tillering is less than 44, it would be expected to respond to a top dressing of 30 kg N ha^{-1} [8].

TABLE IX.PERCENTAGE UTILIZATION OF FERTILIZER NITROGEN BY WHEAT FROM TWO SPLIT APPLICATIONS

N levels (kg/ha)	First split (One third application)			Second split (Two third application)			Total		
	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total
				1994–95					
120	22.41	5.40	27.80	51.11	12.87	63.97	41.54	10.38	51.92
180	20.12	5.17	25.30	39.66	9.91	49.58	33.15	8.33	41.48
				1995–96					
120	24.74	5.08	29.82	52.82	10.88	63.69	43.46	8.95	52.40
180	21.22	4.54	25.75	42.37	8.88	51.26	35.32	7.43	42.76
				1996–97					
120	25.62	4.93	30.54	51.46	10.79	62.24	42.84	8.83	51.68
180	21.65	4.72	26.37	41.74	9.12	50.86	35.04	7.65	42.70
210	19.69	4.45	24.14	39.10	8.88	47.98	32.63	7.40	40.04
240	17.48	4.87	22.35	33.85	7.70	41.55	28.39	6.76	35.15
				1997–98					
120	18.68	5.21	23.89	38.83	11.84	50.67	32.11	9.63	41.74
180	17.50	5.73	23.23	32.68	11.07	43.75	27.62	9.29	36.91
120 D	16.95	7.17	24.12	43.10	13.26	56.36	34.38	11.23	45.61
180 D	21.52	6.72	28.23	40.63	10.88	51.51	34.26	9.49	43.75

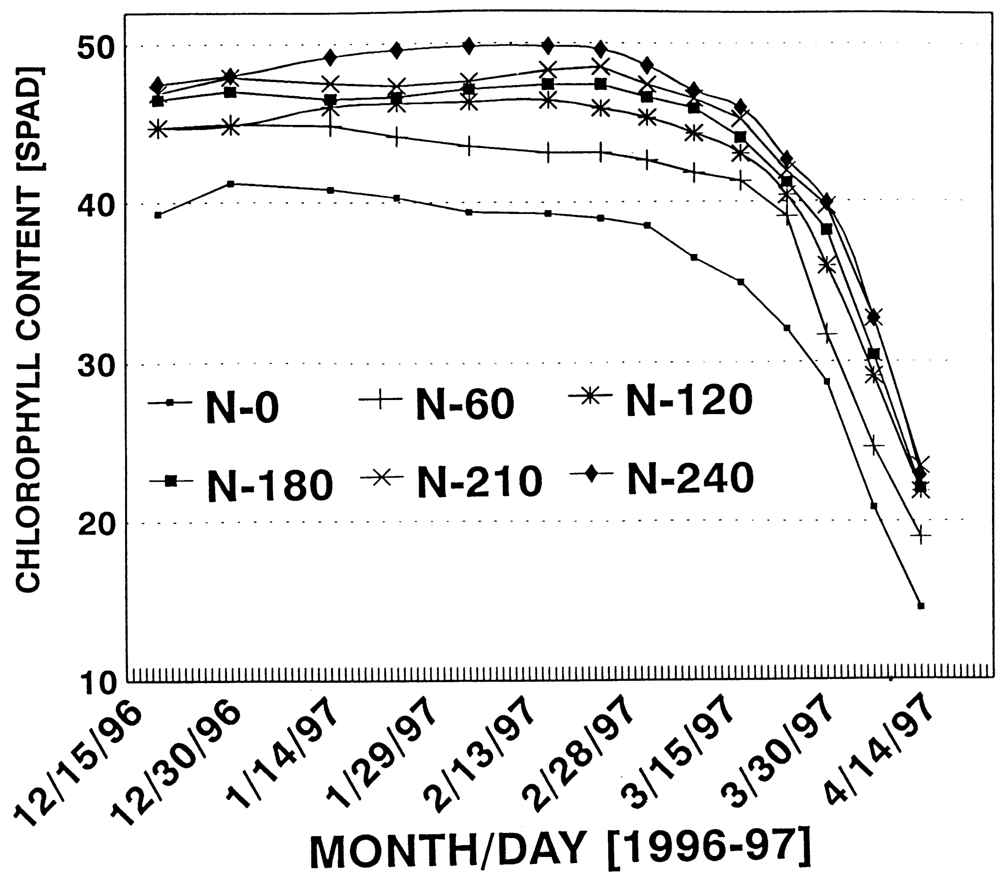

Fig. 5. Changes in chlorophyll content in upper three leaf blades of wheat during growth (1996–1997).

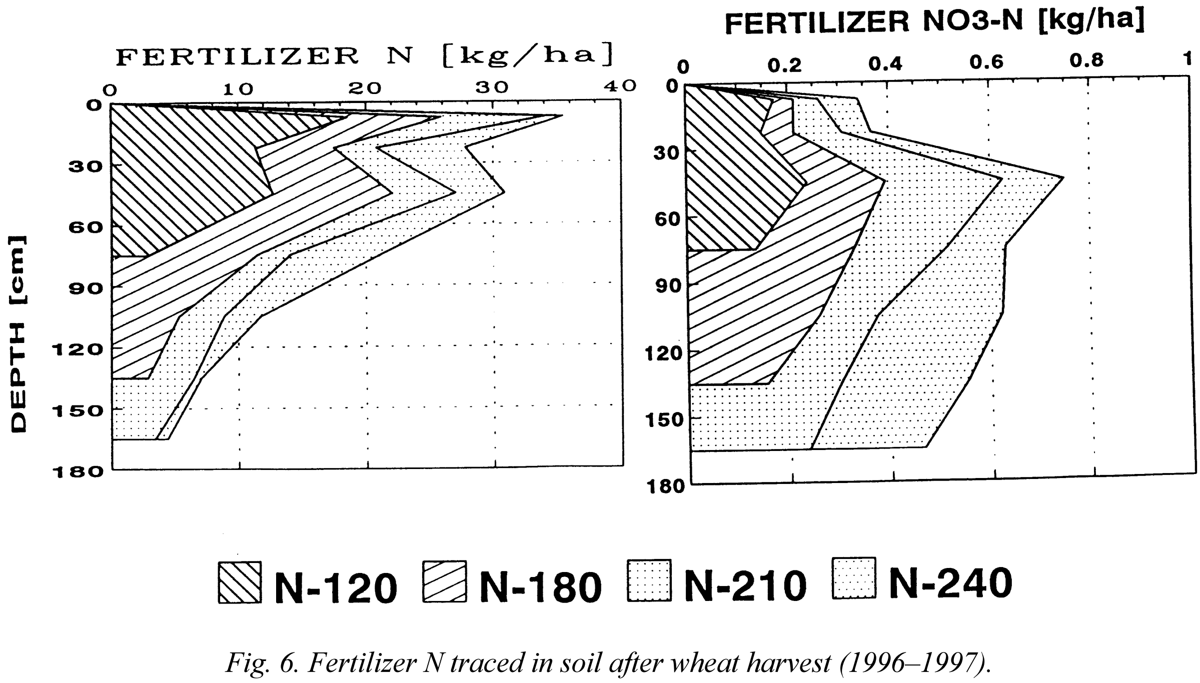

Fig. 6. Fertilizer N traced in soil after wheat harvest (1996–1997).

3.8. Residual N

With $N_{1.0}$, residual fertilizer N after wheat harvest could be traced to 90 cm, but not more deeply; the bulk of the N was in the upper 60 cm (Fig. 6). But, with $N_{1.5}$, it could be found at 150 cm, a substantial portion of which was below 90 cm, and fertilizer-derived NO_3^- was found even at 150 to 180 cm. The trends were similar over the 4 years. With applications of 210 and 240 kg N ha^{-1}, more fertilizer N was traced to lower soil depths after wheat harvest.

The fertilizer-N budgets are presented in Table X. In the fourth year, 1997–98, less was traced to the soil and less was recovered in the crop. The unaccounted-for fertilizer N was in excess of 20%, whereas it was only approximately 10% for the previous three seasons. This was primarily due to less-efficient utilization of the first one third basal application.

TABLE X. FERTILIZER NITROGEN BALANCE IN SOIL-PLANT SYSTEM AFTER WHEAT HARVEST DURING FOUR SEASONS

N Levels	Crop removal (%)	Residual in soil (%)	Unaccounted N (%)
		1994–95	
120	51.92	38.59	9.49
180	41.48	47.06	11.46
		1995–96	
120	52.40	40.04	7.56
180	42.76	49.34	7.90
		1996–97	
120	51.68	37.87	10.45
180	42.70	45.73	11.57
210	40.04	49.95	10.01
240	35.15	52.99	11.86
		1997–98	
120	41.74	36.33	21.93
180	36.91	42.32	20.77
120 D	45.61	33.48	20.91
180 D	43.75	34.49	21.76

3.9. Soil-moisture

The soil-moisture profiles, monitored with the neutron probe, showed that changes occurred mainly in the upper 60 cm. Moisture content at lower layers (60 to 90, 90 to 120, and 120 to 150 cm) remained similar throughout wheat growth and in excess of the upper limit of drainage (ULD) value (Fig. 7). With each irrigation, maximum values near to the ULD were reached in the upper 60 cm. The decreases in soil moisture in the 0 to 15 cm layer with the $N_{1.5}$ treatment were rapid compared to those with $N_{1.0}$ probably due to higher transpirational losses.

The soil-moisture tension records over the four seasons showed trends similar to those for profile moisture contents.

3.10. Computer simulation

The simulation of data sets with the CERES-Wheat model failed to match the growth data and consistently predicted 50 to 60% less total biomass and grain yield. However, the simulated and measured data for extractable soil water during the wheat growth were in agreement over all seasons (Fig. 8). The simulation also predicted a large amount of water being drained.

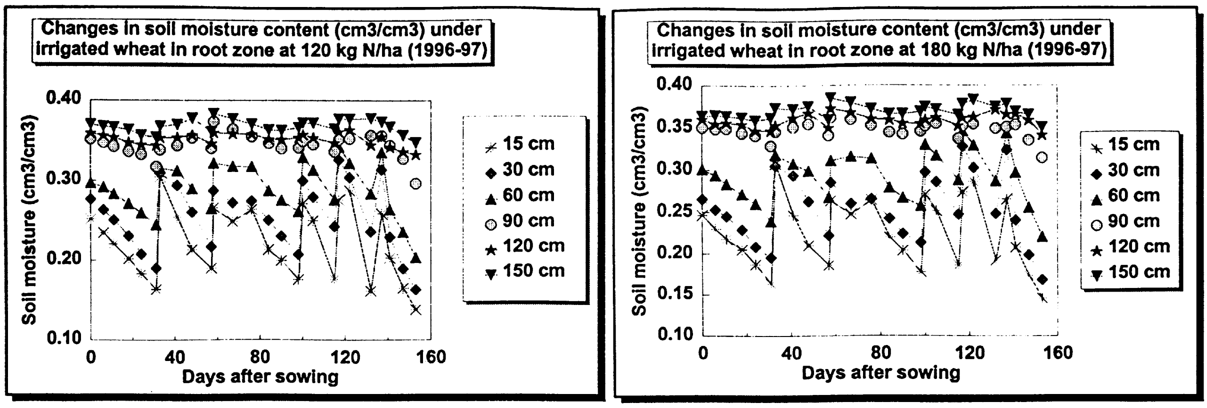

Fig. 7. Changes in soil moisture content (cm^3/cm^3) under irrigated wheat in root zone.

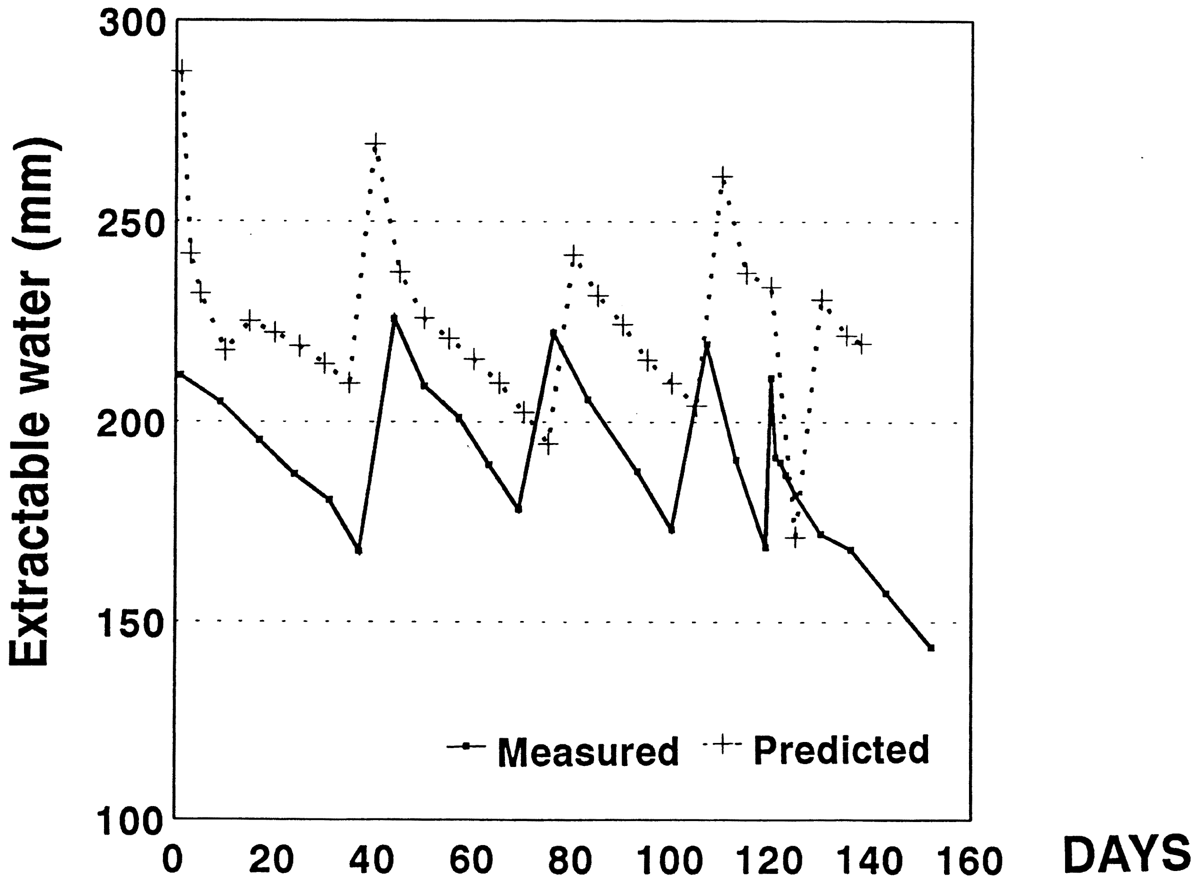

Fig. 8. Extractable soil water measured and predicted by CERES-wheat model during wheat growth season (1995–1996).

4. CONCLUSIONS

The results of four years of experimentation with irrigated wheat showed that the application of 50% more fertilizer N than that recommended in the region, i.e. 180 compared to 120 kg N ha^{-1}, increased grain yields by about 0.6 Mg ha^{-1}, which would economically beneficial to the, but would result in pollution of the environment by NO_3^-. Furthermore, the efficiency of uptake of fertilizer N under the best possible management conditions at the recommended level of 120 kg N ha^{-1} was only about 50% and under adverse weather conditions dropped significantly, as in the fourth year of experimentation (1997–98). In all seasons, the efficiency of uptake of 180 kg N ha^{-1} was approximately 10% less than that obtained with the recommended rate. There is a need to develop fertilizer-management practices that strike a balance between crop needs and supply to improve fertilizer-assimilation efficiency and, consequently, reduce environmental pollution.

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NITROGEN-USE EFFICIENCY OF IRRIGATED WHEAT

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Abstract

Field experiments with irrigated wheat were conducted from 1994 to 1998, using ^{15}N, with the objective of identifying appropriate ways of managing applied N to maximize economic profit, minimize N losses and avoid environmental pollution. Fertilizer application was partitioned with one third applied at sowing and two thirds added at Zadoks growth-stage 30 (Z-30), or two thirds at sowing and one third at Z-30, at total rates of 84, 167 and 250 kg N ha^{-1}. Urea and ammonium sulphate were compared as N-sources at sowing, whereas ammonium nitrate was used at Z-30. The optimum agronomic rate based on the average of the first two years was 178 kg N ha^{-1}. The economic optimum was 118 kg N ha^{-1}. The uptake of N from ammonium fertilizer was 20% higher than that from nitrate. Soil mineral N was relatively high at sowing and subsequent mineralization resulted in uptake of 90 kg N ha^{-1} from the zero-applied-N control plots. Soil-supplied N is, however, not considered when farmers decide on the rate of fertilizer to be applied, potentially resulting in high losses. Nitrogen-15 constituted a useful tool for understanding the relative contributions of soil and fertilizer to the N-nutrition of wheat.

1. INTRODUCTION

Humanity must live in harmony with the environment. One of the greatest challenges of the next century will be to meet the increasing food and fiber needs of the global population without degrading the limited resources of land and water. World food requirements will be determined by two factors: population growth and per capita food consumption. The United Nations Population Agency's medium projection estimates that 6 billion will be reached by the year 2000 and about 8 billion by 2025, before stabilizing at around 10 billion toward the end of the 21st century. Over 90% of the projected 4 billion additional people will reside in what are now low-income developing nations [1].

Even if the often inadequate per capita nutritional levels of 1990 were maintained, annual food production in 2025 would need to be 60% greater (7.4 Gt gross weight) than it was in 1990 (4.6 Gt). However, if dietary improvements are realized among the poor in low-income, food-deficient countries, annual world food demands by 2025 could be as great as 8.2 Gt, twice the 1990 production level.

The most immediate solution is the intensification of agricultural production on currently cultivated land through increased cropping intensity and/or higher yields per unit area. Increasing production of cereals is, therefore, strategically vital to ensure food self-sufficiency, to which end water and N-fertilizers are the most important inputs. There is a trend to allocate available resources to the most productive irrigated areas for greatest profit, which may lead to inefficient use of material inputs and, ultimately, cause environmental pollution through leaching and volatilization of nutrients, particularly N.

Nitrogen is commonly deficient in arable soils, and thus is a constraint to optimal crop production. It is the mineral element required in greatest quantity by crops and is the nutrient most often deficient. As a result of its critical role, often low supply, and high cost, efficient management of N is critical. There are two complementary approaches: (1) determining the best fertilizer-management practices, (i.e. application timing, placement and type of fertilizer), and (2) making use of genotypes that are efficient in nutrient uptake and utilization, (i.e. same yield with lower inputs).

Irrigation is available for about 40% of wheat production, with which efficiency of use of applied nutrients is often low. Nitrogen effects are generally the largest in intensively cropped areas, as in parts of Mexico. Efficiency of N use may be compromised, not only as a result of losses due to volatilization, and/or by denitrificaton, fixation, and leaching, but also because the N is taken up or utilized inefficiently by the plant. Poor uptake efficiency occurs when soil mineral-N levels are high or if the genotype, disease, water shortage or lodging limit the yield response. Commonly, delaying N application decreases losses without affecting total uptake, and alleviates situations that induce low utilization efficiency [2].

The objectives of this research program were:

— To increase production and productivity of irrigated wheat by improving N-use efficiency,
— To use ^{15}N to investigate efficiency of uptake of fertilizer N,
— To assess yield responses of wheat to splitting fertilizer rates, placement and sources of N,
— To calibrate equipment and methods for monitoring N-status of soil and plant,
— To use generated data to validate and refine various relationships in the CERES-Wheat simulation model.

2. MATERIALS AND METHODS

2.1. Site

The field experiments were conducted from October 1994 to June 1998, at the experimental station at Yaqui Valley, Sonora, Mexico (CIANO-CIMMYT), 27°N 109°W, 40 m altitude, on a coarse sandy clay soil, mixed montmorrillonitic typic calciorthid, low in organic matter, an alkaline pH in 1:2.5 0.01 *M* $CaCl_2$, and adequate K fertility. Table I shows physical and chemical soil properties from samples taken before fertilizer application; bulk density was determined in the bed to be 1.22 g cm^{-3}.

The location is classified as hot, desertic and semi-tropical, characterized by a hot summer, with highest temperatures 30 to 38°C after anthesis. The mean minimum temperature is 7°C and the mean maximum is 23°C. The average rainfall is about 250 mm, with approximately 80 mm during wheat growth. These conditions, according to CIMMYT, are representative of mega-environment 1 (ME 1). More than 40% of wheat production in developing countries occurs under ME-1 conditions [3].

2.2. Crop

The following rotations were used: 1994–95, soybean/spring wheat; 1995–96, maize/spring wheat; 1996–97, cotton/spring wheat; 1997–98, safflower/spring wheat. Bread-type spring wheat, *Triticum aestivum* cv. Rayon F-89, was sown around 30 November of each year and harvested around 10 June. Seeding rate was between 60 to 80 kg ha^{-1} on 80-cm beds with two rows spaced 30 cm, with a north-south orientation.

2.3. Basal inputs

Triple superphosphate, at 60 kg P_2O_5 ha^{-1}, was banded with the N fertilizer. Five irrigations were applied between 12 November and 31 March, to bring 60 cm of the soil profile to field capacity.

TABLE I. EXPERIMENTAL SITE CHEMICAL AND PHYSICAL PROPERTIES

Soil Depth cm	pH 1:2 H_2O	pH 1:2.5 $CaCl_2$ 0.01M	O.M. %	TN-Kj %	P-Bray ppm	P-Olsen ppm	K ppm	Ca ppm	Mg ppm	Na pm
0–15	8.45	7.80	1.00	0.05	17.38	4.78	449	4822	409	471
15–30	8.55	7.83	0.57	0.05	10.89	10.89	340	4900	459	458
30–60	8.38	7.87	0.40	0.04	0.40	8.61	219	5489	413	1391
60–90	8.13	7.85	0.26	0.03	0.26	7.58	229	8348	376	2105

Soil Depth cm	E.C. mmho.cm^{-1}	F.C. 1/3 Bar % Moisture	P.W.P. 15 Bar % Moisture	Clay %	Silt %	Sand %	Texture
0–15	0.85	38.08	21.07	40.67	22.23	37.10	Clay
15–30	1.68	38.11	21.74	40.18	23.32	36.50	Clay
30–60	2.83	39.69	21.59	43.58	24.83	31.59	Clay
60–90	2.85	37.68	21.05	41.06	29.73	59.21	Clay

2.4. Treatments

The experiments had a randomized complete block design with three replications each with a plot size of 8 × 6 m (divided longitudinally into two halves for yield and sampling). The urea treatments in 1994–95 were: N_0 unfertilized check, N_1 84 kg N ha $^{-1}$, N_2 167 kg N ha^{-1} and N_3 250 kg N ha^{-1}. There were two isotope sub-plots (1.5 × 1.5 m) in each treatment. The first installment, one third, of the isotope was applied in one micro-plot at the time of sowing. Later, the remaining two thirds was applied with unenriched urea. In the other micro-plot, the first one third was applied as unenriched urea at the time of sowing, and the remaining two thirds was applied with ^{15}N enriched urea (10% a.e.) immediately before jointing, i.e. at Zadoks growth stage 30 (Z-30).

On the basis of the results of the first 2 years, in 1996–97 treatment N_2, 84 kg N ha^{-1}, was eliminated to look in more detail at the split applications. The treatment design for the experiments for 1994–95 to 1997–98 are shown in Table II. During the 1997–98 season, two sources of N, urea and ammonium sulphate, were applied at sowing, and ammonium nitrate was applied at Z-30. All were enriched ^{15}N at 10% a.e. (Table II and III).

2.5. Sampling

From sowing to harvest, plant and soil samples were collected at important stages of development (sowing, Z-30, anthesis and harvesting). The soil was sampled by taking three cores, 2 cm diameter, randomly from each plot, at four depths: 0 to 15, 16 to 30, 31 to 60 and 61 to 90 cm, for the physical-chemical characterization of the profile. Additional samples were taken from each micro-plot, at 0 to 15 and 16 to 30 cm, to assay total N and ^{15}N enrichment.

TABLE II. NITROGEN APPLIED LEVELS AND DESIGN OF ^{15}N LABELED FERTILIZER APPLICATION*

		Kg N ha^{-1}			
Code	Description	1994/95	1995/96	1996/97	1997/98
N 0.0	Control	0	0	0	0
N 0.5	Below optimum rate	84	84	-	-
N 1.0	Optimum rate	167	167	167	167
N 1.5	50% above the optimum rate	250	250	250	-

Design of ^{15}N labeled fertilizers application

Code	Splitting at sowing, DC30	1994/95 and 1995/96 Microplots	1996/97 Microplots
	1/3, 2/3	M1 (1/3*-2/3)	- - -
N 0.5		M2 (1/3 -2/3*)	
84 kg/ha	2/3, 1/3	M1 (2/3*-1/3)	
		M2 (2/3-1/3*)	
	1/3, 2/3	M1 (1/3*-2/3)	M1 (1/3*-2/3)
N1.0		M2 (1/3 -2/3*)	M2 (1/3 -2/3*)
167 kg/ha	2/3, 1/3	M1 (2/3*-1/3)	M1 (2/3*-1/3)
		M2 (2/3-1/3*)	M2 (2/3-1/3*)
			3/3* at sowing
	1/3, 2/3	M1 (1/3*-2/3)	M1 (1/3*-2/3)
N 1.5		M2 (1/3 -2/3*)	M2 (1/3 -2/3*)
250 kg/ha	2/3, 1/3	M1 (2/3*-1/3)	M1 (2/3*-1/3)
		M2 (2/3-1/3*)	M2 (2/3-1/3*)
			3/3* at sowing

TABLE III. DESIGN OF ^{15}N LABELED FERTILIZERS APPLICATION* WITH THE OPTIMUM RATE, 167 KGN HA^{-1} (1997/98)

Treatments :			
Fertilizers and timing of application:			
at sowing	at DC 30	Splitting	Microplots
UREA	NO_3-NH_4	1/3, 2/3	M1 (1/3U* - 2/3 NO_3-NH_4)
			M2 (1/3U - 2/3 NO_3*-NH_4)
			M3 (1/3U- 2/3 NO_3-NH_4*)
		2/3, 1/3	M1 (2/3U* - 1/3 NO_3-NH_4)
			M2 (2/3U - 1/3 NO_3*-NH_4)
			M3 (2/3U - 1/3 NO_3-NH_4*)
Ammonium	NO_3-NH_4	1/3, 2/3	M1 (1/3 A.S* - 2/3 NO_3-NH_4)
Sulfate (AS)			M2 (1/3 A.S. - 2/3 NO_3*-NH_4)
			M3 (1/3 A.S.- 2/3 NO_3-NH_4*)
		2/3, 1/3	M1 (2/3 A.S.* -1/3 NO_3-NH_4)
			M2 (2/3 A.S.- 1/3 NO_3*-NH_4)
			M3 (2/3 A.S.- 1/3 NO_3-NH_4*)

Plant samples were dried (70°C) weighed, and milled. Nitrogen concentrations of plant and soil samples were determined by the Kjeldahl distillation method. The $^{15}N/^{14}N$ ratios in grain, straw and soil were assayed by mass spectrometry at the IAEA Laboratory, Seibersdorf, Austria.

Percent N derived from fertilizer (Ndff) and from soil (Ndfs), fertilizer-N uptake and N utilization were calculated from ^{15}N-enrichment data [4].

Light interception was measured using a Decagon ceptometer, which was held first above the canopy on each plot and then four measurements were taken at ground level within the canopy by placement diagonally from the top of one bed to the top of that adjacent.

Leaf chlorophyll readings were made with a Minolta SPAD meter at Z-30, booting and anthesis.

2.6 Yield

Grain and straw yields were collected from two randomly chosen areas (2 m^2) on each large plot.

Plant height, spikes per m^2, spike length, grains per spike and 1,000-grain weight were recorded using standard procedures. The significance of differences between average values were determined by analysis of variance (ANOVA) using the Student-Newman-Keuls test.

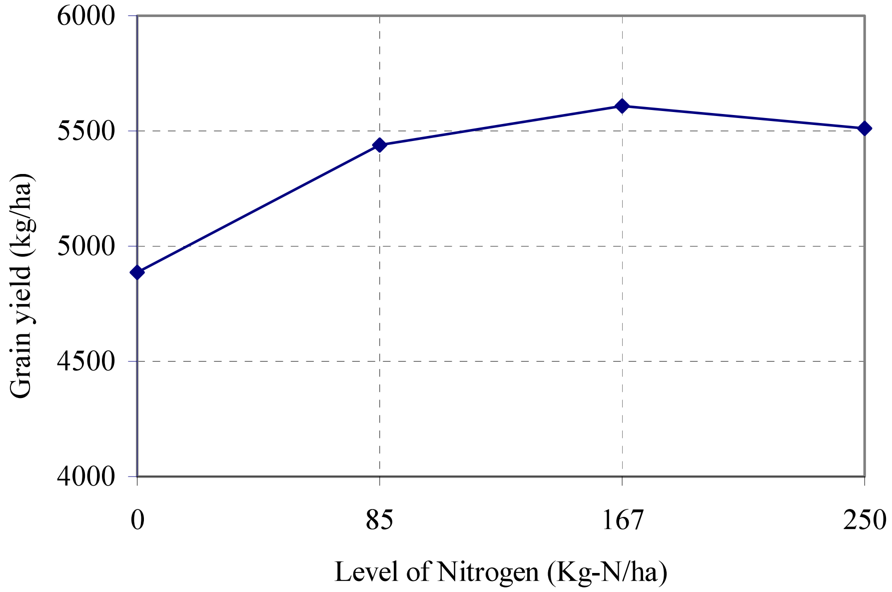

FIG. 1. Grain yield response of spring wheat cultivar Rayon at four levels of N fertilization.

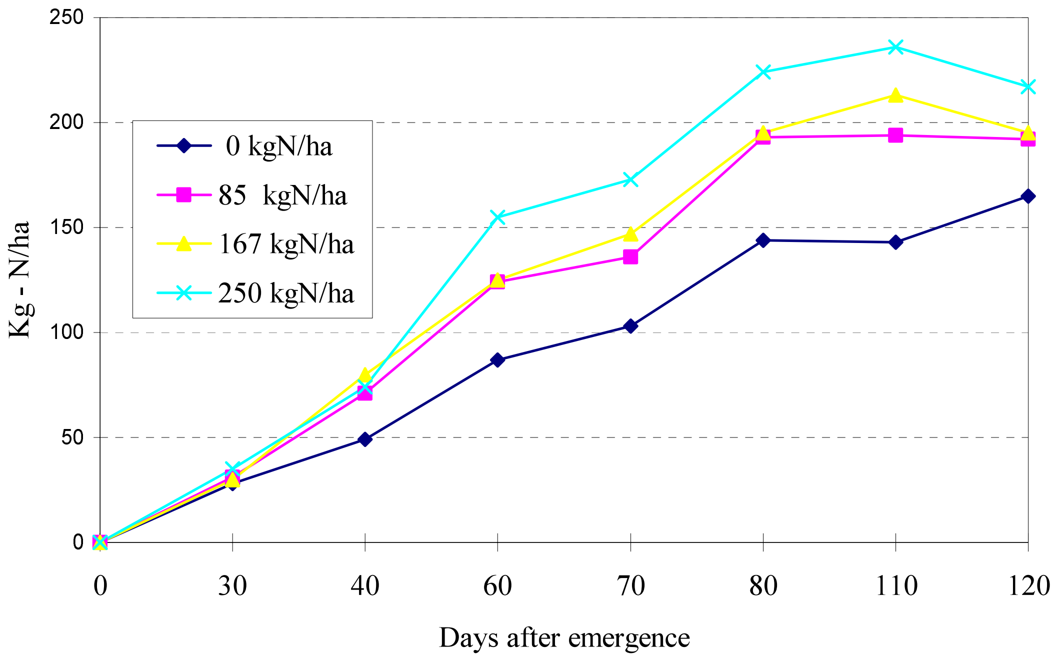

FIG. 2. Above ground biomass accumulation of spring wheat during the growing season under four levels of N fertilization.

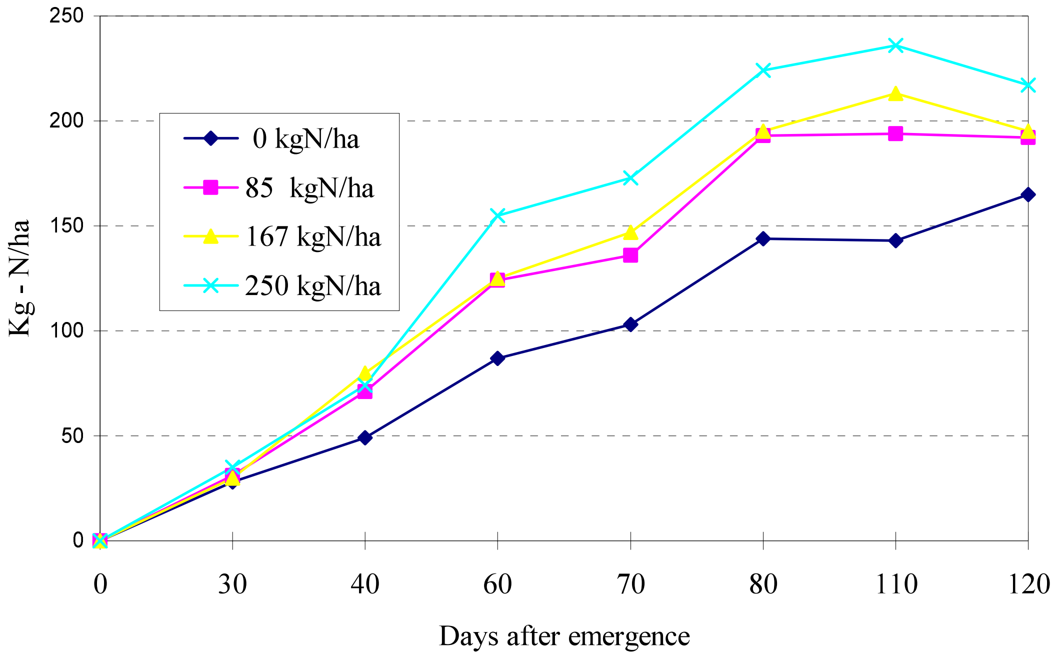

FIG. 3. Nitrogen above ground biomass (kg N/ha).

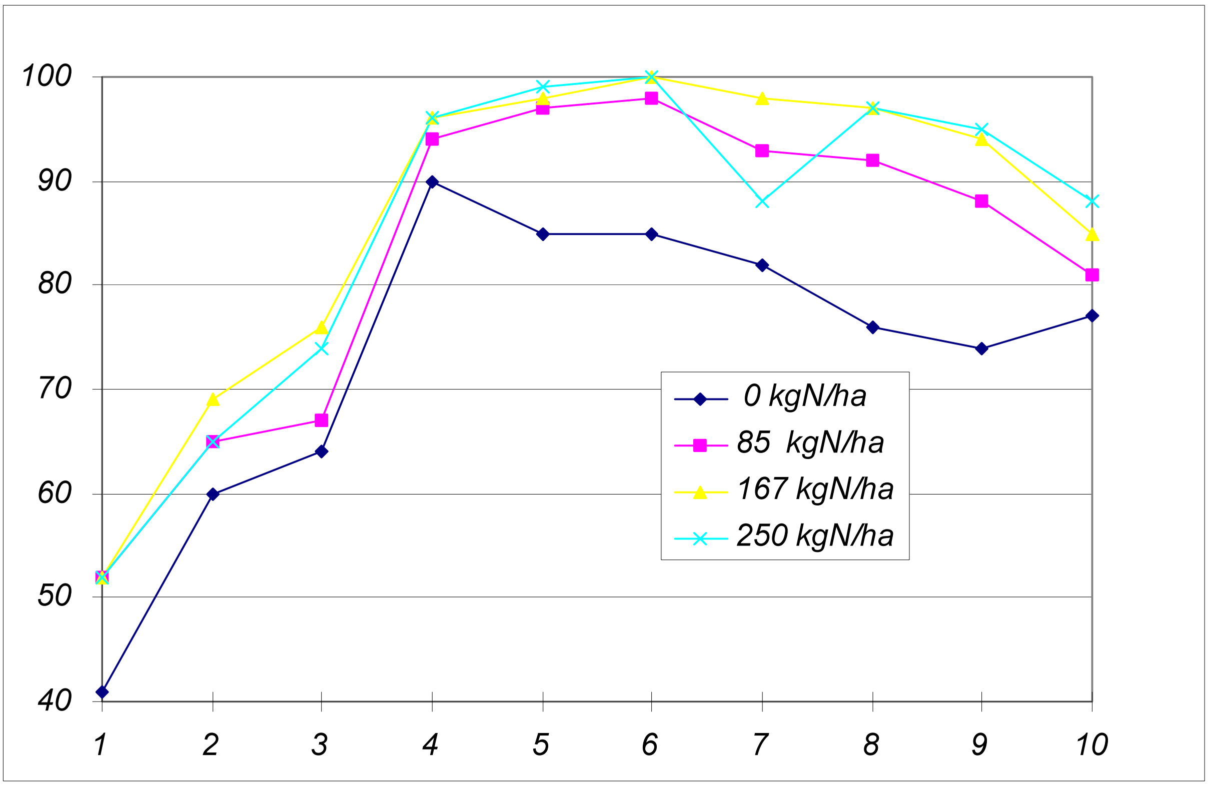

FIG. 4. Light interception (%) measurements made from emergence to harvest maturity.

TABLE IV. CORRELATION BETWEEN LEAF CHLOROPHYLL, GRAIN YIELD AND TISSUE NITROGEN MEASUREMENT AT THREE GROWTH STAGE (ZADOK´S 30, 45 AND 69), DURING THE SECOND SEASON 1995/96

Growth stage: (Zadok's)	SPAD units with:	R^2
30	Grain yield	0.4 n.s.
	Tissue (N%)	0.52 **
45	Grain yield	0.87 **
	Tissue (N%)	0.44**
69	Grain yield	0.75 **
	Tissue (N%)	0.41 **

TABLE V. MEASURED VALUES OF NDFF AND NUE IN THE ^{15}N TREATMENTS

Microplot	**Treatment code, kgN/ha**		**N content kg**	**Total-N (%)**	**NDFF (%)**	**NUE (%)**
	N 0.5, 84	Grain	2.23	93.00	8.07	8.94
	1/3	Straw	0.78	61.69	28.21	20.71
		total	1.30	154.69	16.10	29.65
	N1.0, 167	Grain	2.28	80.53	16.66	8.03
M1	1/3	Straw	0.80	51.44	51.25	15.78
		total	1.30	131.97	30.14	23.82
	N1.5, 250	Grain	2.35	99.79	20.72	8.27
	1/3	Straw	0.88	68.28	58.86	16.08
		total	1.39	168.07	36.22	24.35
	N 0.5, 84	Grain	2.15	89.87	14.88	13.37
	2/3	Straw	0.75	57.83	19.47	11.26
		total	1.16	147.70	16.68	24.63
	N1.0, 167	Grain	2.25	79.47	27.33	21.72
M2	2/3	Straw	0.95	63.05	49.16	30.99
		total	1.11	142.52	36.08	52.71
	N1.5, 250	Grain	2.35	99.48	24.04	23.91
	2/3	Straw	0.82	63.61	69.02	43.49
		total	1.26	163.09	41.33	67.40

TABLE VI. FERTILIZER N UTILIZATION OF WHEAT C.V. RAYON F-89

Treatment Code, Kg N/ha	Grain yield kg/ha	TDM (kg/ha)	N yield (KgN/ha)	FN yield (kgN/ha)	N.U.E. (%)
N 0.5, 84 1/3*	4180	11891	154.69	24.91	29.65
N 0.5, 84 2/3**	4584	12740	147.70	24.63	29.37
N 0.5, 84, TOTAL				**49.54**	**58.97**
N 1.0, 167 1/3*	3536	10173	131.97	39.78	23.82
N 1.0, 167 2/3**	4584	12871	142.52	62.71	31.56
N 1.0, 167, TOTAL				**92.49**	**55.38**
N 1.5, 250 1/3*	4242	12023	168.07	60.87	24.35
N 1.5, 250 2/3**	4891	12992	163.09	67.40	26.96
N 1.5, 250, TOTAL				**128.27**	**51.31**

TABLE VII. DISTINCT CRITERIA TO CONSIDER THE EFFICIENCY DERIVED FROM THE APPLIED N FERTILIZER

Treatment Code, kg N/ha	Agronomic Efficiency	Ecophysiological Efficiency	Physiological Efficiency	Nitrogen Use Efficiency (NUE %)
N 1.0, 167 total (3/3)	29.60	1.06	58.55	87.90
N 1.0, 167 2/3, 1/3	34.99	1.11	108.42	45.22
N 1.0, 167 1/3, 2/3	36.36	1.14	120.31	54.56
N 1.5, 250 total (3/3)	18.31	0.67	61.50	53.22
N 1.5, 250 2/3, 1/3	20.48	0.70	100.26	37.98
N 1.5, 250 1/3, 2/3	22.17	0.73	114.19	35.68

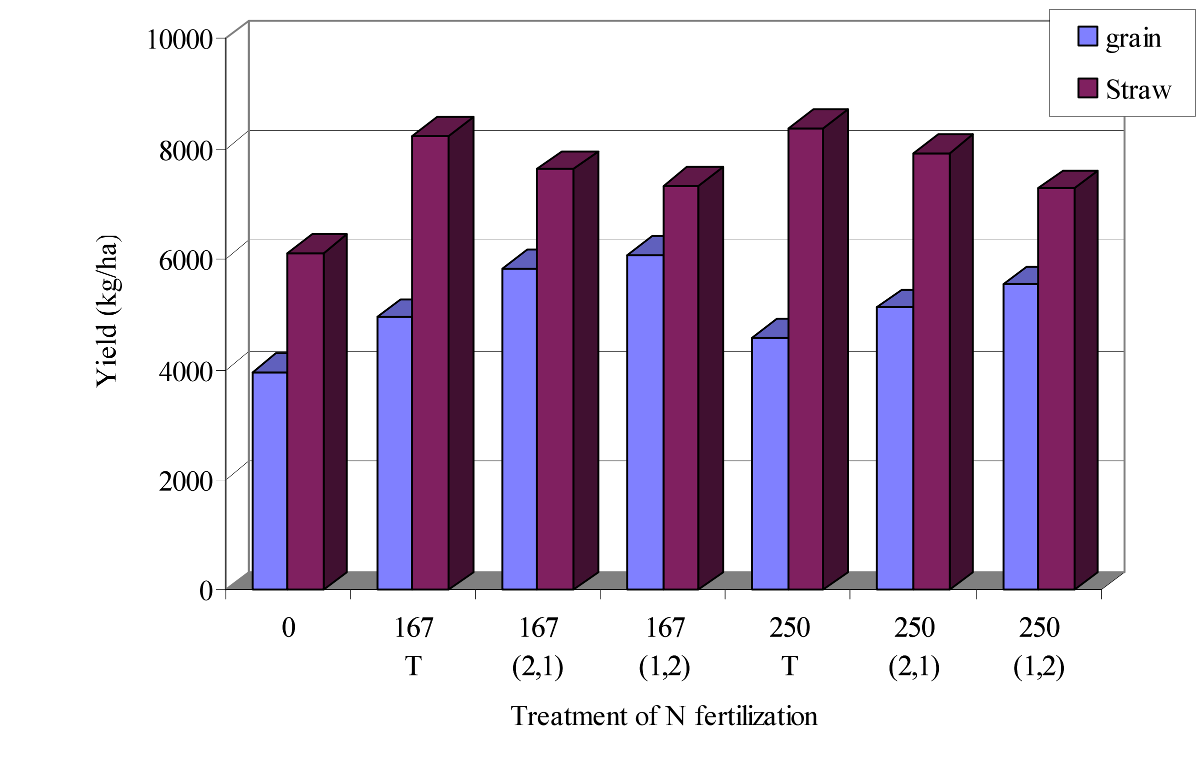

FIG. 5. Grain and straw yield response of spring wheat c.v. Rayon under irrigation at three levels of N fertilization and splitting.

3. RESULTS

3.1. 1994–95 and 1995–96

There was a quadratic interaction between N rate and grain yield. (Fig. 1). During the first season, 1994–95, grain yield without N was relatively high (85% of the maximum yield) indicating abundant residual N in the soil after the soybean crop, possibly related to the poor growth of the legume; its yield was only 1 t ha^{-1} due to white fly (*Bemisia argentifoli*), whereas it is usually approximately 2.5 t ha^{-1}. (This infestation, in the summer of 1993, was the first on soybean in the Yaqui Valley, and resistant cultivars and chemical control were unavailable.) The high level of initial soil N precluded strong yield responses to applied N.

The effects of fertilizer N were highly significant during the 1995–96 season, when wheat was grown after unfertilized maize. During the first 2 years, a quadratic response to N was observed (Fig. 1). The optimum agronomic rate was 178 kg N ha^{-1} and the optimum economic rate, using a price ratio of 2.77, was 118 kg N ha^{-1}.

Nitrogen-treatment differences developed during the post-anthesis period. The lower biomass in the unfertilized check was associated with less light interception and lower chlorophyll content in the upper leaves resulting in lower radiation-use efficiency (Fig. 2). The unfertilized check had the lowest values for light interception; maximum light-interception occurred in all treatments by anthesis (Fig. 3).

Leaf chlorophyll meter readings ranged from 30 to 45 SPAD units (Fig. 4) and the values increased with growth stage. Meter readings taken at Z-30 were not affected by N, however, this changed between booting and anthesis. In consequence, at these growth stages the instrument was effective as means of revealing N deficiency (<33 SPAD units). It is suggested that 43 SPAD units is

TABLE VIII. MEASUREMENTS OF NDFF AND NUE IN THE ^{15}N TREATMENTS

Microplot	Treatment code, kg N/ha		N content (%)	N yield (kg/ha)	NDDF %	F N yield KgN/ha	NUE (%)
M1	N 1.0	Grain	2.38	117.71	71.76	84.47	50.58
	167	Straw	0.82	67.27	92.68	62.34	37.32
	total (3/3)	Biomass	1.41	184.98	79.36	146.81	87.90
	N 1.0, 167	Grain	2.26	131.62	49.34	64.94	38.88
	2/3, 1/3	Straw	0.72	55.24	51.39	28.39	17.00
		Biomass	1.38	186.66	49.95	93.33	55.88
	N 1.0, 167	Grain	2.28	139.22	36.80	51.23	30.68
	1/3, 2/3	Straw	0.68	49.63	47.06	23.36	13.99
		Biomass	1.30	174.25	42.81	74.59	44.67
M2	N 1.5, 250	Grain	2.31	106.24	70.39	74.28	29.91
	total (3/3)	Straw	0.78	62.44	73.33	58.28	23.31
		Biomass	1.31	168.68	78.88	133.06	53.22
	N 1.5, 250	Grain	2.29	117.57	56.68	66.64	26.66
	2/3, 1/3	Straw	0.74	58.82	81.08	47.69	19.08
		Biomass	1.35	176.39	64.82	114.33	45.74
	N 1.5, 250	Grain	2.30	128.46	26.72	34.33	13.73
	1/3, 2/3	Straw	0.79	53.77	35.14	18.89	7.56
		Biomass	1.42	182.23	29.20	53.22	21.29
	Control	Grain	2.12	83.66	0.71	0.59	0.00
	N-0	Straw	0.42	25.66	3.33	0.86	0.00
		Biomass	0.92	109.31	1.32	1.45	0.00

critical at booting: readings above that value indicate excessive application of N. The correlation between chlorophyll-meter reading and yield was stronger than that with shoot %N. The poor correlation with foliar N may be explained by the fact that the readings were taken from the uppermost expanded leaves whereas shoot %N was determined from whole-plant samples (Table IV) [5].

Grain yield, N content in grain and Ndff increased with applied N (Table V). However, N-uptake efficiency decreased as applied N increased, 59, 55 and 51%, for N_1, N_2, and N_3, respectively (Table VI).

Experimental data from CIANO-CIMMYT indicates that, in the Yaqui Valley, the economical optimum N-rate on wheat is around 167 kg N ha^{-1}.

TABLE IX. NITROGEN DERIVED FROM SOIL SEASON 1996/97

MICROPLOT 1				MICROPLOT 2			
Treatment code, Kg N/ha		%	KgN/ha	Treatment code, Kg N/ha		%	KgN/ ha
N 1.0, 167	Grain	28.24	33.24	N 1.0, 167	Grain	N.D.	N.D.
total (3/3*)	Straw	7.32	4.92	total (3/3*)	Straw	N.D.	N.D.
	Biomass	20.64	38.16		Biomass	N.D.	N.D.
N 1.0, 167	Grain	50.66	66.68	N 1.0, 167	Grain	71.47	38.80
(2/3*, 1/3)	Straw	48.61	26.85	(2/3*, 1/3)	Straw	64.14	18.91
	Biomass	50.05	93.53		Biomass	69.42	57.71
N 1.0, 167	Grain	63.20	87.98	N 1.0, 167	Grain	55.48	61.82
(1/3*, 2/3)	Straw	52.94	26.27	(1/3*, 2/3)	Straw	9.77	41.33
	Biomass	57.19	114.25		Biomass	43.24	103.15
N 1.5, 250	Grain	29.01	31.46	N 1.5, 167	Grain	N.D.	N.D.
total (3/3*)	Straw	6.67	4.16	total (3/3*)	Straw	N.D.	N.D.
	Biomass	21.12	35.62		Biomass	N.D.	N.D.
N 1.5, 250	Grain	43.32	50.93	N 1.5, 167	Grain	64.47	41.34
(2/3*, 1/3)	Straw	18.92	11.13	(2/3*, 1/3)	Straw	39.86	34.23
	Biomass	35.18	62.06		Biomass	53.39	75.57
N 1.5, 250	Grain	73.28	94.14	N 1.5, 167	Grain	34.70	83.32
(1/3*, 2/3)	Straw	64.86	34.88	(1/3*, 2/3)	Straw	4.23	2.19
	Biomass	70.80	129.02		Biomass	25.90	85.51

Total N content from soil for all treatments = 0.06%

3.2. 1996–97

3.2.1. Yield

Yield and yield-contributing characters of wheat varied significantly with applied N. Significant variations were recorded for length of spike, number of spikes per m^2, number of grains per spike, and, hence, number of grains per m^2 (Table VII). Plant height, number of plants per m^2 and 1000-grain weight showed no significant variation.

The grain-yield response to N produced a better quadratic than linear fit (Fig. 4). Grain yield without N was relatively high (65% of the maximum), again indicating large amounts of residual N before the wheat crop. For the fertilized treatments, the highest yield was recorded with 167 kg N ha^{-1} with one third applied at sowing and the remainder close to Z-30; the lowest yield was obtained with 250 kg N ha^{-1} applied in total at sowing.

Straw yields increased linearly with N rate applied at sowing (Fig. 5). The biomass accumulation during the growing season was similar in all fertilized treatments and lower in the unfertilized treatment.

TABLE X. YIELD TOTAL-N AND N CONTENT, SEASON 1997/98

Treatment	Microplot			N %	Total-N kg ha^{-1}	Yield t ha^{-1}
Urea applied at sowing						
			Grain	1.82	73.16	4.02
T1	M1	N=0	Straw	0.27	16.42	6.08
			Total	2.09	89.58	10.10
	M1	Urea-^{15}N	Grain	2.82	211.50	7.50
		at sowing	Straw	0.53	39.06	7.37
			Total	1.69	250.56	14.87
T2			Grain	2.79	215.67	7.73
167 kg N ha^{-1}	M2	$NH_4N^*O_3$	Straw	0.48	35.52	7.40
(1/3–2/3)			Total	1.66	251.19	15.13
			Grain	2.68	207.16	7.73
	M3	$N^*H_4NO_3$	Straw	0.54	39.42	7.30
			Total	1.64	246.58	15.03
			Grain	2.64	184.01	6.97
	M1	Urea-^{15}N	Straw	0.54	44.98	8.33
		at sowing	Total	1.50	238.99	15.30
T3			Grain	2.65	183.65	6.93
167 kg N ha^{-1}	M2	$NH_4N^*O_3$	Straw	0.53	43.99	8.30
(2/3– 1/3)			Total	1.49	227.64	15.23
			Grain	2.65	185.50	7.00
	M3	$N^*H_4NO_3$	Straw	0.52	43.68	8.40
			Total	1.49	229.18	15.40
Ammonium sulphate applied at sowing						
	M1	A.S.-^{15}N	Grain	2.57	198.66	7.73
		at sowing	Straw	0.45	33.30	7.40
			Total	1.53	231.96	15.13
T4	M2	$NH_4N^*O_3$	Grain	2.52	196.56	7.80
167 kg N ha^{-1}			Straw	0.46	33.58	7.30
(1/3–2/3)			Total	1.52	230.14	15.10
	M3	$N^*H_4NO_3$	Grain	2.61	199.14	7.63
			Straw	0.45	33.75	7.50
			Total	1.54	232.89	15.13
	M1	A.S.-^{15}N	Grain	2.52	173.12	6.87
		at sowing	Straw	0.44	36.21	8.23
			Total	1.39	209.33	15.10
T5	M2	$NH_4N^*O_3$	Grain	2.51	171.43	6.83
167 kg N ha^{-1}			Straw	0.44	36.43	8.28
(2/3–1/3)			Total	1.38	207.86	15.11
	M3	$N^*H_4NO_3$	Grain	2.53	174.57	6.90
			Straw	0.44	36.52	8.30
			Total	1.39	211.09	15.20

TABLE XI. MEASUREMENTS OF RECOVERY FERTILIZER RATE (RFR, %) AND NITROGEN DERIVED FROM SOIL (NFS, %) IN THE TREATMENTS OF THE 1997/98 SEASON

TREATMENT	RFR (%)	NDFS (%)
167 kg N ha^{-1} (1/3 + 2/3)		
Urea at sowing — $NH_4N^*O_3$	23.38	76.72
Urea at sowing — $N^*H_4NO_3$	52.26	47.73
167 kg N ha^{-1} (2/3 + 1/3)		
Urea at sowing — $NH_4N^*O_3$	44.24	55.76
Urea at sowing — $N^*H_4NO_3$	56.83	47.73
167 kg N ha^{-1} (1/3 + 2/3)		
Am. Sulphate at sowing — $NH_4N^*O_3$	24.57	75.43
Am. Sulphate at sowing — $N^*H_4NO_3$	63.40	36.59
167 kg N ha^{-1} (2/3 + 1/3)		
Am. Sulphate at sowing — $NH_4N^*O_3$	42.12	57.88
Am. Sulphate at sowing — $N^*H_4NO_3$	66.33	37.67

* Enriched fertilizer 3.5% a.e.

3.2.2. Efficiencies

Table VII shows criteria to consider effects from applied N fertilizer. Applying the total amount at the time of sowing produced the highest N-use efficiencies values, but had the lowest grain yield, agronomic, ecophysological and physiological efficiencies.

With 167 kg N ha^{-1}, split one third at sowing and two thirds at Z-30 resulted in higher yield N-use efficiency as compared to splitting two thirds at sowing and one third at Z-30.

The high N rate (N_3, 250 kg N ha^{-1}) resulted in lower values of the parameters above mentioned, but increased the amount of residual N when it was applied in total at sowing.

3.2.3. Nitrogen from soil

Nitrogen derived from soil was important for all split treatments, but less so when N was applied only at sowing. Although the available soil N was the same for all treatments, Ndfs increased with the applied N level. This finding may be attributed to a positive influence of N on root development resulting in exploitation of a greater volume of soil (Table IX), known as the priming effect or added-N interaction [6, 7, 8].

3.3. 1997–98

Weather conditions were exceptionally favorable, resulting in production of 7.30 t ha^{-1} and uptake of 167 kg N ha^{-1}. The harvest index (HI) was 0.46. The unfertilized check yielded only 4.02 t ha^{-1} grain with a HI of 0.60 and an uptake of 90 kg N ha^{-1}. The splitting of N, one third plus two thirds was better than two thirds plus one third with ammonium sulphate or urea. The 167 kg N ha^{-1} treatment, one third as urea at sowing and two thirds as ammonium nitrate at Z-30 resulted in 17% more N-yield than when applied two thirds as ammonium sulfate at sowing and one third as ammonium nitrate at Z-30. The comparison of $^{15}NH_4NO_3$ and $NH_4{}^{15}NO_3$ revealed that NH_4^+-N was used more efficiently than NO_3^--N, with twice more in grain than in straw (Tables X and XI).

4. CONCLUSIONS

(1) Nitrogen level had a significant positive effects on yield:
– The optimum agronomic rate was 178 kg N ha^{-1};
– The optimum economic rate was 118 kg N ha^{-1}.

(2) The chlorophyll meter was an effective indicator of N deficiency or excess.

(3) The splitting of applied N improved agronomic, ecophysiological and ecological efficiency values. One third at sowing and two thirds at Z-30 was more efficient than two thirds at sowing and one third at Z-30.

(4) The lower the N rate applied at sowing the higher was the N derived from soil.

(5) Nitrogen-use efficiency decreased as the N-rate increased.

(6) There was no significant difference between urea and ammonium sulfate applied at sowing.

(7) Ammonium-N in the soil was more efficiently used than NO_3^--N.

(8) The amount of residual soil N should be taken into account when deciding the N rate to avoid the application of excessive rates of N, and consequently reduce environmental pollution.

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INCREASING NITROGEN-USE EFFICIENCY BY WHEAT IN VOLCANIC ASH SOILS

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Abstract

Timing of application and type of N fertilizer, irrigation and interactions with S, genotypes and rotational effects were studied and progress made in selecting conditions for increasing fertilizer-N efficiency with wheat. Results indicated that residue incorporation in the rotation, optimum irrigation (>170 mm), three split applications of N and nutritional-problem correction (acidification and sulfur deficiency), promoted wheat yields and fertilizer-N efficiency. Applied-N recoveries were only about 50%. However, grain yields of 6 to 8 t ha^{-1} were achieved when the soil was managed appropriately. The chlorophyll meter may be useful to define wheat N requirement if used in conjuction with well fertilized reference strips within the same field.

1. INTRODUCTION

Chile's importation of fertilizer has doubled in the past decade, and concomitant expenditure has tripled. Approximately 60% are N fertilizers, the cost of which is less than nationally produced sodium nitrate.

The average yieldd of wheat has increased from 3 to 4 t ha^{-1} over the past 7 years, However, during that period, the sale price diminished 25%, which means less profitability for farmers.

Chile has 5.4 Mha of arable land, of which 50 to 60% are volcanic ash soils [1]. Annually, wheat is sown on approximately 0.4 Mha, 80% of which are on volcanic ash soils, which are characteristically deep, with high organic matter content, low bulk density, good drainage and high water-retention capacity. Compared with other soils, they generally require more N to produce similar amounts of available N. The causes of organic matter stabilization are complex and yet to be fully elucidated, however, allofane plays a role [2]. Nitrogen losses can be considerable and poor use efficiency may be exacerbated by volatilization, denitrification and leaching, or because N is not utilized efficiently or not taken up by the wheat. The latter condition can arise if soil mineral N is abundant or if genotype, disease, water shortage or lodging limit yield response. In many situations, delaying N application can lessen N losses without reducing uptake, and thus foster high efficiency of use of fertilizer N.

It is, therefore, fundamentally important to manage fertilizer N efficiently in these soils. In this work, timing, type of fertilizer, irrigation, interaction with S, genotypes and rotational effects were studied with the objective of elucidating conditions for increasing fertilizer-use efficiency of wheat in Chilean volcanic ash soil.

2. MATERIALS AND METHODS

2.1. Experiment 1, N × irrigation interaction

Spring wheat (*Triticum aestivum* L.)was grown on a San Carlos soil for the 1995–96 growing season. The experiment was conducted at the Irrigation Experiment Station of the Universidad de Concepción, near the city of San Carlos, 36°21'S 71°55'W. The previous crop was common bean (*Phaseolus vulgaris* L.); P and K fertilizers were applied at optimum rates.

A line-source sprinkler system was used to establish a gradient of increasing drought delineated by distances 0 to 5, 5 to 10 and 10 to 15 m from the sprinkler line. Irrigation water was measured in catch cans placed along an axis perpendicular to the sprinkler line at intervals of 2 m. Total irrigation water applied (Y, mm) decreased with distance from the line-source (X, m) according to the relationship:

$$Y = 220.5 + 1.82X - 0.85X^2 \qquad (r^2 = 0.995)$$

There were four irrigations between 18 October and 8 December. The total applied by block ranged from 57 to 221 mm at distances of 15 to 1 m from the line-source, respectively. Plots were placed at right angles to the line-source with four fertilizer-N levels applied (0, 75, 150 and 225 kg N ha^{-1} as urea). The N-level factor was arranged within each water level as a split-plot design. Each plot was 5×15 m. All treatments were replicated four times. Nitrogen rate was split in two applications: one third at planting and two thirds at Zadoks growth stage 30 (GS-30, end of tillering). Within each fertilized treatment micro-plots of five 1.2-m rows were installed (Table III) with ^{15}N-enriched urea (2.9% a.e.) applied at the same dosages as in the main plot.

TABLE I. FERTILIZER TREATMENTS

N rate (kg N/ha)	Planting	Second Application
0	-	-
75	1/3	2/3
150	1/3*	2/3
	1/3	2/3*
225	1/3*	2/3

* ^{15}N fertilizer was applied to these plots

TABLE II. TIME OF APPLICATION TREATMENTS

Treatment	N Treatment (kg N/ha)			
	Zadoks 00 (Planting)	Zadoks 30 (1st node detectable)	Zadoks 37 (Flag leaf just visible)	Zadoks 55 (1/2 of inflorescence emerged)
1.- (0)	0	0	0	0
2.- (150)	150	0	0	0
3.- (75/75)	75	75	0	0
4.- (50/50/50)	50	50	50	0
5.- (37/37/37/37)	37.5	37.5	37.5	37.5
6.- (15/37/60/37)	15	37.5	60	37.5

TABLE III. GENOTYPES USED IN THE EXPERIMENT

1.-SNA 208	9.- SAETA	17.- QU-P-1772-91
2.-CIKO	10.- PEUMO	18.- QU-P-1867-91
3.- CHACAY	11.- MAQUI	19.- QU-P-2211-89
4.- CANELO	12.- FAMA	20.- L-5755-82
5.- COYAN	13.- COLONO	21.- L-5761-256
6.- HUAYUN	14.- TS-506	22.- L-9004-18
7.- NOBO	15.- V-28	23.- L-9101-7
8.- DOMO	16.- QU-P-1751-91	24.- 9112 -2473

2.2. Experiment 2, timing of N

The soil was a Typic Hapludand of the Diguillin series. The trial was planted at the Quilamapu Experiment Station, INIA, 36º32'S 71º55'W, altitude 217 m. A randomized complete-block design was used, with six timing treatments and four replicates. Nitrogen fertilizer was applied at 150 kg N ha^{-1}, with basal optimum P and K applied. Plot size was 3 × 5 m with 20 cm between rows for yield components. The plots were labelled by applying urea enriched in ^{15}N at 1.264% a.e to seven 1-m rows. Cultivar Candela was planted and irrigation was supplied on October 26, November 13 and November 29.

2.3. Experiment 3, genotype

Twenty-four genotypes were examined in a trial that was run at the Universidad de Concepción Experiment Station, 36º34'S 72º10'W, altitude 144 m. The soil was a Typic Hapludand, of the Diguillín series. A randomized complete-block design was used with four replicates. Nitrogen was applied at 160 kg ha^{-1}, as were optimum levels of P and K, basally. The planting date was August 12, and N fertilizer application was on September 28. Each plot had five 3-m rows spaced at 20 cm for yield determination. One row per genotype was labelled with urea at 1.164% a.e ^{15}N.

2.4. Experiment 4, effects of N and S

The trial was on a Santa Barbara silt loam (Typic Fulvudand) of the following characteristics: pH 5,5; NO_3^--N, 9 mg L^{-1}; P Olsen, 13 mg L^{-1}; organic matter, 11%; K, 0.17 cmol kg^{-1}; Al 0.12 cmol kg^{-1} and a range of extractable SO_4^{2-}-S in the 90-cm profile from 7 to 13 mg L^{-1} (extracted with $CaHPO_4$).

Three N levels, 80, 160, 240 kg N ha^{-1} as urea, and three S levels, 0, 20 40 kg S as gypsum, had a factorial arrangement and were broadcast after plowing (GS-30). The experimental design was a randomized block with four replications.

Plots were 6×20 m and were sown under no-till management and fertilized with 150 kg P_2O_5 ha^{-1} and 150 kg K_2O ha^{-1}. Microplots (1 m^2) were fertilized with urea enriched in ^{15}N at 2.7 % a.e.

2.5. Experiment 5, type of N fertilizer and liming

This experiment has been conducted since 1996 with a wheat/oat rotation under no-till management. The soil was a Santa Barbara, silt loam (Typic Fulvudand) having the following characteristics: pH 5.8; NO_3^--N, 22 mg L^{-1}; P Olsen, 7 mg L^{-1}; OM, 10.5%; K, 0.64 cmol kg^{-1}; Al 0.05 cmol kg^{-1}; and extractable SO_4^{2-}-S 15 mg L^{-1} ($CaHPO_4$ extract). A randomized block design was used. Treatments were as follows:

- Control without N + triple superphosphate (TSP),
- Sodium nitrate + TSP,
- Urea + mono-ammonium phosphate (MAP),
- Urea + MAP + 0.5 t lime ha^{-1},
- Urea + MAP + 1.0 t lime ha^{-1}.

Nitrogen was supplied at 150 kg ha^{-1} and P at 150 kg P_2O_5 ha^{-1}. One third of the N was applied at sowing and the remainder at emergence of the first node. Soprocal lime, 90% equivalent to pure $CaCO_3$, was broadcast. Potassium was supplied throughout at 150 kg K_2O ha^{-1}.

Plots were 6 × 20 m and were sown under no-till management. Micro-plots (1 m^2) were fertilized with 15 kg N ha^{-1} as urea enriched in ^{15}N at 10% a.e.

2.6. Experiment 6, residues

This experiment is part of a co-ordinated research project on soil organic matter. Here we present data on the effect of residues on N-uptake efficiency by irrigated wheat. Micro-plots were installed in an experiment that began 5 years ago, testing several rotations (main plots, 168 m^2) at two rates of fertilization (sub-plots) under irrigated condition. There were four replicates. In Treatment 1, N was applied at 160 kg ha^{-1}. The rotation was maize/wheat/common bean/barley; residues were incorporated from the first growing season. In Treatment 2, N was again applied at 160 kg ha^{-1}. The rotation was maize/wheat/red clover/red clover; residues were not incorporated. The micro-plots were 6.25 m^2, and ^{15}N-enriched (6.72% a.e.) ammonium sulphate was applied at 160 kg N ha^{-1}. Maize residue was applied at 8.0 t ha $^{-1}$, 2 months before sowing.

Chemical properties of the soil at the initiation of the experiment were: Treatment 1: pH 5.7; total N 0.43%; OM 9.02%; NH_4^+-N 45 mg kg^{-1}; NO_3^--N 14 mg kg^{-1}; P Olsen 12 mg kg^{-1}; K 0.33 cmol kg^{-1}. Treatment 2: pH 5.2; total N 0.46%; OM 8.74%; NH_4^+-N 96 mg kg^{-1}; NO_3^--N 17 mg kg^{-1}; P Olsen 11 mg kg^{-1}; K 0.17 cmol kg^{-1}.

3. RESULTS

3.1. Experiment 1, N × irrigation interaction

Minimum temperatures during the growing season ranged from 1 to 15°C and maxima from 15 to 35°C. The highest temperatures occurred after anthesis. This growing season was usually warm and dry, with a seasonal total precipitation of only 75 mm as compared to the 30-year average of 180 mm. The total pan evaporation was 550 mm. Soil moisture content was measured in the sub-plot fertilized with 150 kg N ha^{-1}. Four irrigations were applied in the season and available water increased with the level of irrigation. Available water content of the more-irrigated plots declined more rapidly as consequence of better crop development and evapotranspiration. Time domain reflectometry was unsatisfactory because of high variability in the generated data; the correlation coefficients with volumetric water content were only 0.69** and 0.42*, in the 0 to 20 and 20 to 80 cm layer, respectively.

Chlorophyll-meter readings ranged from 28 to 51 SPAD units and increased with growth stage. Meter readings at GS-30 were not affected by N rate or irrigation treatment, whereas at GS-45 and 69 there were significant ($P \leq 0.01$) effects of N. In consequence, at these later stages of development, the instrument was effective as an indicator of N deficiency. We suggest that, at GS-45, 44 SPAD units is a critical value above which a significant excess of fertilizer N has been applied. Our results indicate that stress from drought does not affect late-season chlorophyll-meter readings. Consequently, the instrument is useful for monitoring crop-N status even under moisture-stress conditions.

Chlorophyll-meter readings of leaves at GS-30 were not good predictors of grain yield. However, at GS-45 and GS-69 the SPAD data accounted for 72 to 85% of the variation in grain yield, respectively (Table IV). The relationship with yield was stronger than that with tissue-N concentration. The poor correlation with foliar N can be explained by the fact that the readings were taken from the uppermost expanded leaves at GS-30 and GS-45 and from the flag leaf at GS-69, whereas tissue N was determined from whole-plant samples.

Grain yields ranged between 1.9 t ha^{-1} to 7.5 t ha^{-1}. The interaction of N rate × water on grain yield was significant (Table V). Quadratic yield increases were found under different soil-water

TABLE IV. CORRELATION BETWEEN LEAF CHLOROPHYLL, GRAIN YIELD AND TISSUE NITROGEN MEASUREMENT AT THREE GROWTH STAGE (ZADOKS 30, 45 AND 69)

Growth Stage	SPAD units with	R^2
Zadoks 30	Grain Yield	0.03 ns
	Tissue N (%)	0.47**
Zadoks 45	Grain Yield	0.85**
	Tissue N (%)	0.46**
Zadoks 69	Grain Yield	0.72**
	Tissue N (straw)	0.36*
	Tissue N (spike)	0.20 ns

TABLE V. GRAIN YIELD AS AFFECTED BY N RATE TREATMENTS AND IRRIGATION LEVELS

N rate	Irrigation level		
	100 mm	170 mm	218 mm
0	2.31	2.72	2.85
75	3.13	4.86	5.17
150	4.16	5.83	6.75
225	4.32	6.19	7.67

TABLE VI. EFFECT OF N FERTILIZER APPLICATION RATE AND IRRIGATION ON TOTAL N UPTAKE BY SPRING WHEAT AND N DERIVED FROM FERTILIZER AND SOIL

PARAMETER	N RATE (kg ha-1)				N RATE (kg ha-1)				N RATE (kg ha-1)			
	0	75	150	225	0	75	150	225	0	75	150	225
	IRRIGATION 218 mm				IRRIGATION 170 mm				IRRIGATION 100 mm			
SOIL N SUPPLY	120	120	120	120	120	120	120	120	165	165	165	165
FERT. N SUPPLY	0	75	150	225	0	75	150	225	0	75	150	225
TOTAL N SUPPLY	120	195	270	345	120	195	270	345	165	240	315	390
TOTAL N UPTAKE	33	71	130	159	33	78	136	154	34	72	91	109
UPTAKE FROM FERT.	0	27	72	104	0	30	76	100	0	22	43	63
UPTAKE FROM SOIL	33	44	58	55	33	48	60	54	34	50	48	46
NUE (%)*		36	48	46		40	50	45		30	29	28
AUE (%)* *		51	65	56		60	69	54		51	38	33

(*) NUE: % real fertilizer-N uptake efficiency
(**) AUE : % apparent fertilizer-N uptake efficiency

TABLE VII. EFFECT OF TIME OF APPLICATION AND IRRIGATION ON N UPTAKE EFFICIENCY BY SPRING WHEAT

N rate	Water level, mm		Planting 1/3 dose	Second application (GS-30) 2/3 dose
			......................NUE (%)............................	
150	W1	218	49.6	47.0
	W2	170	48.3	51.1
	W3	100	30.2	28.1
225	W1	218	39.2	49.7
	W2	170	38.4	47.7
	W3	100	26.9	28.5

TABLE VIII. GRAIN YIELD AND YIELD COMPONENTS OF SPRING WHEAT (AVERAGE OF FOUR REPLICATES)

Treatment	Grain yield(a)	Straw yield	Kernel number		Kernel size	Spike number	Plant height	Harvest index	Grain protein(b)
	Mg ha-1	Mg ha-1	n° m-2	n° spike-1	mg	n° m-2	cm	%	%
0	4.24	5.43	21555	45	51.2	479	98	43.9	9.49
150	7.57	11.05	27738	46	51.3	603	108	40.8	9.12
75/75	7.94	13.79	26852	49	51	548	109	36.1	9.37
50/50/50	8.58	13.63	28106	47	49.1	598	108	38.7	9.63
37/37/37/37	7.30	10.95	24672	48	51.5	514	106	39.9	10.07
15/37/60/37	7.89	11.73	28150	50	49.3	563	106	40.2	9.81
LSD(0.05)	0.18	0.23	ns	ns	ns	ns	5.9	ns	0.37

(a) Dry weigth (b) Grain N content x 6.25

treatments in response to increased N. The increase in grain yield due to 221 mm of irrigation was 5 t ha^{-1} at a rate of 225 kg N ha^{-1}, but only 1 t ha^{-1} without N applied.

Irrigation and N rate did not affect individual kernel weight, but did significantly increase spikes per square meter, kernels per square meter and kernels number per spike; the water × N interaction was not significant.

Increasing water application increased fertilizer-N uptake efficiency. Fertilizer-N efficiency estimates at applications up to 170 mm water were significantly greater ($P \leq 0.01$) than with an irrigation of 100 mm (Table VI). The greatest concentrations of mineral N frequently occur in the upper part of the soil, therefore its uptake is likely to be inhibited when the soil dries. Nitrogen uptake was reduced by drought and this effect was exacerbated by the fertilizer being applied to the surface.

Rate of application affected N-uptake efficiency only in treatments with optimum irrigation. The highest efficiency was achieved with 150 kg N ha^{-1} and was not influenced by time of application (Table VII). In contrast, with 225 kg N ha^{-1} the second application was more effectively taken up, mainly with optimum water levels (W1, W2).

TABLE IX. TOTAL FERTILIZER AND SOIL N YIELDS IN WHEAT GRAIN AND STRAW AS INFLUENCED BY TIME OF N APPLICATION

Treatment	Total			Fertilizer			Soil		
	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total
	N yield (kg ha-1)								
0	64.5	16.3	80.9	-	-	-	64.5	16.3	80.9
	(79.8)	*(20.2)*					*(79.8)*	*(20.2)*	
150	110.1	34.1	144.3	30.4	9.9	40.3	79.7	24.2	103.9
	(76.3)	*(23.7)*		*(75.3)*	*(24.7)*		*(76.7)*	*(23.3)*	
75/75	121.9	49.5	171.4	34.6	16.1	50.7	87.3	33.3	120.7
	(71.1)	*(28.9)*		*(68.2)*	*(31.8)*		*(72.4)*	*(27.6)*	
50/50/50	131.8	46.3	178.0	42.3	17.0	59.4	89.5	29.2	118.7
	(74.0)	*(26.0)*		*(71.3)*	*(28.7)*		*(75.4)*	*(24.6)*	
37/37/37/37	118.0	36.0	154.0	44.4	14.0	58.3	73.7	22.0	95.7
	(76.6)	*(23.4)*		*(76.0)*	*(24.0)*		*(77.0)*	*(23.0)*	
15/37/60/37	125.0	39.9	164.9	49.9	15.7	65.6	75.1	24.2	99.2
	(75.8)	*(24.2)*		*(76.1)*	*(23.9)*		*(75.7)*	*(24.3)*	
LSD(0.05)	*40.5*	*19.6*	*57.4*	*7.8*	*4.7*	*10.9*	*ns*	*ns*	*ns*

Figures in parentheses indicate percentages of total plant N from respective sources distributed in grain and straw of wheat.

TABLE X. APPARENT FERTILIZER RECOVERY AND ISOTOPE RECOVERIES AT DIFFERENT TIMES OF N APPLICATION TREATMENTS

Treatment	Apparent fertilizer recovery %	Isotope(^{15}N) recovery fraction %
150	42.27	26.87
75/75	60.36	33.80
50/50/50	64.77	39.57
37/37/37/37	48.77	38.89
15/37/60/37	56.02	43.76
LSD(0.05)	*ns*	*7.26*

TABLE XI. COEFFICIENT OF DETERMINATION OF THE LINEAR RELATIONSHIP BETWEEN LEAF CHLOROPHYLL, LAI, GRAIN YIELD AND TISSUE NITROGEN MEASUREMENTS AT TWO GROWTH STAGES (ZADOKS 30 AND ZADOKS 69)

Growth stage[(1)]		R^2 SPAD
Zadoks 30	Grain yield	0.16ns
	Tissue N (%)	0.57**
	LAI	0.18ns
	N uptake (kg ha^{-1})	0.31ns
Zadoks 69	Grain yield	0.59**
	Tissue N (straw)	0.58**
	Tissue N (spike)	0.49*
	LAI	0.77**
	N uptake (kg ha^{-1})	0.77**

TABLE XII. MINERAL NITROGEN CONTENT (mg N kg^{-1}) BEFORE CULTIVATION AND GROWTH STAGES ZADOKS 30, AND ZADOKS 89 (HARVEST)

Depth	Timing Treatment 0		150		75/75		50/50/50		37/37/37/37		15/37/60/37	
	NO3	NH4	NO3	NH4	NO3	NH4	NO3	NH4	NO3	NH4	NO3	NH4
Before planting												
0–5	13.3	2.3	13.3	2.3	13.3	2.3	13.3	2.3	13.3	2.3	13.3	2.3
5–20	22.5	7	22.5	7	22.5	7	22.5	7	22.5	7	22.5	7
20–40	8.3	2.4	8.3	2.4	8.3	2.4	8.3	2.4	8.3	2.4	8.3	2.4
40–60	1.8	8.2	1.8	8.2	1.8	8.2	1.8	8.2	1.8	8.2	1.8	8.2
60–80	1.5	9.9	1.5	9.9	1.5	9.9	1.5	9.9	1.5	9.9	1.5	9.9
Zadoks-30												
0–5	3.7	4.4	3.7	7.5	2.3	10.5	3.0	8.1	0.7	5.8	1.4	7.4
5–20	4.4	4.4	2.8	4.9	5.1	7.4	2.8	6.5	3.0	10.2	3.7	12.6
20–40	3.4	5.3	2.9	6.5	5.1	8.6	2.8	8.6	2.4	16.9	4.2	11.6
40–60	2.3	10.7	2.7	13.6	0.7	5.0	1.9	7.6	0.7	7.2	1.4	3.9
60–80	1.4	11.3	1.4	20.6	1.3	14.0	1.3	10.3	1.4	8.3	1.3	3.2
Zadoks-89												
0–5	4.8	19.5	2.8	8.4	5.5	16.1	3.1	12.6	16.3	26.34	17.3	31.2
5–20	10.3	2.3	8.6	3.1	10.1	3.2	8.9	4.3	8	3.4	7.8	6.3
20–40	5.8	1.7	3	2.5	9.2	1.9	7.2	3.2	5.7	4.5	4.2	6.3
40–60	2.2	4.7	2.2	3.1	3.1	3.5	3.1	8	3	6	1.3	3.5
60–80	3.5	2.2	1.4	4.1	1.3	4.8	3.4	2.9	2.2	4.3	2.5	8.8

The contribution made by native soil N to total-N taken up by spring wheat was affected by the N and water treatments. Irrigation increased N uptake and the 150 kg N ha^{-1} rate produced the highest uptake of soil N. The uptake of native soil N was higher with N applied than in the check without N fertilization, attributable to positive "priming" or "added N interaction".

3.2. Experiment 2, timing of N

Grain and straw yields were affected by time of application of N (Table VIII). The greatest responses to N occurred with split applications: 50 kg N ha^{-1} applied at planting, 50 kg N ha^{-1} at first node detectable and 50 kg N ha^{-1} at flag leaf just visible. The lowest responses in grain yield occurred when all N was applied at planting or when 25% of the rates was applied at anthesis. The contribution of soil N to total-plant N was not affected by the time of fertilizer application. Isotope recovery ranged from 27 to 44%. The application of N at anthesis improved grain quality but decreased grain and straw yields. Apparent and isotope recovery fractions were appreciably different (positive priming or added N interaction). Consequently, when N is applied early it is likely to be lost, whereas when supplied to match the demand for N by the crop, it is more efficiently recovered.

TABLE XIII. GRAIN YIELD AND YIELD COMPONENTS OF 24 SPRING WHEAT GENOTYPES; GENOTYPES IN RANK ORDER BY GRAIN YIELD (AVERAGE OF FOUR REPLICATES)

Genotype	Grain Yield(*)	Straw Yield	Harvest Index	Kernel number		Kernel size	Spike
	Mg ha^{-1}	Mg ha^{-1}		n° spike^{-1}	n° m^{-2}	mg	n° m^{-2}
14 TS-506	6.57	9.26	0.42	31	15 500	47	508
6 HUAYUN	6.54	8.59	0.43	33	14 980	40	454
16 QU-P-1751-91	6.54	8.76	0.43	35	16 887	42	482
5 COYAN	6.43	7.63	0.46	30	16 676	44	565
13 COLONO	6.41	8.16	0.44	33	15 241	44	465
22 L-9004-18	6.39	8.14	0.44	31	13 561	54	434
23 L-9101-7	6.34	9.41	0.40	24	16 131	40	665
17 QU-P-1772-91	6.29	8.09	0.44	38	18 736	40	500
21 L-5761-256	6.29	7.39	0.46	39	16 927	45	437
9 SAETA	6.26	8.56	0.42	36	17 387	45	480
15 V-28	6.21	7.21	0.46	33	15 774	42	485
18 QU-P-1867-91	6.15	7.75	0.44	38	13 918	50	371
1 SNA-208	6.11	6.62	0.48	37	15 633	52	420
11 MAQUI	6.10	6.22	0.50	37	15 843	44	431
20 L-5755-82	6.08	7.59	0.45	35	14 775	47	428
8 DOMO	5.95	7.13	0.46	31	18 787	41	611
19 QU-P-2211-89	5.92	9.16	0.39	42	19 431	38	468
10 PEUMO	5.80	7.45	0.44	31	15 488	39	500
24 L-9112-2473	5.79	8.24	0.41	37	19 935	38	542
7 NOBO	5.77	6.77	0.46	38	19 592	42	522
4 CAMELO	5.68	8.61	0.40	33	14 778	39	451
3 CHACAY	5.57	8.18	0.41	31	15 881	40	508
12 FAMA	5.36	7.40	0.42	36	15 811	39	445
2 CIKO	5.27	7.05	0.43	27	12 411	45	460
LSD(0.05)	*0.54*	*0.59*	*0.03*	*7*	2448	*4*	*70*

(*) Dry weight

3.3. Experiment 3, genotype

Cultivars differed significantly in fertilizer-N recovery, which ranged from 50 to 77%. Available N use efficiency (grain yield per unit of available N, Gw/Nav) and N-utilization efficiency (grain yield per unit of N assimilated, Gw/Nt) both declined linearly with increasing plant N derived from fertilizer (Ndff), plant N derived from soil (Ndfs), plant N and fertilizer-N recovery.

Genotype differences in grain yield were not associated with N uptake from soil or fertilizer but were linked to total-N accumulation and N utilization efficiency (grain yield per unit of available soil-N).

High efficiency in N *utilization* was manifested as high N-harvest index (between 72 to 90%). This suggests that selection for higher N-harvest index would not be effective in improving grain yield of Chilean spring wheat.

TABLE XIV. N DERIVED FROM FERTILIZER, N DERIVED FROM SOIL AND FERTILIZER N RECOVERY OF 24 SPRING WHEAT GENOTYPES; GENOTYPES IN RANK ORDER BY N DERIVED FROM FERTILIZER (AVERAGE OF FOUR REPLICATES)

Genotype	NDFF*	NDFS**	Total plant N	Fert. N recovery
	kg ha-1	kg ha-1	kg ha-1	%
23 L-9101-7	123.8	76.5	200.3	77.4
17 QU-P-1772-91	106.4	72.1	178.6	66.5
14 TS-506	104.3	75.0	179.3	65.2
20 L-5755-82	102.3	75.9	178.3	64.0
9 SAETA	101.0	86.9	187.9	63.1
24 L-9112-2473	99.9	68.3	168.2	62.4
4 CAMELO	99.8	67.5	167.3	62.4
8 DOMO	97.0	77.4	174.4	60.6
22 L-9004-18	96.8	80.9	177.8	60.5
3 CHACAY	95.8	56.2	152.0	59.9
13 COLONO	95.7	61.0	156.7	59.8
6 HUAYAN	95.6	77.5	173.2	59.8
18 QU-P-1867-91	95.3	68.7	164.0	59.6
21 L-5761-256	95.2	75.0	170.2	59.5
5 COYAN	94.5	64.1	158.6	59.1
16 QU-P-1751-91	92.6	85.2	177.8	57.9
11 MAQUI	92.5	63.4	155.8	57.8
2 CIKO	91.0	65.7	156.7	56.8
19 QU-P-2211-89	89.9	70.1	160.0	56.2
10 PEUMO	89.4	69.9	159.3	55.8
12 FAMA	85.9	74.5	160.3	53.7
1 SNA-208	85.0	71.1	156.0	53.1
15 V-28	81.5	60.1	141.5	50.9
7 NOBO	79.6	76.6	156.2	49.8
LSD(0.05)	*12.3*	*ns*	*ns*	*7.6*

* NDFF = Plant N derived from fertilizer N
**NDFS = Plant N derived from soil N

Genotypes Coyan, Colono and Huayan were highest in grain yield potential and highest available-N-use efficiency. The contribution of soil N (non-fertilizer) to total plant N was not affected by genotype. The selection for utilization efficiency should be more effective in improving overall N use efficiency than selection for uptake efficiency.

3.4. Experiment 4, effects of N and S

Increased yields from applied S were observed mainly at optimum rates of N application (Table XVIII). The quadratic response to application of N was highly significant and there was a distinct tendency for the S-response curve to be quadratic also (F value significant at 20%). Where no S was added, 240 kg N ha^{-1} produced maximum yield, whereas with 20 kg S ha^{-1}, 160 kg N ha^{-1} was sufficient. These observations agreed with published work in which no S response was observed unless the rate of applied N was optimum. At 160 and 240 kg N ha^{-1} rates, S application tended to increase grain weight per spike and grain number per spike.

TABLE XV. NITROGEN USE EFFICIENCY RATIOS FOR GRAIN YIELD AND GRAIN N OF 24 SPRING WHEAT GENOTYPES; GENOTYPES IN RANK ORDER BY Gw/Nav AVERAGED

	Genotype	Gw/Nav	Nav	Ng	Ng/Nt	Gw/Nt	Nt/Nav	Ng/Nav	Gw/Ng
15	*V-28*	30.0	207.0	118.0	0.83	44.0	0.68	0.57	52.6
13	*COLONO*	28.8	222.2	127.9	0.82	40.9	0.70	0.58	50.1
5	*COYAN*	28.6	224.1	130.4	0.82	40.5	0.71	0.58	49.3
1	*SNA-208*	27.6	221.5	132.0	0.85	39.3	0.70	0.60	46.3
11	*MAQUI*	27.6	221.3	125.2	0.80	39.3	0.70	0.56	48.7
6	*HUAYAN*	27.5	238.6	142.8	0.82	38.1	0.72	0.60	45.8
16	*QU-P-1751-91*	26.9	243.3	144.1	0.90	36.8	0.73	0.59	45.4
14	*TS-506*	26.9	244.8	145.5	0.81	36.7	0.73	0.59	45.2
18	*QU-P-1867-91*	26.8	229.5	133.0	0.81	37.7	0.71	0.58	46.2
21	*L-5761-256*	26.7	235.7	142.3	0.84	37.0	0.72	0.60	44.2
22	*L-9004-18*	26.3	243.2	141.9	0.80	36.0	0.73	0.58	45.1
19	*QU-P-2211-89*	26.3	225.5	128.0	0.80	37.1	0.71	0.57	46.3
7	*NOBO*	26.0	221.6	123.8	0.79	37.0	0.70	0.56	46.6
10	*PEUMO*	25.9	224.7	128.1	0.81	36.9	0.71	0.57	45.2
17	*QU-P-1772-91*	25.9	244.0	151.8	0.85	35.7	0.73	0.62	41.5
3	*CHACAY*	25.8	217.4	115.9	0.77	37.4	0.70	0.53	48.0
20	*L-5755-82*	25.0	243.7	144.1	0.88	34.4	0.73	0.59	42.2
9	*SAETA*	25.0	253.3	146.7	0.79	34.3	0.74	0.58	42.7
8	*DOMO*	25.0	239.8	138.6	0.80	34.6	0.72	0.58	43.0
24	*L-9112-2473*	24.8	233.6	123.3	0.73	34.7	0.72	0.53	46.9
4	*CAMELO*	24.5	232.7	126.2	0.75	34.2	0.72	0.54	45.0
23	*L-9101-7*	23.8	265.8	144.3	0.72	31.6	0.75	0.54	43.9
12	*FAMA*	23.7	225.8	126.7	0.79	33.5	0.71	0.56	42.3
2	*CIKO*	23.7	222.2	128.5	0.82	33.8	0.70	0.58	41.0
	LSD(0.05)	*2.1*	*27.9*	*22.2*	*0.04*	*3.8*	*0.03*	*0.04*	*3.9*

N efficiency terminology

Gw= grain yield

Nav = available N = N supply minus N losses = aprox. by summing Nt and inorganic soil at harvest

Ng = grain N

Nt = aboveground plant N

Gw/Nav= available N use efficiency = (Nt/Nav)(Gw/Nt)

Nt/Nav = available N uptake efficiency

Ng/Nav = available grain N accumulation efficiency = (Nt/Nav)(Ng/Nt)

Ng/Nt = N harvest index

TABLE XVI. COEFFICIENT OF DETERMINATION OF THE LINEAR RELATIONSHIP BETWEEN NITROGEN EFFICIENCY COMPONENTS

	Gw/Nav	*Nav*	*Ng*	*Ng/Nt*	*Gw/Nt*	*Nt/Nav*	*Ng/Nav*	*Gw/Ng*	*NDFF*	*NDFS*	*Plant N*	*^{15}N rec %*
Gw/Nav	1.00											
Nav	-0.47*	1.00										
Ng	Ns	0.85**	1.00									
Ng/Nt	0.44*	ns	ns	1.00								
Gw/Nt	0.97**	-0.67**	-0.39*	0.39*	1.00							
Nt/Nav	-0.46*	0.99**	0.85**	ns	-0.67**	1.00						
Ng/Nav	0.35*	ns	0.66**	0.81**	ns	ns	1.00					
Gw/Ng	0.81**	-0.60**	-0.60**	ns	0.85**	-0.60**	ns	1.00				
NDFF	-0.39*	0.82**	0.59**	ns	-0.55**	0.80**	ns	ns	1.00			
NDFS	Ns	0.74**	0.76**	ns	-0.51**	0.76**	ns	-0.60**	ns	1.00		
Plant N	-0.47*	0.99**	0.85**	ns	-0.67**	0.99**	ns	-0.60**	0.82**	0.74**	1.00	
^{15}N rec%	-0.39*	0.82**	0.59**	ns	-0.55**	0.80**	ns	ns	1.00	ns	0.82**	1.00

TABLE XVII. MINERAL NITROGEN CONTENT (mg N kg^{-1}) BEFORE CULTIVATION AND GROWTH STAGE ZADOKS 30, AND ZADOKS 89 (HARVEST)

Depth	Z-0		Z-30		Z-89	
cm	N-NO3	N-NH4	N-NO3	N-NH4	N-NO3	N-NH4
	mg N kg^{-1}					
0–5	4.5	6.0	57.8	30.1	3.2	1.1
5–20	6.5	5.5	12.3	3.8	0.4	2.2
20–40	8.0	8.0	9.1	2.0	0.1	1.4
40–60	8.0	5.6	4.7	1.3	0.1	1.1
60–80	5.2	2.8	3.7	1.7	0.1	0.7

TABLE XVIII. EFFECT OF N AND S RATES ON WHEAT GRAIN YIELD AND OTHER YIELD COMPONENTS

Treatment (kg N/ha)	(kg SO_4/ha)	Grain (t/ha)	Straw (t/ha)	H.I.	GW/S (g)	G/S	TGW (g)
80	0	4.34	5.09	0.46	1.68	34	48.9
	20	4.41	5.18	0.46	1.62	32	50.5
	40	4.70	5.74	0.45	1.63	33	49.6
160	0	5.34	6.45	0.45	1.73	37	46.9
	20	6.55	7.61	0.46	1.73	37	46.6
	40	6.21	7.19	0.46	1.9	41	46.4
240	0	5.82	6.67	0.47	1.74	38	46.2
	20	5.91	6.77	0.47	1.75	39	45.6
	40	6.05	7.23	0.46	1.89	42	45.1
F test	N	8.0**	7.3**	ns	ns	5.3*	17.7**
	S	ns	ns	ns	ns	ns	ns
	NxS	ns	ns	ns	ns	ns	ns

Note: H.I.= Harvest Index; GW/S = Grains weight/spikes; G/S = Grains/spike; TGW = Thousand grain weight.

TABLE XIX. EFFECT OF N AND S RATES ON CHLOROPHYLL CONTENT AND LEAF AREA INDEX AT ANTHESIS GROWTH STAGE

Treatment N/ha	SO_4-S/ha	Chlorophyll (spad unit)	Leaf area index
80	0	47.6	1.43
	20	48.0	1.61
	40	48.2	1.58
160	0	50.6	2.47
	20	50.9	2.60
	40	49.2	2.62
240	0	48.9	2.75
	20	48.8	2.10
	40	51.3	3.20

TABLE XX. CORRELATION COEFFICIENTS

	Grain yield	N uptake	Chlorophyll	Leaf area index
Grain yield	1			
N uptake	0.97**	1		
Chlorophyll	0.73*	0.72*	1	
Leaf area index	0.85**	0.86**	0.84**	1

TABLE XXI. NITROGEN UPTAKE BY WHEAT FROM SOIL AND FERTILIZER AND PERCENT RECOVERY OF APPLIED N

kg N/ha	kg S/ha	Total N uptake (kg/ha)	NDFF (kg/ha)	NDFS (kg/ha)	Recovery of applied N (%)
80	0	80.4	31.3	49.1	39.1
	20	74.9	28.8	46.1	36.0
	40	76.3	26.8	49.5	33.5
160	0	106.0	59.4	46.6	37.1
	20	134.6	73.0	58.6	45.6
	40	120.7	62.8	57.9	39.3
240	0	122.5	80.4	42.1	33.5
	20	126.4	82.4	44.0	34.3
	40	127.7	79.1	48.6	33.0

TABLE XXII. EFFECT OF FERTILIZERS TREATMENTS ON GRAIN, STRAW PRODUCTION AND HARVEST INDEX

Treatment	Grain(*)	Straw	Harvest index
Control without N	3.42	4.76	0.42
Sodium nitrate + TSP	6.67	8.79	0.43
Urea + MAP	6.56	8.06	0.45
Urea + MAP+Lime $_{0.5}$	6.96	8.51	0.45
Urea + MAP+Lime $_{1.0}$	6.99	9.15	0.44
DMS $_{0.05}$	1.04	1.59	ns

(*) Grain yield base dry weight.

TABLE XXIII. NITROGEN UPTAKE BY WHEAT FROM SOIL AND FERTILIZER AND PERCENT RECOVERY OF APPLIED N

Treatment	Total N uptake (kg/ha)	NDFF (kg/ha)	NDFS (kg/ha)	Recovery applied N (%)
Control without N	47.0		47.0	
Sodium nitrate + TSP	130.5	70.2	60.3	46.8
Urea + MAP	124.4	63.3	61.1	42.2
Urea + MAP+Lime $_{0.5}$	127.6	66.5	61.1	44.3
Urea + MAP+Lime $_{1.0}$	133.6	78.6	55.0	52.4

TABLE XXIV. EFFECT OF FERTILIZER TREATMENTS ON YIELD COMPONENTS

Treatment	Grain weight/Plant (g/plant)	Weight 100 grains (g)	Grain/spike	Spikes/m^2
Control without N	1.24	4.32	29	376
Sodium nitrate + TSP	1.97	4.85	41	480
Urea + MAP	1.67	4.72	35	518
Urea + MAP+Lime $_{0.5}$	1.67	4.68	36	541
Urea + MAP+Lime $_{1.0}$	1.66	4.51	37	480

TABLE XXV. EFFECT OF TREATMENTS ON CHLOROPHYLL CONCENTRATION AND LEAF AREA DURING THREE GROWTH STAGES

Treatment	Chlorophyll (*)			Leaf area (cm^2/plant)		
	Zadoks 30	Zadoks 37	Zadoks 55	Zadoks 30	Zadoks 37	Zadoks 55
Control without N	36.6	31.7	27.6	10.9	32.2	42.7
Sodium nitrate + TSP	38.0	44.8	39.5	13.3	83.5	58.8
Urea + MAP	40.6	41.5	38.7	11.9	66.4	68.1
Urea + MAP+Lime $_{0.5}$	40.7	41.8	38.9	13.6	73.7	82.0
Urea + MAP+Lime $_{1.0}$	42.8	40.8	35.9	20.1	81.2	65.6
$DMS_{0.05}$	2.8	5.2	5.7	4.9	17.6	19.4

(*) SPAD units

TABLE XXVI. EFFECT OF TREATMENTS ON pH (WATER) 5 MONTHS AFTER SOWING

TREATMENT	Depth		
	0 - 5 cm	5 - 15 cm	15 - 30 cm
Control without N	6.47	6.20	6.36
Sodium nitrate + TSP	6.43	6.11	6.51
Urea + MAP	5.56	5.56	5.73
Urea + MAP+Lime $_{0.5}$	6.25	6.10	6.07
Urea + MAP+Lime $_{1.0}$	6.25	5.94	6.02

TABLE XXVII. EFFECT OF RESIDUES ON N UPTAKE EFFICIENCY AND SPRING WHEAT YIELD

Variable	Treatment 1 (*)	Treatment 2 (**)
Grain yield, t/ha	5.35	4.31
Straw yield, t/ha	7.72	5.70
Grain protein (%)	11.91	12.34
N grain, (kg/ha)	101.8	85.0
N straw, (kg/ha)	23.0	21.0
N derived from fertilizer (grain) (kg N/ha)	63.1	48.0
N derived from fertilizer (straw) (kg N/ha)	15.0	12.0
N derived from soil (grain) (kg N/ha)	37.8	37.0
N derived from soil (straw) (kg N/ha)	8.0	9.0
N uptake efficiency (%)	48.8	37.5

(*)Treatment 1. N-fertilization 160 kg N/ha; Rotation Maize-**Wheat**-Common beans-Barley. With incorporation of residues from first growing season. All N applied at tillering.
(**)Treatment 2. N-fertilization 160 kg N/ha; Rotation Maize-**Wheat**-Red clover-Red clover. Without incorporation of residues. All N applied at tillering.

Sulphur requirement was closely related to the amount of N applied. Because both N and S are involved in protein synthesis, the full benefit from the addition of one is dependent on an ample supply of the other. In this case, the magnitude of response to N increased with the rate of S applied.

Chlorophyll meter readings were well correlated with N uptake, grain yield and leaf area index (Tables XIX and XX).

These results indicate that, despite a relatively low S requirement, the yield potential of wheat in Central-South Chile may be constrained by an inadequate supply of S from soil and atmosphere. In the present study, there was no yield advantage in applying more than 20 kg S ha^{-1} as gypsum, which was sufficient to increase the crop S content above the critical threshold value for deficiency (0.2%).

Neither N nor S fertilizer application had significant effects on plant uptake of soil-derived N (Table XXI). However, there was a trend depending on the S rate applied: average Ndfs values were 46, 50 and 52 kg N ha^{-1} at 0, 20 at 40 kg S ha^{-1}, respectively.

Recovery of ^{15}N varied between 33 and 46% and increased slightly at 160 kg N ha^{-1}. Nitrogen-uptake efficiency can be considered low in this experiment, at less than 40%.

3.5. Experiment 5, type of N fertilizer and liming

Yields with the treatments that included lime and N were slightly superior to those only with N (Table XXII). Nevertheless, these differences were not significant. Different yield components such as 100-grain weight, grains per spike and grain weight per plant were favored slightly in the sodium nitrate + TSP treatment, whereas grains per m^2 was inferior in comparison with the other fertilizer treatments. Nitrogen-uptake efficiency ranged between 42 to 52% and was not affected by fertilization treatments.

Chlorophyll-meter readings immediately before tillering were lowest in the sodium nitrate treatment, probably due to leaching losses of N resulting from high rainfall. Later on, upon applying the second dose of N at the end of tillering, this situation was reversed and chlorophyll readings increased.

The application of ammonium fertilizers without neutralization meant a decrease in pH and loss of cations. In general, the pH value with urea and mono-ammonium phosphate was 0.5 units lower than with sodium nitrate + TSP.

Lime application (0.5 and 1.0 t ha^{-1}) neutralizes the acidifying effects of urea and mono-ammonium phosphate and increases pH and bases over time. The economic analysis indicated that the treatments with lime were the most profitable. The net profit of the treatment with lime was superior by about 40 to 102 dollars compared with the other fertilizer treatments. The use of lime in order to neutralize ammonium fertilizers was technically equivalent to using nitrate or alkaline reaction fertilizers.

3.6. Experiment 6, residues

Residue incorporation increased grain yields by 1 t ha^{-1} and straw by 2 t ha^{-1}. This management practice also increased the fertilizer N recovered by wheat, whereas the contribution of N from soil was similar in both rotations and was not affected by residue incorporation. Better fertilizer-N efficiency was possibly a consequence of an improvement in soil physical properties and a more balanced nutrition in the maize/wheat/bean/barley rotation.

4. CONCLUSIONS

The results indicate that residue incorporation in the rotation, optimum irrigation (>170 mm), N-application timing (three split), and correction of nutritional problems (acidification and S deficiency) improved wheat yields and fertilizer-N efficiency. The highest efficiencies achieved in these volcanic soils were in the order of 50%, which demonstrates important losses. The contributions made by native soil N to total-N taken up by wheat, from about 40 to 80 kg N ha^{-1}, were not affected significantly by fertilizer treatments.

Volcanic soils have a high production potential when managed appropriately. The optimum grain yields varied between 6 and 8 t ha^{-1}. Results indicate that the chlorophyll meter can be used to separate N-responsive from non-responsive treatments,, however there was variability between experimental sites and genotypes at the same growth stage. In order to use these instruments with the purpose of defining N requirements it would be necessary to have well fertilized reference strips within the same field.

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INCREASING WHEAT PRODUCTION WHILE DECREASING NITROGEN LOSSES FROM AMMONIUM BICARBONATE

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Abstract

The objectives of a 4-year field experiment were i) to investigate the effects of rate and timing of application of ammonium bicarbonate on N-uptake efficiency by irrigated winter wheat, ii) to determine the fate of fertilizer N in wheat followed by maize, and iii) to study nitrate dynamics in the soil after N-fertilizer application to evaluate groundwater pollution by leaching. Nitrogen-application rates significantly affected wheat grain yields and straw dry matter. Grain yields were higher with 150 than with 225 kg N ha^{-1}, whereas the highest fractional recoveries of N from ammonium bicarbonate occurred with 75 kg N ha^{-1} (38.5% in 1994–95 and 33.5% in 1996–97). On the basis of grain yield, N recovery and soil-N balance, ammonium bicarbonate at 150 kg N ha^{-1}, was the optimum rate, when applied basally and as a top dressing to wheat. Subsequent yields of maize stover and grain were affected by N applied to the wheat, suggesting that fertilizer recommendations, in terms of rate and timing, should be made on the basis of effects on the cropping rotation as a whole. Water-holding capacity of the soil was poor, therefore large applications of N are likely to cause nitrate pollution of ground water.

1. INTRODUCTION

Nitrogen is the most important limiting nutritional factor for crop production. Fertilizer inputs are, therefore, required to obtain acceptable yields, but the amounts of fertilizer N that are taken up by crops are usually relatively low, 20 to 50%, and dependent on several factors including management practice. In China, approximately 45% of fertilizer N is applied as ammonium bicarbonate, estimated at 45 Mt annually. The fraction of N applied as ammonium bicarbonate that is taken up by crops can be as low as 25%, due to instability and volatilization [1]. Improper use further adds to losses of N [2]. Since the 1970s, there have been several studies on the physical and chemical characteristics of ammonium bicarbonate [3, 4] with a view to improving its efficiency of uptake by crops, with some success [5, 6, 7, 8].

The objective of this work was (a) to investigate the effects of rate and timing of ammonium bicarbonate on N-uptake efficiency by winter wheat under irrigation in Hebei province; (b) to investigate the fate of fertilizer N on current and subsequent crops; and (c) to study dynamics of nitrate in the soil after fertilizer application and evaluate groundwater pollution caused by leaching.

2. MATERIALS AND METHODS

2.1. Experiment site

The experiment was conducted from October 1994 through August 1998, at the Agricultural Experiment Station of Hebei Academy of Agricultural Sciences in Shijiazhuang city, 38°02'N 114°25'E. This is in Hebei province, part of the North China Plain, which is important in winter-wheat production in rotation with maize. The fertilizers chiefly used are ammonium bicarbonate and urea. Because of ammonium bicarbonate's powder formulation and losses of N by volatilization, farmers generally prefer urea.

In this region, fertilizer applications to winter wheat are generally 150 kg N ha^{-1} and 75 kg P_2O_5 ha^{-1} for soils of medium fertility. The climate is semi-arid with a cold, dry winter, and hot summer. Relative humidity is high in summer and low in winter. Climatic characteristics are shown in Table I. The experiment field was 80 to 100 m above sea level and the water table was at 18 m; fertilizer experiments had not previously been done at this site. The field layout is shown in Fig. 1.

TABLE I. THE CLIMATE CHARACTERISTICS IN SHIJIAZHUANG, HEBEI PROVINCE

Climate indexes	Recorded data
Annual mean temperature(°C)	12.9
Mean temperature of February (°C)	-2.7
Mean temperature of July (°C)	26.7
Lowest temperature (°C)	-26.5
Highest temperature (°C)	42.7
Annual mean rainfall (mm)	556
Annual mean Frostless period (days)	194

* Data recorded from December 31, 1984–December 31, 1993 provided by Shijiazhuang Meteorology Bureau\

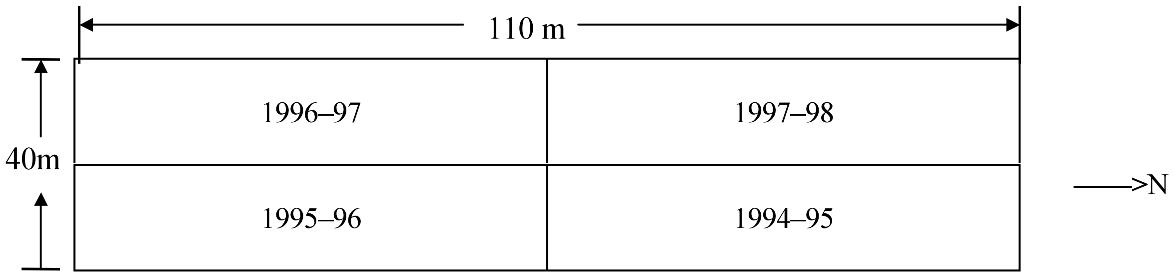

FIG. 1. Design of experimental site, 1994–98.

2.2. Soil

The soil has been classified as cinnamon or drab; physical and chemical characteristics are described in Tables II and III.

TABLE II. SELECTED CHEMICAL CHARACTERISTICS OF THE SOIL COLLECTED FROM THE EXPERIMENT FIELD

Indexes	Measured value	Classification
Total Nitrogen (%)	0.092	
Available Nitrogen(mg kg^{-1} soil)	90.7	Medium response to N
Available P_2O_5 (mg kg^{-1} soil)	43.4	Medium response to P
Available K_2O(mg kg^{-1} soil)	240	Low response to K
Organic matter (%)	1.88	
pH (in water)	7.88	

TABLE III. SELECTED PHYSICAL CHARACTERISTICS OF THE SOIL COLLECTED FROM THE EXPERIMENT FIELD

Code	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	O.M. (%)	S.W.C. (%)	B.D. (g cm^{-3})
A1	0–15	53.4	32.3	14.3	1.91	43.5	1.17
A2	16–26	54.4	31.3	14.3	1.73	28.1	1.55
A3	27–47	51.9	30.3	17.8	0.82	33.9	1.40
A4	48–75	50.9	31.1	17.8	0.67	36.2	1.35
A5	76–107	49.9	32.3	17.8	0.59	32.0	1.44
A6	108–146	47.9	28.3	23.8	0.71	40.8	1.32

[a]B.D. = bulk density, [b]O.M.= organic matter, [c]S.W.C.= saturated water content

2.3. Crops

The rotation used in this experiment was wheat/maize/wheat. Winter wheat (*Triticum aestivum* L. cv. 71-3) was sown around 10 October and harvested around 10 June of each year. Maize (*Zea mays* L. cv. Yedan 13) was planted immediately after the wheat and harvested around 25 September each year.

2.4. Fertilizers

From 1994 to 1997, the N was applied as ammonium bicarbonate (17% N, moisture content 3%) and ^{15}N-enriched (5.54% abundance) ammonium bicarbonate. For the 1997–98 growing season, urea (Ncontent 46%, H_2O content 2.7%) and ^{15}N-enriched urea (5.32% ^{15}N) were used. The unenriched fertilizers were provided by Zhengdong Chemical fertilizer factory, Shijiazhuang city, and the ^{15}N-enriched counterparts were supplied by the Shanghai Research Academy of Chemical Industry.

2.5. Treatments

2.5.1. Rates and timing of N

The N-rate design is shown in Table IV. The application-timing design was as shown in Tables V and VI; applications were variously made at sowing and/or at jointing.

TABLE IV. NITROGEN APPLICATION RATES(kg N ha^{-1})

Code		1994/95	1995/96	1996/97	1997/98
N0.0	Control	0	0	0	0
N0.5	Low 50% of optimum rate	75	50	75	75
N1.0	Optimum rate	150	100	150	150
N1.5	Above 50% of optimum rate	225	150	225	225

*The nitrogen fertilizer used in 1994/95, 1995/96 and 1996/97 was ammonium bicarbonate, the nitrogen fertilizer used in 1997/98 was urea.

TABLE V. DESIGN OF NITROGEN FERTILIZATION IN MICROPLOTS DURING IRRIGATED WINTER WHEAT SEASONS OF 1994/95 AND 1996/97

Code	At sowing(ZS** 00)	At jointing(ZS 31)
N0.0	1/3*	2/3*
N0.5	1/3*	2/3*
N1.0	1/3*	2/3*
N1.5	1/3*	2/3*

* ^{15}N labeled nitrogen fertilizer applied ** FEEKES scale

TABLE VI. DESIGN OF NITROGEN FERTILIZATION IN MICROPLOTS DURING IRRIGATED WINTER WHEAT SEASONS OF 1995/96 AND 1997/98

Code	At sowing(ZS 00**)	At jointing(ZS 31)
	1/3*	2/3
N1.0	1/3	2/3*
	1/3*	2/3*
	1/3*	2/3
N1.5	1/3	2/3*
	1/3*	2/3*

* ^{15}N labeled nitrogen fertilizer applied ** FEEKES scale

2.5.2. Plots

During the 1994–95 and 1995–96 growing seasons, plot size was 9.0×5.5 m; for 1996–97 and 1997–98, it was 7.5×7.0 m. Each was divided into two equal sub-plots, one for sampling and the other for yield. The ^{15}N micro-plots, 1.0×0.6 m, were located within the yield sub-plots. During 1994–95 and 1996–97, each $N_{0.5}$, $N_{1.0}$ and $N_{1.5}$ yield sub-plot contained one micro-plot and for 1995–96 and 1997–98, each $N_{1.0}$ and $N_{1.5}$ yield sub-plot contained three micro-plots (Tables IV, V and VI). All treatments were randomly located and replicated three times.

2.5.3. Fertilization

All N-fertilizer applications were incorporated to a depth of 10 cm (Table IV, V and VI). In addition, calcium monophosphate was applied just before sowing at a rate of 75 kg P_2O_5 ha^{-1}. Nitrogen and P were not applied to the subsequent maize crops.

2.5.4. Irrigation

Irrigation timing and amounts were as recommended by local farmers. Each winter-wheat crop was irrigated six times (Table VII) by flooding.

TABLE VII. IRRIGATION TIMING AND AMOUNT DURING THE GROWING SEASON OF WINTER WHEAT

Growing season	Irrigation	1st	2nd	3rd	4th	5th	6th
1994/95	Date	10/20/94	11/20/94	03/13/95	04/15/95	05/05/95	05/26/95
	Amount			4 m^3	per plot		
1995/96	Date	10/19/95	12/01/95	04/01/96	04/24/94	05/16/96	05/28/96
	Amount			4 m^3	per plot		
1996/97	Date	10/20/96	12/03/96	03/15/97	04/10/97	05/02/97	05/24/97
	Amount			4 m^3	per plot		
1997/98	Date	10/12/97	11/29/97	03/24/98	04/15/98	05/11/98	05/28/97
	Amount			4 m^3	per plot		

2.6. Sampling and analysis

During the wheat-growing season, plants and soil were sampled at sowing and at Zadoks growth stages Z-20, -31, -41, -51 and -90. The maize was sampled only at maturity. At final harvest, three blocks (each 1×2 m) of winter wheat or maize were removed from each yield sub-plot and weighed for stover dry matter and grain yield after drying. Soil samples, three cores of 2 cm diam, were randomly taken from sampling sub-plots and separated into 0 to 15, 16 to 30, 31 to 50, 51 to 75, and 76 to 100 cm sections, except during 1994–95 when the soil-sampling sections were 0 to 20, 21 to 40, 41 to 60, and 61 to 80 cm. Each section was mixed thoroughly, quickly analyzed for water content, and stored at 4°C pending determinations of total-N and inorganic-N content. Soil-N was determined by the Kjeldahl distillation method using 0.01 *M* H_3BO_3 as the absorbing solution after digestion in concentrated sulphuric acid. Soil mineral N was determined using a distillation apparatus (Tecator, Sweden) with 2 *M* KCl. After being dried at 70°C, weighed and milled, plant samples (root, straw, grain and husk separately) were determined for N content by Kjeldahl distillation. The $^{15}N/^{14}N$ ratios of plant and soil samples were determined by mass spectrometry (ZHT-03, Beijing Analysis Co.).

3. RESULTS AND DISCUSSION

3.1. Yield

Yield differences from season to season were probably due to climatic conditions rather than to soil fertility which was largely uniform. There were significant responses in grain and straw yields to N application, except for the 1994–95 trial (Table VIII) in which straw weights with 75 and 150 kg N ha^{-1}

were not significantly different, although significantly lower than with 225 kg N ha^{-1}. For the 1996–98 and 1997–98 seasons, straw yields with 150 kg N ha^{-1} were significantly higher than those with 75 kg N ha^{-1} and similar to those with 225 kg N ha^{-1}. The 150 kg N ha^{-1} treatment produced the highest grain yields, although in 1994–95 and 1995–96, they were not significantly higher than those with 75 or 100 kg N ha^{-1}.

TABLE VIII. DRY MATTER, STRAW YIELD AND GRAIN YIELD OF WINTER WHEAT AS INFLUENCED BY NITROGEN APPLICATION RATE

Growing season	Fertilization Code	Dry matter t ha^{-1}	Dry matter LSD	Straw yield t ha^{-1}	Straw yield LSD	Grain yield t ha^{-1}	Grain yield LSD
1994/95	N0.0	12.14	c*B**	7.00	bA	5.14	bB
	N0.5	14.78	aA	8.39	aA	6.39	aA
	N1.0	14.70	aA	8.02	aA	6.68	aA
	N1.5	13.12	bB	7.94	bA	5.08	bB
1995/96	N0.0	11.61	cC	6.91	cC	4.70	bB
	N0.5	13.63	bB	8.61	bB	5.02	bB
	N1.0	15.85	aA	9.62	aA	6.23	aA
	N1.5	16.45	aA	9.99	aA	6.46	aA
1996/97	N0.0	15.77	dC	11.12	bB	4.65	cB
	N0.5	17.10	cB	10.92	bB	6.18	bA
	N1.0	19.26	aA	12.49	aA	6.77	aA
	N1.5	18.21	bA	12.06	aA	6.15	bA
1997/98	N0.0	15.66	cB	10.76	bB	4.90	cB
	N0.5	16.62	bB	10.67	bB	6.05	bA
	N1.0	18.21	aA	11.54	aAB	6.67	aA
	N1.5	18.23	aA	12.06	aA	6.17	bA

* $LSD_{0.05}$ **$LSD_{0.01}$

TABLE IX. HARVEST INDEXES OF WINTER WHEAT AS INFLUENCED BY NITROGEN APPLICATION RATE

Growing season	Code	values	LSD	
1994/95	N0.0	0.423	ab*	A**
	N0.5	0.432	ab	A
	N1.0	0.454	a	A
	N1.5	0.390	b	A
1995/96	N0.0	0.404	a	A
	N0.5	0.368	a	A
	N1.0	0.393	a	A
	N1.5	0.392	a	A
1996/97	N0.0	0.294	c	B
	N0.5	0.361	a	A
	N1.0	0.356	a	A
	N1.5	0.337	b	A
1997/98	N0.0	0.312	c	B
	N0.5	0.361	a	A
	N1.0	0.366	a	A
	N1.5	0.338	b	B

* $LSD_{0.05}$ ** $LSD_{0.01}$

TABLE X. NITROGEN YIELD OF WINTER WHEAT AS INFLUENCED BY NITROGEN APPLICATION RATE

Growing season	Code	Whole kg ha^{-1}	Whole LSD$_{0.05}$	Straw kg ha^{-1}	Straw LSD$_{0.05}$	Grain kg ha^{-1}	Grain LSD$_{0.05}$
1994/95	N0.0	161.9	d	46.1	b	115.8	b
	N0.5	218.1	b	73.3	a	144.9	a
	N1.0	232.7	a	74.4	a	158.3	a
	N1.5	199.9	c	82.2	a	117.7	b
1995/96	N0.0	213.0	b	61.6	b	151.4	c
	N0.5	254.3	a	90.0	a	164.3	b
	N1.0	262.5	a	83.9	a	178.6	a
	N1.5	266.2	a	85.5	a	180.7	a
1996/97	N0.0	189.8	c	63.5	c	126.3	c
	N0.5	217.7	b	74.6	b	143.1	b
	N1.0	271.8	a	88.9	a	182.9	a
	N1.5	226.4	b	83.4	a	143.0	b
1997/98	N0.0	196.0	c	59.6	b	136.4	c
	N0.5	223.5	b	70.3	b	153.2	b
	N1.0	265.7	a	86.7	a	179.0	a
	N1.5	226.4	b	88.7	a	137.7	c

*LSD$_{0.05}$

TABLE XI. NITROGEN RECOVERY OF WINTER WHEAT AS INFLUENCED BY NITROGEN APPLICATION RATE AND TIMING

Growing season	Code	Timing	Straw %	Straw LSD$_{0.05}$	Grain %	Grain LSD$_{0.05}$
1994/95	N0.5	1/3*+3/2*	12.62	a	25.89	a
	N1.0	1/3*+3/2*	10.12	b	22.18	b
	N1.5	1/3*+3/2*	8.75	c	13.67	c
1995/96		1/3*+3/2	18.31	a	37.23	a
	N1.0	1/3+3/2*	10.56	c	21.00	cd
		1/3*+3/2*	10.28	c	20.89	d
		1/3*+3/2	14.48	b	30.60	b
	N1.5	1/3+3/2*	7.94	d	16.78	e
		1/3*+3/2*	10.45	c	22.09	c
1996/97	N0.5	1/3*+3/2*	10.46	a	23.04	a
	N1.0	1/3*+3/2*	9.34	a	21.65	a
	N1.5	1/3*+3/2*	7.09	b	17.78	b
1997/98		1/3*+3/2	13.57	b	28.45	a
	N1.0	1/3+3/2*	17.42	a	18.48	d
		1/3*+3/2*	9.67	c	23.04	b
		1/3*+3/2	12.45	b	23.04	b
	N1.5	1/3+3/2*	13.58	b	20.45	c
		1/3*+3/2*	10.02	c	23.43.	b

* ^{15}N-labeled fertilizers applied

When the N-application rate was increased to 225 kg N ha^{-1}, grain yield decreased and, in some cases, e.g. 1994–95, was not significantly higher than that of the zero-N control, probably because excessive N affected nutrient balance, thus increasing plant susceptibility to deficiencies in moisture and P and K. Another possible reason was that excessive fertilizer decreased the normally positive effects of N on photosynthesis, which affected grain filling and final grain yield [9], as indicated by the significantly lower harvest index with 225 kg N ha^{-1} than with 150 kg N ha^{-1} (Table IX).

TABLE XII. THE BALANCE OF FERTILIZER NITROGEN AS INFLUENCED BY NITROGEN APPLICATION RATE AND TIMING (% OF APPLIED)

season	Code	Timing	recovery in plant	in soil (0–105 cm)	Unaccounted kg N ha^{-1}	% of applied
1994/95	N0.5	1/3*+3/2*	38.51	38.40	17.31	23.09
	N1.0	1/3*+3/2*	32.35	46.77	31.39	20.92
	N1.5	1/3*+3/2*	22.45	61.58	88.15	39.18
1995/96		1/3*+3/2	55.51	35.35	3.14	9.44
	N1.0	1/3+3/2*	31.17	41.19	18.40	27.64
		1/3*+3/2*	32.07	38.97	30.06	30.06
		1/3*+3/2	45.07	40.24	7.34	14.68
	N1.5	1/3+3/2*	24.71	45.77	29.61	29.51
		1/3*+3/2*	32.54	47.07	30.22	20.15
1996/97	N0.5	1/3*+3/2*	33.50	34.40	22.65	32.20
	N1.0	1/3*+3/2*	30.99	48.29	30.11	20.07
	N1.5	1/3*+3/2*	24.87	47.49	62.14	27.62
1997/98		1/3*+3/2	42.02	37.20	10.38	20.77
	N1.0	1/3+3/2*	35.90	43.57	20.35	20.53
		1/3*+3/2*	31.71	44.01	36.42	24.28
		1/3*+3/2	35.59	35.91	21.45	28.60
	N1.5	1/3+3/2*	34.03	40.43	38.31	25.54
		1/3*+3/2*	33.45	44.21	50.26	22.34

* ^{15}N-labeled fertilizers applied

TABLE XIII. YIELD OF NEXT CROP (MAIZE)

Growing season	Previous fertilizer code	Amount of N in soil at the end of previous crops (kg N ha^{-1}) 0–30cm	31–50cm	Yield of maize (kg ha^{-1}) Straw	Grain
1995	N0.0	3286	1988	4954	3925
	N0.5	3962	2268	6192	4237
	N1.0	4244	2380	6284	4153
	N1.5	4325	2604	6509	4846
1997	N0.0	3324	1889	4500	4400
	N0.5	4096	2347	5639	5850
	N1.0	4332	2456	6277	5910
	N1.5	4468	2565	6194	7472

3.2. Nitrogen content

Plant N significantly increased with applied N up to 150 kg N ha^{-1}, but with 225 kg N ha^{-1} was significantly lower than with 150 kg N ha^{-1} (Table X). Straw N with 150 kg N ha^{-1} was similar to that with 225 kg N ha^{-1}, whereas the grain N was significantly higher with 150 kg N ha^{-1}. These data indicate that excessive N supply may adversely affect N uptake by winter wheat.

3.3. Nitrogen recovery

Recovery of applied ^{15}N varied depending on fertilizer type, N rate and timing (Tables XI and XII). When one third of ammonium bicarbonate was applied at sowing and two thirds at jointing (Z-31), the highest fractional recovery was obtained from 75 kg N ha^{-1}, at 38.5% in 1994–95 and 33.5% in 1996–97. With 100 and 150 kg N ha^{-1} as ammonium bicarbonate, the recoveries were 32%, 32.5% and 31% in 1994–95, 1995–96 and 1996–97, respectively. When the application rate was 225 kg N ha^{-1}, the recovery was as low as 22% in 1994–95 and 25% in 1996–97.

TABLE XIV. FERTILIZER NITROGEN UPTAKE BY NEXT CROPS

Growing season	Previous fertilizer code	Amount of fertilizer N in soil at the end of previous crops (kg N ha^{-1}) 0–30cm	31–50cm	Fertilizer N uptake by next crops (kg N ha^{-1}) Straw	Grain
1995	N0.5*	23.46	5.34	2.46	5.13
	N1.0*	46.69	23.47	7.89	7.89
	N1.5*	104.24	34.33	13.45	18.92
1997	N0.5*	22.46	3.40	1.65	3.01
	N1.0*	47.74	25.68	6.03	6.80
	N1.5*	78.09	28.77	12.37	19.86

*- ^{15}N labeled fertilizer applied both at sowing(1/3) and at jointing(2/3).

TABLE XV. SOIL WATER CONTENT WITH RELATION TO IRRIGATION (N0.0)

Irrigation date prior to sampling	Sampling date	Soil profile (cm)	Water content (% vol.)
	1994-10-05	0–20	16.46
		21–40	14.70
		41–60	17.25
		61–80	14.03
1994-10-20	1994-10-26	0–20	18.06
		21–40	16.97
		41–60	16.16
		61–80	12.34
1994-11-18	1994-11-21	0–20	23.25
		21–40	20.35
		41–60	19.24
		61–80	17.89
1995-03-13	1995-03-26	0–20	12.95
		21–40	15.68
		41–60	16.85
		61–80	18.74
1995-04-15	1995-04-26	0–20	19.10
		21–40	18.11
		41–60	16.45
		61–80	16.32
1995-05-26	1995-06-15	0–20	20.40
		21–40	19.23
		41–60	17.56
		61–80	19.31

As a general rule-of-thumb, when 75 kg N ha^{-1} are applied as ammonium bicarbonate, approximately 150 kg N ha^{-1} N will be removed as grain from the system, therefore, even with the return of straw to the soil, 75 kg N ha^{-1} would be lost. Under such circumstances, soil fertility will decrease rapidly. With 150 kg N ha^{-1} applied, the rate recommended in Hebei province, and 150 kg N ha^{-1} removed in grain, if the straw is returned then the soil N should be maintained. In this work, application of 150 kg N ha^{-1} produced the best yield, with recovery of applied N in plant and soil of around 32%.

The recovery of ^{15}N from ammonium bicarbonate, when applied only at sowing, was significantly higher than when applied at jointing and significantly higher than when one third was applied at sowing and two thirds at jointing. These data indicate that ammonium bicarbonate is particularly useful as a basal fertilizer.

When urea was applied at 150 kg N ha^{-1}, N recoveries were relatively high, 42%, 36% and 33%, when applied only at sowing, only at jointing, or one third at sowing and the rest at jointing, respectively. With 225 kg N ha^{-1}, 35.5%, 34% and 33% of N was recovered when applied only at sowing, only at jointing, or one third applied at sowing and two third at jointing, respectively.

TABLE XVI. SOIL WATER CONTENT WITH RELATION TO IRRIGATION (N0.0)

Irrigation date prior to sampling	Sampling date	Soil profile (cm)	Water content (% vol.)
	1995-10-05	0–15	15.64
		16–30	16.70
		31–50	16.98
		51–70	15.87
		71–100	15.65
1995-12-01	1996-12-08	0–15	11.41
		16–30	12.12
		31–50	14.37
		51–70	15.54
		71–100	17.47
1995-12-01	1996-03-19	0–15	13.06
		16–30	14.87
		31–50	11.88
		51–70	12.27
		71–100	18.53
1996-04-01	1996-04-09	0–15	10.86
		16–30	11.71
		31–50	11.89
		51–70	11.71
		71–100	12.35
1996-04-24	1996-05-14	0–15	7.22
		16–30	8.44
		31–50	9.55
		51–70	9.99
		71–100	9.96
1996-05-28	1996-06-13	0–15	13.92
		16–30	12.11
		31–50	10.58
		51–70	10.69
		71–100	11.86

3.4. Fertilizer-N balance

With increases of N-application rate, the fertilizer N remaining in the soil, 0 to 105cm, also increased (Table XII). Also, as N application increased, the amount of unaccounted-for N also increased.

The residual N in soil as a fraction of that applied was lower when applied at sowing than when applied only at jointing or both at sowing and at jointing; between the latter two, there was no significant difference.

3.5. Residual N

The yields of maize stover and grain, for the $N_{1.5}$ treatment to the wheat, were higher than those for the $N_{0.5}$ and $N_{1.0}$ treatments (Table XIII). These data suggest that it is advisable to consider N utilization for current crops and succeeding crops, i.e. the optimum rate and timing of applied fertilizer would be that which maximizes uptake of N by the rotational cropping system as a whole.

When N was applied both at sowing and jointing, about 60 to 70% was recovered in plant and soil (Table VII), of which the latter might be available to the subsequent crop. Part of fertilizer N applied to the wheat was taken up by the maize (Table XIV).

TABLE XVII. SOIL WATER CONTENT WITH RELATION TO IRRIGATION (N0.0)

Irrigation date prior to sampling	Sampling date	Soil profile (cm)	Water content (% vol.)
	1996-10-05	0–15	15.76
		16–30	16.65
		31–50	14.78
		51–70	15.43
		71–100	16.32
1996-10-20	1996-12-01	0–15	13.63
		16–30	15.53
		31–50	14.84
		51–70	16.17
		71–100	18.69
1996-12-03	1997-03-05	0–15	17.62
		16–30	18.78
		31–50	18.97
		51–70	18.17
		71–100	20.42
1996-03-15	1997-04-09	0–15	15.60
		16–30	16.01
		31–50	16.03
		51–70	17.54
		71–100	19.75
1996-04-10	1997-05-01	0–15	11.15
		16–30	13.02
		31–50	15.50
		51–70	16.36
		71–100	17.54
1995-05-24	1997-06-13	0–15	13.91
		16–30	14.22
		31–50	13.99
		51–70	13.52
		71–100	13.96

3.6. Nitrate pollution

3.6.1. Water movement

The winter wheat depended mainly on irrigation due to little rain from October to June (about 350 mm). At sowing, soil-water content was around 16%, and not significantly different between upper and lower layers. For a few days after each irrigation, the water content in the upper soil layers was higher than that in the lower (Tables XV, XVI and XVII). However, eventually the moisture content of deeper soil layers increased and that in upper soil layers decreased. At 3 or 4 weeks after irrigation, the water content deep in the soil generally was much higher than that in the surface layer. These data show that this soil did not retain water for long periods.

3.6.2. Nitrate movement

With N application rates of 50, 75 and 100 kg N ha^{-1}, the soil-nitrate contents at harvest were lower than at sowing, but with rates of 150 and 225 kg N ha^{-1}, the nitrate content at harvest was higher than at sowing (Tables XVIII, XIX and XX).

TABLE XVIII. SOIL NITRATE CONTENT AT SOWING AND AT THE END OF WINTER WHEAT (1994/95)

Sampling time	Fertilization Code	Soil profile (cm)	Nitrate content (mg kg^{-1})
At sowing (1994-10-05)		0–15	10.35
		16–30	9.52
		31–50	11.12
		51–70	4.73
		71–100	3.67
At the end of winter wheat (1995-06-15)	N0.0	0–20	5.70
		21–40	4.79
		41–60	1.45
		61–80	3.23
	N0.5	0–20	9.68
		21–40	7.89
		41–60	5.19
		61–80	1.87
	N1.0	0–20	5.12
		21–40	5.72
		41–60	9.37
		61–80	15.12
	N1.5	0–20	14.28
		21–40	26.24
		41–60	31.50
		61–80	29.25

TABLE XIX. SOIL NITRATE CONTENT AT SOWING AND AT THE END OF WINTER WHEAT (1995/96)

Sampling time	Fertilization Code	Soil profile (cm)	Nitrate content (mg kg^{-1})
At sowing		0–15	11.53
		16–30	9.34
(1995-10-05)		31–50	12.09
		51–70	6.78
		71–100	7.35
At the end of winter	N0.0	0–15	3.53
		16–30	2.76
wheat (1996-06-13)		31–50	1.05
		51–70	0.89
		71–100	0.54
	N0.5	0–15	3.13
		16–30	3.49
		31–50	2.20
		51–70	1.48
		71–100	0.59
	N1.0	0–15	8.78
		16–30	8.84
		31–50	4.85
		51–70	2.41
		71–100	1.36
	N1.5	0–15	5.88
		16–30	10.94
		31–50	3.10
		51–70	0.79
		71–100	0.66

TABLE XX. SOIL NITRATE CONTENT AT SOWING AND AT THE END OF WINTER WHEAT (1996/97)

Sampling time	Fertilization Code	Soil profile (cm)	Nitrate content (mg kg^{-1})
At sowing		0–15	10.87
		16–30	10.23
(1996-10-05)		31–50	9.09
		51–70	10.89
		71–100	5.67
At the end of winter	N0.0	0–15	4.04
		16–30	1.11
wheat (1997-06-13)		31–50	1.11
		51–70	1.10
		71–100	0.74
	N0.5	0–15	1.45
		16–30	2.57
		31–50	0.72
		51–70	0.72
		71–100	0.75
		0–15	9.41
	N1.0	16–30	5.06
		31–50	2.86
		51–70	2.14
		71–100	12.50
		0–15	10.72
	N1.5	16–30	15.93
		31–50	12.58
		51–70	11.10
		71–100	10.75

TABLE XXI. SOIL NITRATE CONTENT AFTER FERTILIZATION (1994/95)

Fertilization Code	Soil profile (cm)	Nitrate content (mg kg^{-1})	
		1995-04-26	1995-05-20
N0.0	0–20	2.73	6.73
	21–40	2.10	4.56
	41–60	1.10	1.23
	61–80	3.26	2.45
N0.5	0–20	9.95	10.76
	21–40	5.93	8.67
	41–60	3.93	6.57
	61–80	3.90	3.78
N1.0	0–20	14.70	6.54
	21–40	11.60	8.43
	41–60	4.37	9.35
	61–80	5.20	15.78
N1.5	0–20	44.90	15.34
	21–40	20.30	24.90
	41–60	12.31	28.65
	61–80	9.03	30.38

- fertilization date was 1995-04-10

TABLE XXII. SOIL NITRATE CONTENT AFTER FERTILIZATION (1995/96)

Fertilization Code	Soil profile (cm)	Nitrate content (mg kg^{-1})	
		1996-04-23	1996-05-14
N0.0	0–15	2.16	1.23
	16–30	1.53	0.96
	31–50	0.66	0.67
	51–70	0.43	0.37
	71–100	0.70	0.61
N0.5	0–15	7.76	6.59
	16–30	4.76	4.41
	31–50	1.63	3.26
	51–70	0.67	1.99
	71–100	0.83	1.92
N1.0	0–15	16.20	30.06
	16–30	9.53	21.06
	31–50	3.77	10.39
	51–70	1.90	10.03
	71–100	1.60	9.85
N1.5	0–15	26.00	30.68
	16–30	12.53	16.39
	31–50	6.53	10.51
	51–70	1.90	9.43
	71–100	1.96	9.28

- fertilization date was 1996-04-05

TABLE XXIII. SOIL NITRATE CONTENT AFTER FERTILIZATION (1996/97)

Fertilization Code	Soil profile (cm)	Nitrate content (mg kg^{-1})	
		1997-04-09	1997-05-01
N0.0	0–15	4.46	9.33
	16–30	2.98	6.57
	31–50	1.87	11.18
	51–70	1.51	7.89
	71–100	1.54	2.66
N0.5	0–15	2.24	8.17
	16–30	1.12	8.18
	31–50	0.75	12.34
	51–70	0	17.29
	71–100	0	11.82
N1.0	0–15	3.70	23.87
	16–30	2.97	23.04
	31–50	2.23	9.02
	51–70	2.25	7.89
	71–100	1.90	7.27
N1.5	0–15	3.34	23.22
	16–30	3.35	24.89
	31–50	2.61	31.45
	51–70	1.49	21.05
	71–100	1.16	31.08

- fertilization date was 1997-04-10

A few days after N fertilization, the soil-nitrate concentrations increased in all layers commensurately with application rate, with more in upper layers than in lower (Table XXI, XXII and XXIII). But by three or four weeks after N application, the nitrate concentration lower in the soil was much higher, particularly with the higher N-application rates. Because this soil retained water poorly, the dissolved nitrate percolated to lower levels relatively easily, therefore increases in N-application rate must exacerbate the potential for nitrate pollution of groundwater.

4. CONCLUSION

— Under different N-application rates, the straw and grain yields of winter wheat varied significantly. Of application rates of 50, 75, 100, 150 and 225 kg N ha^{-1}, the highest grain yield was obtained with 150 kg N ha^{-1},

— Considering grain yield, fertilizer-N recovery, and soil-N balance, when ammonium bicarbonate was used as both basal and top-dressing fertilizer for irrigated winter wheat in areas such as Hebei province, 150 kg N ha^{-1} emerged as the optimum rate for future recommendation,

— When ammonium bicarbonate was applied only at sowing, N recovery was significantly higher than when applied only or partly at jointing, therefore ammonium bicarbonate is best used as a basal fertilizer,

— Water may move readily from upper to lower soil layers, therefore increases of N-application rate pose significant risk of nitrate pollution of groundwater.

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MODIFIED MICRO-DIFFUSION METHOD FOR ^{15}N-ENRICHED SOIL SOLUTIONS

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Abstract

The preparation of solutions for determination of $^{15}N/^{14}N$ isotope ratios is described, with special reference to dilute samples. A micro-diffusion method has been simplified to be more suitable for rapid isotope-ratio determination in soil solutions collected in tensionics. Ammonia expelled during micro-diffusion is captured on acidified filter discs fixed to the caps of gas-tight vials. The discs are transferred to tin capsules for shipment to the Soil Science Unit for ^{15}N-enrichment determination.

1. INTRODUCTION

Several authors (see Bibliography) have described methods to determination of $^{15}N/^{14}N$ isotope ratios in soil solutions and soil extracts, with N-concentrations as low as 5 to 20 mg N L^{-1}, using the micro-diffusion technique, subsequent Dumas combustion and continuous-flow mass spectrometry.

The method described by Brooks et al. [1] has been simplified at the Soil Science Unit to be more suitable for rapid isotope-ratio determination of soil solutions collected in tensionics. Nitrate in the soil solution is reduced to NH_4^+ in the presence Devarda's Alloy. The 140-mL containers used in the Brooks method [1] have been replaced by 20-mL liquid-scintillation vials with fixed stainless steel hooks. A 1-*M* NaOH solution, instead of MgO, raises the pH of the soil solution, therefore no glass beads are required. The NH_3 is collected as NH_4^+ on an acidified filter disc (2.5 *N* $KHSO_4$) fixed to the cap of a gas-tight vial. After a minimum diffusion time of 16 h, the filter disc is transferred to a tin capsule and placed in cluster dishes for shipment to the Soil Science Unit. Immediate shipment is necessary to avoid corrosion of the capsules.

The minimum amount of N in the sample solution required for a mass-spectrometric measurement is 50 µg. Therefore, the concentrations of ammonia (NH_4^+) and nitrate (NO_3^-) have to be determined. In cases where the N-concentration is too low, a pre-concentration step is necessary prior to diffusion.

3. MATERIALS AND METHODS

3.1. Reagents

— Devarda's Alloy, Merck p.a. No. 5341, 40 ± 5 mg per portion,
— NaOH, Merck p.a. No. 6498, ~1 *N*, i.e. 4 g NaOH per 100 mL distilled water,
— $KHSO_4$, Merck p.a. No. 4885, 2.5 *N*, i.e. 34.1 g $KHSO_4$ per 100 mL distilled water.

3.2. Items provided by the Soil Science Unit

— Glass microfibre filters, Whatman GF/D, 10 mm diam, Cat. No. 1823 010,
— Tin capsules, Microanalysis D1008, pressed 8×5 mm,
— Plastic vials, 15–20 mL, screw cap with fixed stainless steel hook, gas tight when closed,
— Plastic vials, 5 mL, for pre-weighed portions of Devarda's Alloy,
— Cluster dishes with coded caps,
— Silica gel for dry storage and transport of filter discs.

3.3. Additional items needed

- Analytical balance, accuracy ± 0.1 mg,
- Stainless steel forceps,
- Automatic pipettes, 10 mL, 1–3 mL variable,
- Rack for interim placement of caps,
- Rack for tin capsules,
- Drying oven or hot-plate,
- Disposable gloves.

3.4. Required amount of N

A minimum of 50 µg N (221 µg NO_3^-) must be collected on each filter disc. The optimum amount is 100 to 200 µg N (443–886 µg NO_3^-). The maximum volume of soil solution to be used for diffusion is 3 mL. The optimum is 2 mL, therefore, the NO_3^- concentration affects the volume of soil solution to be pipetted into the diffusion vial (Table I).

If the N-concentration of the soil solution is lower than 20 mg N L^{-1}, the solutions should be evaporated gently in a drying oven or on a hot-plate to achieve a maximum volume of 3 mL with the desired minimum concentration of 50 µg N. Evaporation to dryness should be avoided, otherwise N-losses may occur (Table II).

TABLE I. RELATIONSHIP BETWEEN NITRATE CONCENTRATION AND VOLUME OF SOIL SOLUTION

N in soil solution (mg L^{-1})	NO_3^- in soil solution[a] (mg L^{-1})	Soil solution for diffusion (mL)
~ 20–50	~ 90–220	3
~ 50–100	~ 220–440	2
~ 100–250	~ 440–1100	1

[a] Ammonium content, usually negligible in soil solutions, is not considered here; the NH_4^+ and NO_3^- contents
can rapidly be analyzed using the Reflectoquant Q® system from Merck.

TABLE II. RELATIONSHIP BETWEEN NITRATE CONCENTRATION AND VOLUME OF SOIL SOLUTION FOR PRE-EVAPORATION

N in soil solution (mg L^{-1})	NO_3^- in soil solution (mg L^{-1})	Soil solution needed for evaporation to max. 3 mL (mL)
~ 5	~ 20	10
~ 10	~ 40	5
~ 15	~ 70	3.5

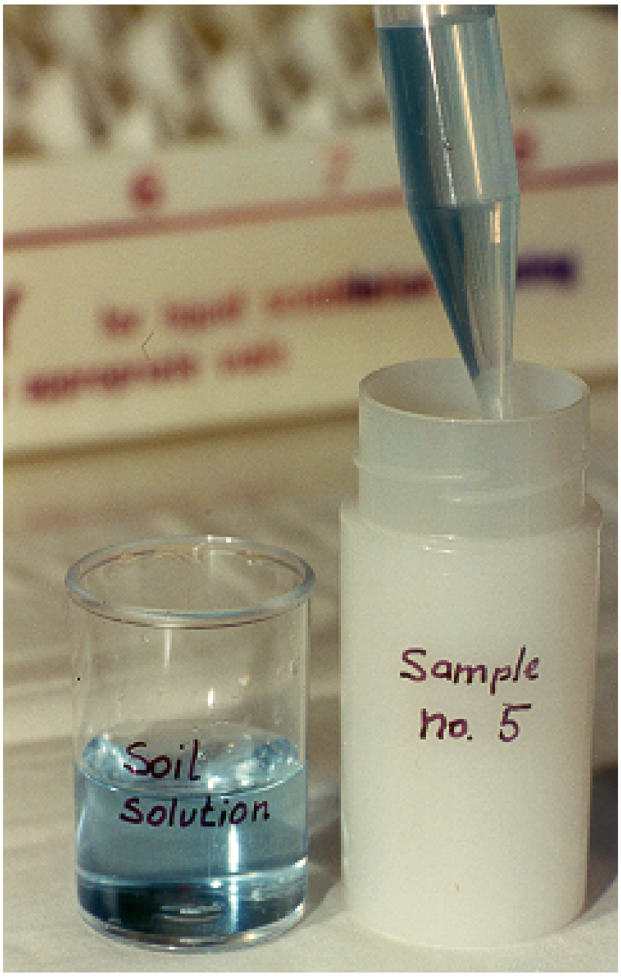
3.5. Procedure

(1) Take soil solutions from the deep freezer and leave it standing in the lab to acquire room temperature.

(2) Pre-weigh the required number of Devarda's Alloy portions (40 ± 5 mg/ portion).

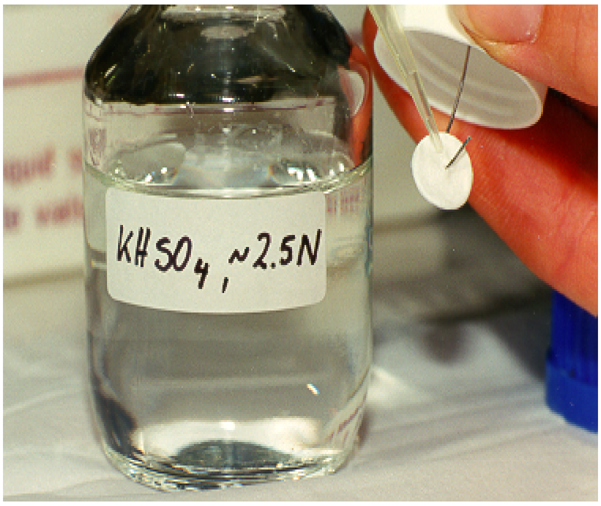
(3) Label the required amount of diffusion vials and open the first vial.

(4) Pipette the required amount of soil solution into the corresponding diffusion vial.



(5) Fix a filter disc to the steel hook of the corresponding vial using forceps.

(6) Pipette 10 ml of 2.5 N KHSO4 onto the filter disc.



(7) Place the cap with the filter disc in a rack.

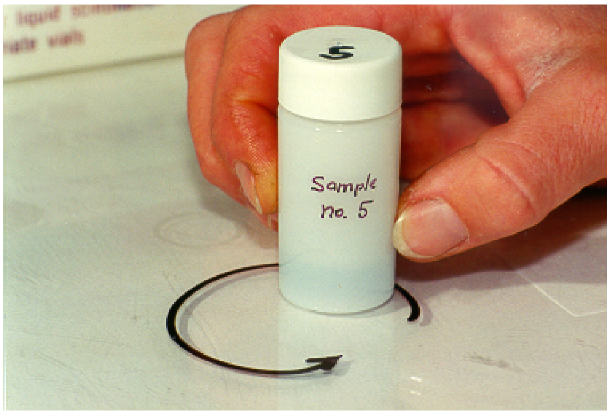
(8) Pipette 1 ml of 1 N NaOH into the diffusion vial.

(9) Add a pre-weighed portion of Devarda's Alloy.

(10) **Immediately** close the vial tightly with the cap plus filter disc.

Note: immediately after addition of Devarda's Alloy, the NH_3^- gas is released from the soil solution and has to be collected on the acidified filter disc, **otherwise the sample is lost**!

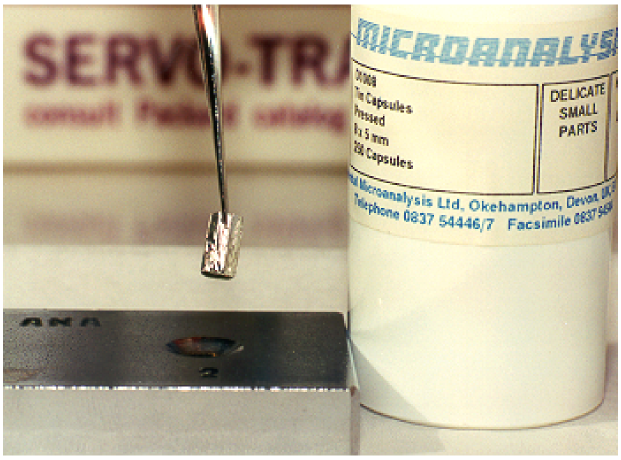
(11) Gently rotate the vial on the table to homogenize the solution without wetting the filter disc!



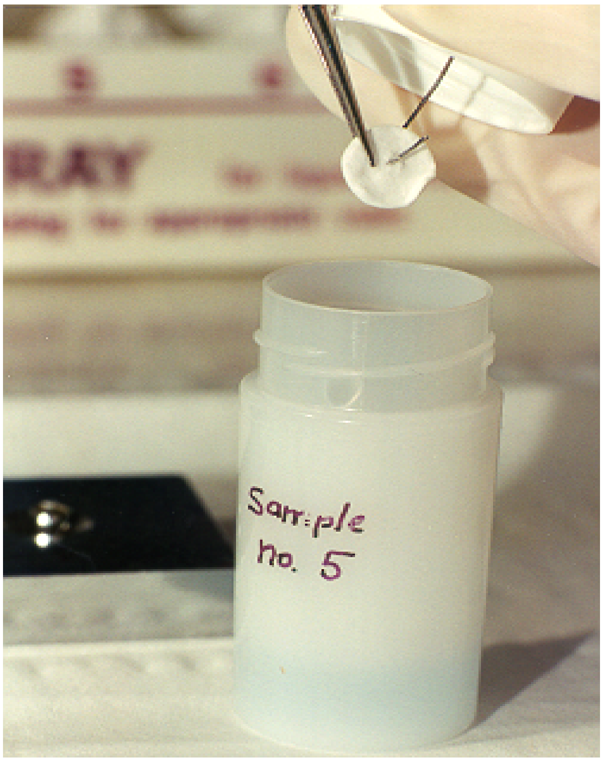
(12) Leave samples standing at room temperature for a minimum of 16 hours.

Note: Clean your hands carefully or use gloves to avoid contamination with traces of ^{14}N and/or ^{15}N.

(13) Place a tin capsule in a gap using forceps.

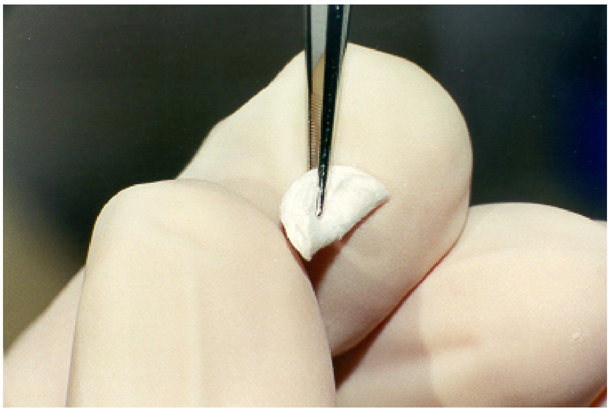


(14) After a minimum of 16 hours of diffusion time open the vial and remove the filter from the steel hook using forceps.

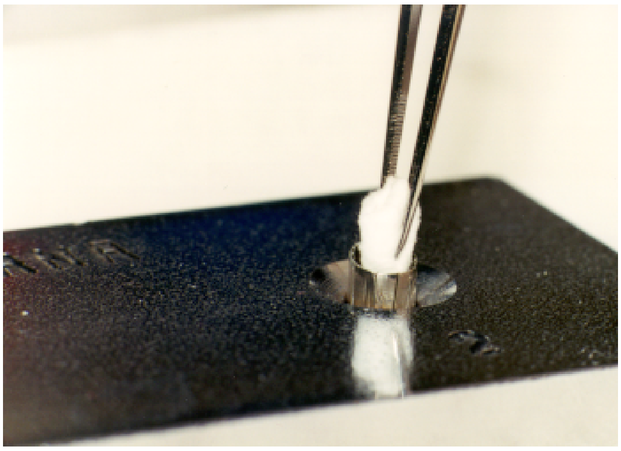


(15) Fold the filter twice using forceps.

Note: If the filter is very wet wrap it in a second clean filter disc and insert both in the tin capsule.

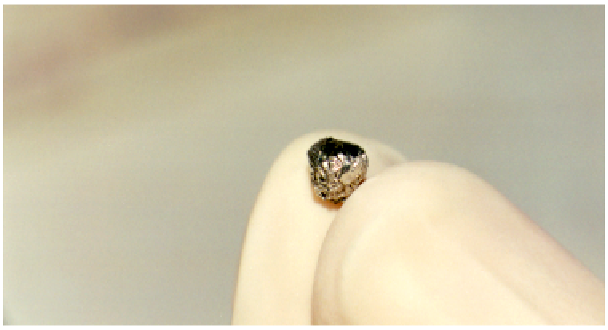


(16) Insert the filter in the tin capsule.



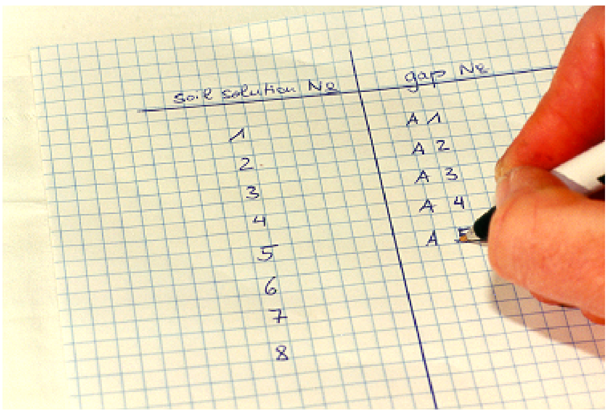
(17) Close the tin capsule using forceps.

(18) Form a little ball.



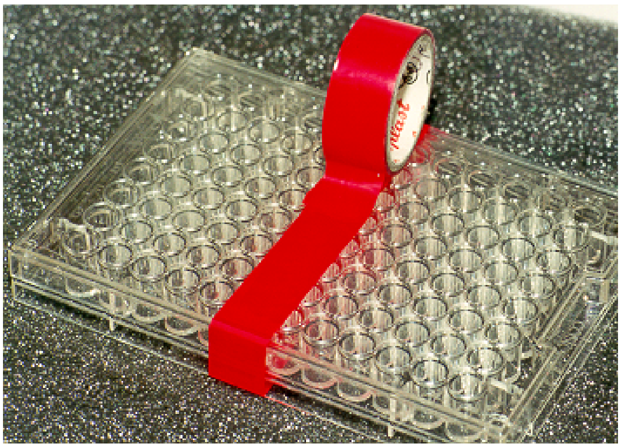
(19) Place the capsule in the coded cluster gap provided by the IAEA.

(20) Note sample number and corresponding cluster gap number.



(21) After insertion of all samples close the cluster dish using a tape to avoid opening during shipment.

Place the cluster dish **in a bag with Silicagel®** and close the bag tightly.



(22) As soon as possible ship samples plus coding list to IAEA.

3.6. Quality control

Two standard samples from a NO_3^--solution with known amounts of N and ^{15}N atom excess (code: STD1, STD2) are to be prepared in the same way as the soil solutions for shipment together with the samples for ^{15}N analysis. The results of the standard analyses will be reported to contractors together with the sample results.

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OPTIMIZING NITROGEN FERTILIZER USE: CURRENT APPROACHES AND SIMULATION MODELS

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Abstract

Nitrogen (N) is the most common limiting nutrient in agricultural systems throughout the world. Crops need sufficient available N to achieve optimum yields and adequate grain-protein content. Consequently, sub-optimal rates of N fertilizers typically cause lower economical benefits for farmers. On the other hand, excessive N fertilizer use may result in environmental problems such as nitrate contamination of groundwater and emission of N_2O and NO. In spite of the economical and environmental importance of good N fertilizer management, the development of optimum fertilizer recommendations is still a major challenge in most agricultural systems. This article reviews the approaches most commonly used for making N recommendations: expected yield level, soil testing and plant analysis (including quick tests). The paper introduces the application of simulation models that complement traditional approaches, and includes some examples of current applications in Africa and South America.

1. INTRODUCTION

The current century has been characterized by accelerating application of new technologies, many of which have resulted in detrimental effects on the environment and on the resources upon which agriculture depends. Nitrogen (N) losses from agricultural and forest soils continue to increase, as a consequence of higher yielding crops, slash-and-burn practices, gaseous conversions, leaching and erosion.

In order to compensate for these losses, modern agricultural practices have started to include the application of organic fertilizers (including green and animal manure, industrial and metropolitan wastes, etc.), and crop/pasture rotation systems [1]. However, in the vast majority of situations, these practices do not supply sufficient N to maintain optimal crop yields. Clearly, present-day crop-production systems are dependent on the use of inorganic fertilizers, with low values for efficiency of use of N.

An additional feature of N dynamics in current agricultural systems is the potentially detrimental effects of N on the environment. Numerous studies have associated low efficiency of use of N from inorganic and organic fertilizers, with potential and actual nitrate contamination of groundwater as well as eutrophication of lakes and lagoons [2, 3]. There is also a growing concern within the agricultural scientific community regarding soil production of N_2O, a "greenhouse" gas that also contributes to loss of stratospheric ozone [4, 5].

The increasing soil-N losses, the still-low efficiency of N fertilizer use, and the potential for environmental contamination are all factors hindering the development of sustainable agricultural production systems. These factors also emphasize the need to develop systems for precisely determining crop-N requirements and consequently establishing adequate N fertilizer recommendations.

Fertilizer-recommendation systems should consider the amount of N that will be available to a crop through the mineralization of the soil organic matter (SOM) and through the decomposition of residues from previous crops. The system should include information on expected gaseous and leaching losses of N throughout the crop-growing season. Consideration should also be given to the varying N requirements of different crop species at different growth stages, and for attaining different expected yield levels. Simple economical and risk analyses of different N fertilizer strategies should be included to assist farmers in the decision-making process.

Agricultural research over the past 50 years has improved understanding of soil fertility and nutrient dynamics, crop-N requirements, soil biological activity, N availability, etc. However, there is still a general need for robust N fertilizer-recommendation systems, especially in humid and sub-humid climates. This is probably due to inherent complexity, as indicated above, and the influence of uncontrollable factors such as weather.

Most existing N fertilizer-recommendation programs use one or a combination of the following indicators: expected crop-yield levels, soil-test information (SOM, total soil N, soil mineral N, soil mineralization potential, soil nitrate content, etc.), and plant-analysis data (total N, nitrate in plant sap, chlorophyll-meter data). Many of these programs do not perform adequately because they fail to consider the complex interactions of factors determining N availability.

Traditional recommendation systems are based on results from field experiments established at several sites oriented to quantify crop response to N fertilizer. Soil-test and plant-analyses results from the same sites are then evaluated as possible indicators or predictors of the crop-growth responses. Additional information is often included on variables such as expected yield levels, previous soil-management practices, previous use of animal or green manures, etc. This research approach usually results in fertilizer recommendations that are likely to be correct for a given situation. However, the probability of an erroneous recommendation for a specific field may still be significant. Moreover, a recommendation may be required for a specific situation not covered in the prior research (different soil type, different weather conditions, new cultivar, etc.).

Computer models capable of simulating the effects of weather, agronomic practices, soil properties and cultivar characteristics on the N dynamics of agricultural systems can make an important contribution to our understanding of crop responses and fertilizer behavior. This in turn may result in developing new, or refining existing, fertilizer-recommendation systems that may be used in a wide range of production conditions.

In this article, we propose that the N sub-model included in the CERES models of DSSAT can be a valuable tool for assisting the decision-making process of defining optimal N fertilizer strategies based on existing knowledge of crop responses to N in different research programs world-wide.

2. CURRENT APPROACHES

2.1. Expected yield level

This is the simplest approach, used when no soil-test or plant-analysis data are available. It is employed also in cases where available soil and plant indicators have been found to perform poorly for developing fertilizer recommendations. It consists of establishing an expected yield level, estimating the soil's ability to supply N, considering an expected efficiency of N fertilizer use (typically 50%), and calculating the amount of fertilizer required to attain the expected yield.

A strong limitation of this approach is the difficulty found in most regions of the world to estimate, a priori, the yield level expected for a specific field under a given set of climatic conditions. For example, Schepers et al. [6] conducted an extensive survey in Nebraska, USA, and found that farmers with lower-yield expectations were able to produce yields at least as high as those of farmers with high-yield expectations.

Another strong limitation lies in estimating the ability of a given soil to supply N throughout the growing season. This is especially difficult in humid and sub-humid climates [7], and/or in production systems that include rotations with legumes or cover crops [1].

Fertilizer-recommendation systems based on expected yields often advise farmers to make their N applications with the expectation of a good year [8]. This is done in order to avoid limiting yields, since the N requirement in a favorable growing season is larger than under poor conditions [9]. However, this practice implies that excessive N is applied in all years during which sub-optimum growing conditions prevail, with consequent economic and environmental costs.

However, consideration of expected yield may be useful when in combination with other indicators such as soil-test and plant-analysis data. Most recommendation systems currently in use world-wide, implicitly or explicitly, include information on expected yield level [6, 10].

2.2. Soil testing

The vast majority of current N fertilizer-recommendation systems use one or several soil-testing procedures to determine optimum fertilizer rates. Extensive reviews of the most common approaches have been published [8].

Two approaches are typically used when considering soil-test data for N fertilizer recommendations: assessing the soil's ability to supply N through mineralization of SOM, or determining the availability of mineral N in the profile at a specific time.

Some recommendation systems are based on SOM content as the sole index of the soil's ability to supply N, with the rationale that higher SOM mineralizes larger amounts of N than lower SOM in the same soil type A first limitation of this approach consists of the difficulty in determining the amount of N that a soil will supply. The potential N mineralization can be estimated with standard procedures, however, the amount of N that a soil will actually supply to a crop in a given growing season is, a priori, difficult to estimate, since it depends on the climatic characteristics of the season, previous soil- and crop-management practices (e.g. tillage, crop-residue disposal), etc.

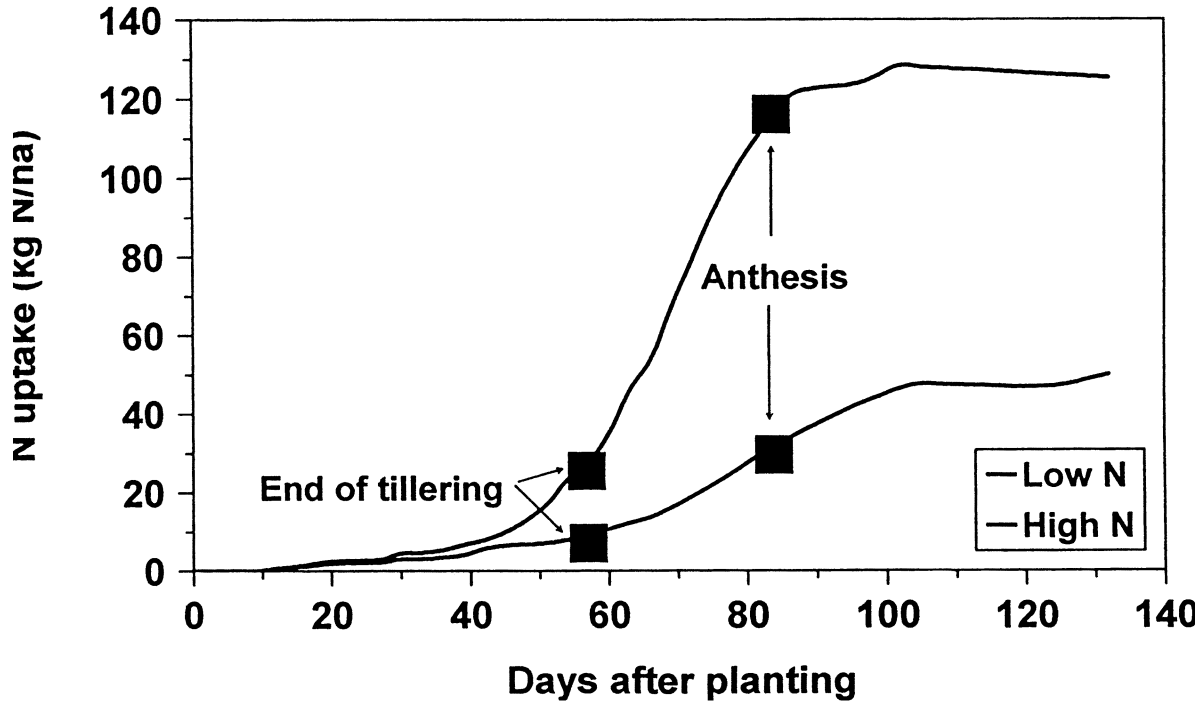

FIG. 1. Nitrogen uptake curves for a winter wheat crop growing in a temperate climate with two levels (high = non-limiting, low = limiting) of plant-available N.

Better results can be expected when considering the amount of mineral N present in the soil profile at a given time. The amount of N required by a crop varies during the growing season, typically following a sigmoidal dry-matter production curve [11]. Thus, N requirements are low during early growth up to a first inflection point at which dry-matter production and N uptake rapidly increase, e.g. onset of stem elongation in wheat and barley [11] or 6-8 leaves in maize [12, 13]. Dry-matter production and N-uptake rates peak during this period and the curve reaches a second inflection point, typically after anthesis, after which both rates gradually decrease (Fig. 1).

Knowing the expected N-uptake curve for a crop in a given location would greatly improve the ability to recommend the optimum N fertilizer rate. Sufficient N should be available in the soil at planting to ensure seedling establishment and initial growth. Although the amount of N required at these stages is low, it has been shown to be qualitatively crucial, since any early deficiency cannot be fully compensated with later fertilizer applications [11]. On the other hand, excessive available N during early growth can result in excessive tiller population, lodging, and stem disease, and in contamination of groundwater with nitrate [2].

The onset of rapid dry-matter production is the second key growth stage at which to plan rational N fertilizer-management strategies. This is the growth stage that immediately precedes the period of maximum rate of N uptake, therefore, available N in the soil should be targeted to fulfill the crop-N requirement for optimal yields [14, 15].

Researchers have also reported that in long-season winter-wheat cultivars other crop-growth stages occurring between emergence and end of tillering may also be important for determining optimal fertilizer recommendations. For example in wheat, mid-tillering (Zadoks growth stage 25 [16]) can be another important growth stage for achieving optimal N fertilizer applications [17].

Several fertilizer-recommendation systems based on the soil mineral-N content (nitrate and ammonium) accommodate the key growth stages described above. In climates with low rainfall, it may be sufficient to consider only the soil mineral-N content at planting [9, 18, 19]. However, in humid and sub-humid climates, large N-losses can be expected via leaching and denitrification during early growth if the N is applied in a single dose at planting. In such situations, researchers usually try to make recommendations based on the soil mineral-N content at the growth stage at which dry-matter production accelerates. For example, many N fertilizer-recommendation systems for maize are currently based on the soil mineral-N content at the 6-8 leaf stage [12, 20–24].

A limitation of recommendation systems based on the soil mineral-N content is that the amount of nitrate may be strongly influenced by rainfall immediately before sampling. This is especially important in well drained soils with samples from the surface 20 cm. An additional limitation of these recommendation systems consists of the fact that they do not consider N losses that may occur after the fertilizer application.

Finally, these systems do not consider the soil's ability to continue supplying N after fertilizer is applied. The contribution of N via mineralization can be important in conditions of high SOM content, and/or in situations where crops are rotated with legumes or cover crops. Recent research has revealed that the contribution of residues from previous crops can be significant and should be considered for determining N fertilizer recommendations [1, 25–29].

The importance of the potential contribution of residues on N fertilizer needs was recently demonstrated by Decker et al. [25] who reported contributions from previous legumes equivalent to 200 kg N ha^{-1}, which resulted in savings of N fertilizer for subsequent maize of up to 76 kg N ha^{-1}. Their research revealed also that the effects of previous legume pastures included an increase in the maize-yield potential, especially in soils with low SOM content and low water-holding capacity.

Many efforts have been made to partially overcome the limitations of recommendation systems based on the soil mineral-N content. A typical approach used with varying degrees of success has been to combine the information on soil mineral-N content with other indices, e.g. yield goals and organic N [10], potentially mineralizable N and crop-residue contribution [26], and SOM content [30].

2.3. Plant analysis

Fertilizer-recommendation systems that use plant analysis are based on the fact that if one can identify a growth stage in which N availability in the soil is critical, the plant should be the best indicator of such availability. Moreover, the total N taken up by a crop is a reflection of N availability during the growing season and, therefore, may be regarded as the best indicator of the soil-N status. Thus, an advantage of plant-analysis data is that they integrate the effects of all factors affecting N availability to the crop (weather conditions, crop-residue decomposition, residual effects of fertilizer, etc.).

Ideally, plant analysis would be carried out at a crop-growth stage that is sufficiently late to indicate expected yields and N requirement, and sufficiently early to allow a good crop response to N application. This approach has been successfully used in southeastern USA to predict optimum N fertilizer rates for winter wheat [31–34]. Research on wheat in Virginia has shown that the end of tillering (Z-30) is the latest growth stage at which the crop can efficiently respond to N fertilizer application. As mentioned above, this is the stage that immediately precedes the maximum rate of crop dry-matter production. Tiller count and/or dry-matter production at Z-30 can help to determine expected grain yields and, consequently, the crop's N requirement [31].

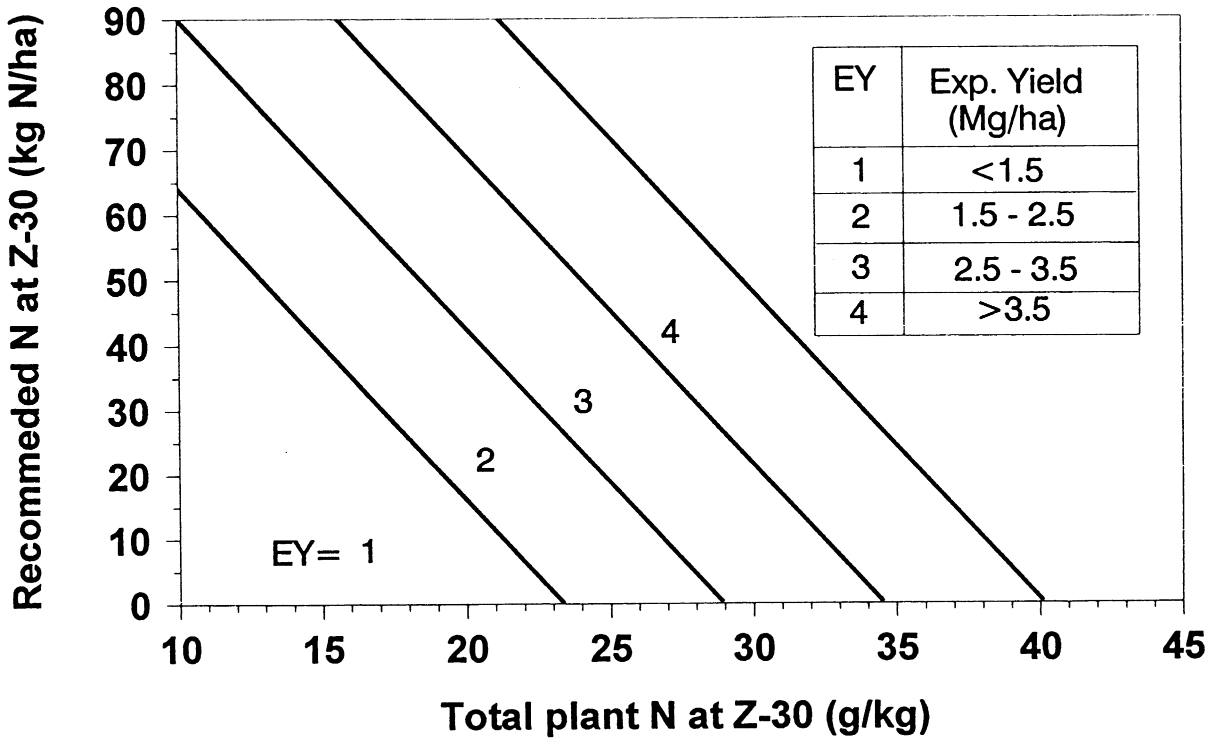

FIG. 2. Nitrogen fertilizer recommended rates at the end of tillering (Zadoks 30) based on plant-N content (g N kg^{-1} dry matter) and expected grain yield. The system includes a basal application of 30-40 kg N ha^{-1} at sowing [35].

Some researchers have also used plant analyses in combination with other indices to make N fertilizer recommendations. For example, Baethgen et al. [35] developed a system for optimal N fertilization of malting barley in Uruguay based on plant analysis and expected yield: a blanket fertilizer rate of 30 to 40 kg N ha^{-1} is applied at sowing to ensure adequate plant establishment and tillering, then are considered (a) the expected yield level for the field and (b) the above-ground plant-N content at the end of tillering (Z-30), to estimate the recommended N rate at that stage of growth (Fig. 2).

Plant analysis, however, presents the same limitation as the soil mineral-N test in that it provides no information on the amount of N that will become available, or the amount of N lost after the plant sample is taken. An additional drawback of plant testing is that plant-N content varies considerably during growth. Researchers have tried to reduce this limitation by combining the information of plant-N content with other parameters such as dry-matter production of tillers [31] or with the number of produced tillers [32] at time of sampling.

More recently, researchers developed fertilizer-recommendation systems with plant analysis that are based on quick tests performed in the field. The advantage of these tests is that a farmer can assess the N status of a crop at critical stages, and avoid potential problems of sample handling, delays in the laboratory analysis, etc., that can be a constraint in less developed countries. Among the most widely used and promising quick plant tests are for stem-nitrate content [36–38] and leaf-chlorophyll readings [13, 39–42].

3. APPLICATION OF CROP-SIMULATION MODELS

The previous section leads to the conclusion that an ideal N fertilizer-recommendation system should consider:

– Crop-yield level expected for the specific field in which the N fertilizer recommendation is needed,
– Expected N release from the soil via mineralization of SOM throughout the current growing season,
– Expected release of N from residues of previous crops throughout the current growing season,
– Possible residual effect of N fertilizer applied to previous crops,
– Potential N losses via erosion, leaching, denitrification and ammonia volatilization, throughout the entire crop growing season.

Developing a fertilizer-recommendation system that considers all of these variables, based exclusively on experimental results, is impossible. The complexity of the factors and their interactions would require a volume of information unfeasible for most research programs. Moreover, such a precise fertilizer-recommendation system is inconceivable since it would require prior information of certain events, e.g. N losses (leaching, denitrification, etc.) and/or gains (mineralization, residue decomposition, etc.) that occur after the fertilizer is applied.

Advances in information technology, including crop-simulation models and decision-support systems such as DSSAT, may provide the best means of overcoming these limitations [43]. A key piece of information that is needed, a priori, when recommending a N fertilizer rate, is the weather that will prevail after the fertilizer is applied. Weather conditions determine N dynamics (mineralization, residue decomposition, N losses, etc.) as well as crop development and production. If daily weather information is available for the site under study, DSSAT can be used to generate possible weather scenarios and evaluate the effectiveness and the risk associated with different N fertilizer strategies. Even at sites where long-term daily weather information is unavailable, weather generators such as WeatherMan [44], which is included in DSSAT, can be applied to generate possible scenarios considering decadal or monthly averages. Moreover, in locations where weather conditions are known to be affected by large-scale anomalies (e.g. El Niño/La Niña/Southern Oscillation [45, 46]), weather generators can be trained to create data conditioned to the expected prevailing phase of such anomalies. Thereafter, these scenarios can be used in the models also included in DSSAT that simulate crop development, growth and production as well as residue decomposition, SOM mineralization and N losses.

Adequate systems are usually required to generate optimal fertilizer recommendations for large regions or even entire countries. A typical approach to achieve this objective consists of selecting sites representative of major agricultural regions and establishing fertilizer-response experiments. Fertilizer recommendations are then developed considering the best average performance. However, the number of sites and years that can be included in this type of program is limited, typically due to financial and/or labor constraints. A decision-support system such as DSSAT can be an excellent tool for extrapolating or interpolating experimental results to help define recommendations for regions for which research data are unavailable.

Although simulation models and computerized decision-support systems for establishing fertilizer recommendations are still in the developmental stage, they have been applied in various parts of the world. Below are examples to illustrate their potential for improving our ability to predict N fertilizer needs.

One of the best examples of the application of crop-simulation models for adjusting N fertilizer inputs was published by Keating et al. [47]. These researchers suggested that, whereas traditional agricultural research compares farming strategies that are fixed over time, most farmers make conditional decisions and adjust their crop- and soil-management practices considering indicators of the current or forthcoming growing season. For example, in climates with a rainy season, farmers typically adjust plant-population density and fertilizer rates in accordance timing and intensity of the first rains.

Keating et al. [47] used the CERES-Maize model to simulate realistic conditional strategies for N fertilizer and plant population in Kenya. On the basis of the theory that with the concept that the date the start of the season is a predictor of potential yield, and, therefore, of the ability of a crop to respond to inputs, they used the model to automatically simulate planting at the onset of the rains, and with various delays. They compared several fixed N fertilizer and plant-population strategies with conditional strategies at two levels of input use. The conditional strategies consisted of adjusting fertilizer rate and plant density considering the delay after the onset rains: for a given level of input use, fertilizer rate and planting density were reduced as the crop was planted at later dates after the onset of the rainy season.

The results indicated that benefits in average returns when using conditional management strategies were small compared to those obtained by simply using fertilizers, with or without forecasts. However, the conditional approach significantly reduced production risks since the number of years with negative gross margins were minimized. Reducing the probability of negative margins is imperative for small holders, but it is increasingly becoming critical also for farmers of medium and large areas.

The research conducted by Keating et al. [47] is an excellent example of the potential benefits of considering research results, weather information, and farmers' attitudes, and applying weather generators and crop-simulation models to provide information that can be essential for making management decisions. Important advances are being made in the use of general circulation models (GCMs) for inter-annual and seasonal climatic predictions at the regional level, especially in El Niño/Southern Oscillation (ENSO) related anomalies [45, 48, 49]. The information produced by GCMs can be entered into generators to create weather scenarios at the regional level for use with crop-simulation models and decision-support systems to assess the possible effects of predicted climatic conditions on crop production and N fertilizer requirements, applying methodology similar to that used by Keating et al. [47].

A major objective of agricultural research is to generate information to enable farmers to make better decisions related to crop- and soil-management strategies. The generated information must, therefore, assist in the solution of a perceived problem, and/or must result in economic, environmental or social benefit. These aspects are intrinsically related to the value of the produced information. Thornton and MacRobert [50] addressed the issue of information value, by studying a “perfect” prediction system, i.e. one in which future weather is known with certainty, for establishing optimal N fertilizer rates for maize in Florida. Their rationale was that if the value of “perfect” information can be shown to be large, it would justify investment in the development of “imperfect” predictors that have most of the benefits of “perfect” counterparts.

Thornton and MacRobert [50] used CERES-Maize to maximize the gross margin of maize production with various rates and timings of N fertilizer, over ten growing seasons. The value of the perfect information system was calculated by comparing the optimal N schedules estimated by the CERES model with the N fertilizer management strategy typically used in the study region. Their results indicated that the mean value of a perfect weather predictor in their conditions was \$105 ha^{-1}. The second largest margin was obtained when applying the average CERES-estimated optimal schedule across all years, which resulted in average gross margins that were \$40 ha^{-1} higher than the corresponding traditional N schedule, with a smaller coefficient of variation. These results indicated that in the absence of a perfect information system, the ex-ante simulation runs would foster improved N fertilizer management.

A decision-support system can also be an excellent tool for evaluating the performance of a proposed N fertilizer regime. As mentioned in 2.3., Baethgen et al. [35] developed a system for optimal N fertilization of malting barley in Uruguay that consisted of applying 30 to 40 kg N ha^{-1} at sowing and then considering the above-ground plant-N content at the end of tillering (Z-30) to estimate the requirement for more N. The authors used the CERES-Barley model with 20 years of measured weather data to compare the yields obtained with the farmers' traditional N fertilizer rates to the yields obtained by applying 40 kg N ha^{-1} at planting and using their proposed recommendation system at Z-30. They also included in the comparison an unfertilized control, a hypothetical case of unlimited N availability throughout the growing season, and a treatment with 40 kg N ha^{-1} applied at planting and unlimited N availability after Z-30. The results indicated that the proposed recommendation system performed better than the farmers' traditional practice and very similarly with the treatment with 40 kg N ha^{-1} applied at planting and unlimited N after Z-30 (Fig. 3). Moreover, comparing the unfertilized check, the farmers' traditional schedule and the proposed recommendation system, the latter allowed for higher gross margins and was the only one with non-negative values (Fig. 4).

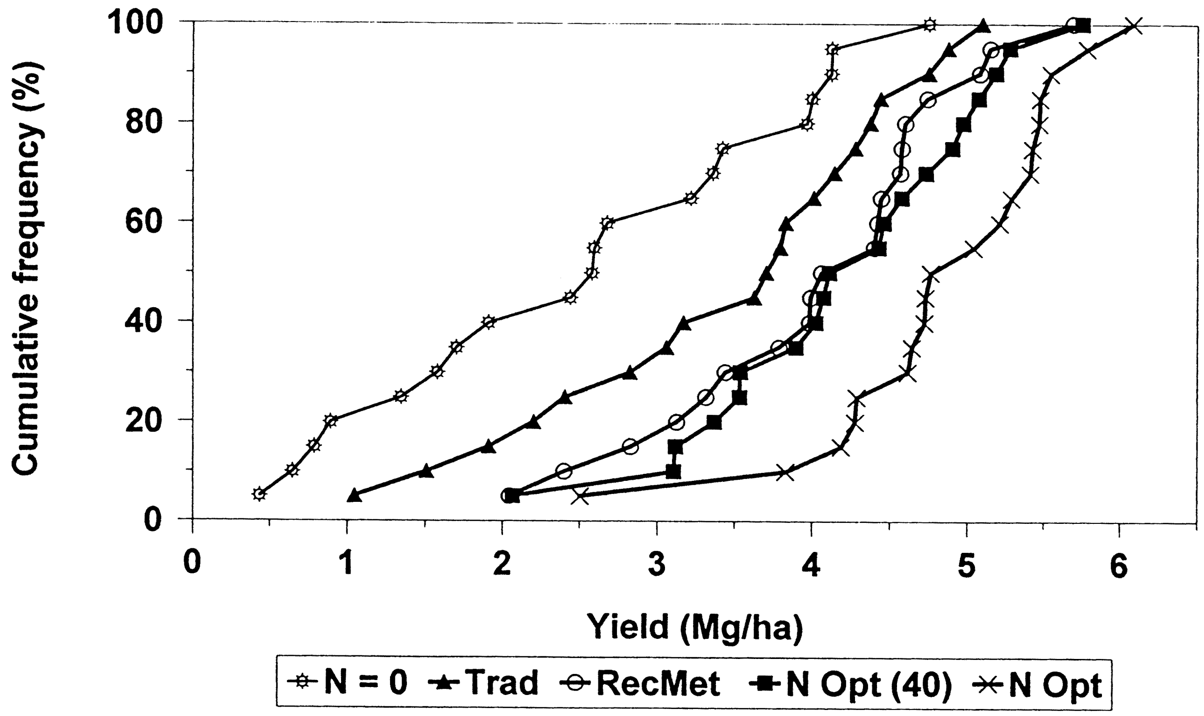

FIG. 3. Cumulative frequency curves of CERES-simulated barley grain yields comparing five N fertilizer strategies: (a) N = 0, no fertilizer applied; (b) Trad: farmers' traditional practice (40 kg N ha^{-1} at sowing); (c) RecMet, recommended method by Baethgen et al. [35]; (d) N Opt(40), 40 kg N ha^{-1} at sowing and non-limiting N availability after Zadoks 30; and (e) N Opt, non-limiting N throughout the growing season.

Clearly, a complexity of factors and interactions are to be considered when making a sound N fertilizer recommendation. One of the key variables to be addressed is expected N release via the decomposition of residues of crops and pastures previously grown in the field in question. In many agricultural production systems, increasing importance is being ascribed to including legume pastures in rotation with crops [25, 27]. In some regions, the pastures are used as green manures, and, in others, they are utilized as fodder for beef, wool and milk production.

Recent research conducted by Crozier et al. [26] evidenced the need of assessing the contribution of N release from decomposition of crop residues, especially in agricultural production

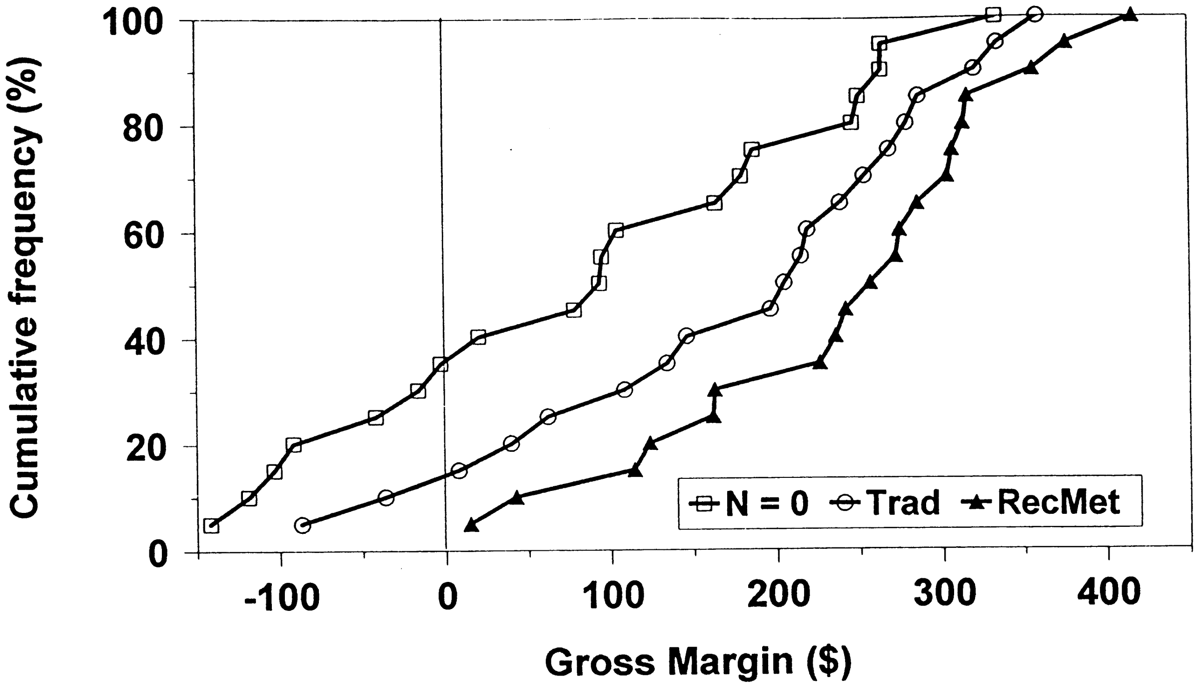

FIG. 4. Cumulative frequency curves of CERES-simulated gross margins ($ ha^{-1}) for barley produced using three N fertilizer strategies: (a) N = 0 no fertilizer applied; (b) Trad, farmers' traditional practice (40 kg N ha^{-1} at sowing); (c) RecMet, recommended method by Baethgen et al. [35].

systems with reduced chemical inputs. The amount of nutrients released via decomposition of plant residues has typically been addressed in studies using litter bags [51, 52, 53]. Litter-bag studies indicate the amount of nutrient remaining in the plant residues after various periods of time, but say nothing of the fate of the released nutrients. The N sub-model [54] included in the CERES models, and other N-dynamics simulation models [55, 56] can also be used to estimate N release from residue decomposition, with the advantage that it can assess the fate of the released N and also consider the effects of weather conditions, soil type, crop- and soil-management practices on the resulting N availability.

Bowen et al. [57] conducted a study to test the ability of the N sub-model of the CERES models to simulate N mineralization, nitrate leaching and maize N uptake after incorporating ten different legumes in an oxisol in the Cerrados of central Brazil. The performance of the N sub-model was adequate for simulating the amount of mineral N present in the soil at intervals up to 320 days after residue incorporation [57]. Under conditions of excessive rainfall, the N availability in the soil was better simulated after modifying the original N sub-model to allow for nitrate retention in the subsoil.

Farmers in many agricultural regions of the world plant annual crops in rotation with pastures that are grazed for beef, wool and dairy production. These diversified production systems usually allow farmers to obtain more stable long-term economic benefits, and result in efficient utilization of the natural resource base [58]. Crop and pasture residues, as well as animal manures, play a key role in the nutrient dynamics of these production systems [59]. The CERES N sub-model used by Bowen et al. [57] can be broadened to take into account the N cycling in animal manure and urine for mixed production systems.

In summary, establishing N fertilizer recommendations that optimize economical results for the farmer and prevent contamination and ensure adequate conservation of natural resources requires the consideration of large numbers of variables and their interactions. It is likely that future recommendations will be based on a combination of traditional approaches (soil and plant tests, yield expectation, etc.) and information from simulation models. It is, therefore, crucial to continue generating research results to improve current indices and develop new ones for establishing good N fertilizer recommendations. It is also critical to continue research programs oriented at improving the performance of N-simulation models. One of the best possibilities for refining N-simulation models, such as the one included in DSSAT, is through the use of isotope techniques that can accurately trace the fate of N applied in fertilizers and organic manures.

4. CONCLUSION

The last few decades have seen rapid expansion in scientific information that has improved our ability to understand N dynamics in various production systems. However, precise and robust fertilizer-recommendation systems remain unavailable for most agricultural regions of the world. A possible cause is that these systems must combine the typical complexities involved in on-farm decision-making with a large number of factors, many of which are uncontrollable, and their interactions that affect the N dynamics of crop production.

The decision-making process, including conclusions on N fertilizer use, requires the ability to accommodate increasingly complex information in space and time. Systematic incorporation of these data into simulation models and decision-support systems will be required to interpret the information and produce realistic projections on agricultural productivity and profitability, and on environmental degradation.

The effectiveness of any given N fertilizer-management system depends on its ability to match the varying requirements of the crop(s) to the spatially and temporally varying characteristics of land. Since mismatches result in reduced benefits, an objective of the recommendation system is to predict when a mismatch will occur, so that an appropriate strategy can be advocated. However, the definition of an appropriate recommendation depends on whether it is intended for a subsistence farmer or a market-oriented grower, given the differences in their aversion to risk. The definition of an adequate recommendation is also increasingly dependent on the effect it will have on the environment and on the natural resource base.

Moreover, many of the events that influence the appropriateness of a fertilizer recommendation occur after the recommendation is developed, since they are directly related to forthcoming weather conditions. Weather generators and weather-information systems are, therefore, also needed to assess the temporal variation of the production system. Recent development and applications of weather generators provide an excellent means of evaluating the stochastic nature of weather parameters. A thorough consideration of weather probabilities will assist farmers in making decisions related to weather risk, such as optimal rates and timing of N fertilizer application.

Finally, since N fertilizer-recommendation systems deal with agroecological variability, all required data must be stored geographically. Geographical information systems must be effectively used to enable users to retrieve soil, historical weather, cultivar and economical information, and adjust fertilizer recommendations to their specific needs.

Farmers will be subject to increasing pressure to adopt fertilizer-management practices that prevent environmental contamination while optimizing their economical returns. Establishing such practices will require the consideration of a large number of factors and their interactions. Future recommendations will likely be based on a combination of current approaches (soil and plant indices, yield expectation, etc.) and information from simulation models. It is, therefore, crucial to continue research to improve indicators of N availability and to refine N-simulation models, including the use of isotope techniques that can accurately trace the fate of N applied as synthetic fertilizers and organic manures.

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FIELD MEASUREMENTS OF GROUNDWATER POLLUTION FROM AGRICULTURAL LAND USE

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Abstract

This study was carried out in a problem area located to the northeast of Vienna. Several devices were installed for collecting water samples from the soil profile to measure nitrate concentration: suction cups, soil-water samplers, tensiometers and small lysimeters. Measurements of N leaching from four levels of fertilizer application were made at Gross Enzersdorf under irrigated wheat using suction cups and lysimeters. In order to determine fertilizer-N uptake by plants and the amounts retained in the soil and leached, ^{15}N-enriched fertilizer was applied to micro-plots. The nitrate concentrations below the root zone were measured for winter wheat followed by a cover crop, using suction cups. Soil-water contents were measured in the soil profile with a neutron probe and gypsum blocks, and suctions were measured with tensiometers at four depths. The yields of crops together with total N in grain and straw from fertilizer and soil were calculated. Also presented are data on the mineralization, immobilization and actual fertilizer used by the crops. Winter wheat took up between 27% and 44% of the applied fertilizer. The storage of fertilizer N in soil ranged between 22% and 36%, and only a small fraction was leached.

1. INTRODUCTION

It has been widely reported that water resources are prone to contamination from point and diffuse sources within agricultural watersheds. Non-point-source agricultural pollution of groundwater has become a threat to the environment over the past 30 years [1–3]. The relationship between N pollution and agricultural practices is largely uncontested except for some controversy. Nitrogen in the form of nitrate is a fundamentally important nutrient for plants. High rates of mineralization and excessive fertilization increase the amount of N leaching into the soil profile. Nitrate is very soluble and therefore moves with water in the soil from agricultural areas to pollute groundwater. Nitrogen transformations in soil are complex and dynamic, and have the potential to cause substantial N-losses not only via leaching, but also as a result of ammonia volatilization, and denitrification.

For some years, scientists at the Institute for Hydraulics and Rural Water Management, University of Agricultural Sciences, Vienna, have been studying the problem of N leaching in agricultural areas. Current research encompasses shallow and deep soils with various degrees of cultivation, and various N-fertilizer carriers (e.g. mineral fertilizers, liquid manure, sewage sludge). Simple field-testing and measurement sites have been set up at various locations where groundwater samples are collected at different depths to determine the extent of N leaching into groundwater.

To measure the water content of soil profiles, several devices are available, including gypsum blocks and neutron probes. Similarly, technologies have been developed to measure pollution of groundwater by monitoring nitrate concentration. These provide information on the movement of N in and from agricultural areas. As nitrate in groundwater can come from fertilizer application and/or soil mineralization, fertilizers are often labelled with distinguishing isotopes. Cover crops planted during fallow seasons are also important users and contributors of N; they assimilate and store N, and during subsequent tillage are incorporated into the soil and slowly release N by mineralization. Considering these aspects, the current research project was undertaken with the objective of measuring and comparing various soil-water content and soil-water sampling devices. Other objectives included measuring nitrate concentration below the root zone, together with determining the fate of fertilizer applied at four rates to winter wheat followed by a cover crop.

Over the past several years, concern has been growing over the maintenance of quality of Austria's vast water resources [4]. On the plains, where groundwater is a major source of drinking water, nitrate concentrations have increased dramatically in the past four decades. Among the various land uses causing groundwater pollution, agriculture is generally recognized to be a chief contributor. The

TABLE I. GROUNDWATER POLLUTION IN AUSTRIA (BUNDESMINISTERIUM FÜR UMWELT, 1996)

State	Total investigated area		One critical substance above limit		Contaminated area by nitrate	
	km^2	%	km^2	%	km^2	%
Burgenland	1,685	100	1,685	100	1,442	85
Carinthia	898	100	571	63	100	11
Lower Austria	3,039	100	2,025	66	1,909	62
Upper Austria	2,379	100	2,032	85	1,352	56
Salzburg	171	100		0		0
Styria	753	100	559	74	518	68
Tyrol	414	100	101	24		0
Vorarlberg	261	100	216	82		0
Wien	318	100	318	100	318	100
Austria	**9,918**	**100**	**7,507**	**75**	**5,639**	**56**

TABLE II. RATES OF FERTILIZER IN $kg.ha^{-1}$ NITROGEN

Treatments		Unfertilized	Fertilized 100%	Fertilized 150%	Fertilized 200%
Winter wheat	1995/96	0	120	180	240
Cover crop	1996	0	0	0	0
Soybean	1997	0	60	90	120
Winter barley	1997/98	0	120	180	240

pollution in each province is presented in Table I. Components investigated included nitrate, nitrite, ammonium, chloride, phosphate, sodium, potassium, atracine and its metabolites, tetrachlorethen and 1.1 dichlorethen. The government of Austria has forbidden the use of atracine as a pesticide, therefore it was not included in our list of pollutants. Table II presents the total area investigated for pollution control, the area contaminated by at least one of the above mentioned controlled substances and the area contaminated by nitrate, for all nine states of Austria.

In Lower Austria, total groundwater area is about 3,000 km², with 66% contaminated because at least one pollutant was found to be above its threshold value. Out of this, about 62% is contaminated by nitrate only. Table II shows also that groundwater contamination by nitrate has reached serious proportions, which was the main reason the present research was undertaken.

During the last few decades, mechanization has contributed to an intensification in agriculture leading to higher nitrate concentrations in groundwater reserves [5]. In Austria, the limit for nitrate in drinking water has been set at 50 mg NO_3^- L^{-1} [6]. Periodical testing of aquifers has revealed that 17 to 20% are in excess of that limit. Literature and reports on nitrate in aquifers indicate that about half of that pollution is caused by agricultural activities, the other half is contributed by point sources, e.g. business, industry and sewerage [7]. Current pollution is such that for an aquifer of a depth of 25 m (pore volume 0.35) a nitrate concentration of 60 mg L^{-1} would take more than 30 years to fall to 30 mg L^{-1}, if a nitrate-free percolation rate of 200 mm $year^{-1}$ were available [8].

The use of N-fertilizers in Austria increased from 12 kt N in 1946 to 118 kt in 1970. Since 1970, a slow reduction to 103 kt N has occurred [9]. Despite this trend, nitrate concentrations in groundwater have increased with enrichments in organic N in the upper soil layers. The mineralization of organic N to ammonium and, in turn, its nitrification to nitrate add to the effects of fertilization. Leaching of N to the groundwater occurs mainly in the form of nitrate; ammonium is immobile in soils.

The aim of this work was to establish the suitability of four devices for determining soil-water quality, through the measurement of the nitrate content and ^{15}N-content in the sampled soil solutions. The experiment was part of a larger project of sixteen plots, in each of which eight suction cups and one small lysimeter were installed. Twelve of these plots were used in this work for suction-cup/lysimeter comparisons; six plots were equipped also with tensionics, and three contained soil-water samplers.

2. MATERIALS AND METHODS

2.1. Site

The experiment was located in the northeast of Vienna, Austria (48°25'N 16°30'E). The climate diagram shows precipitation and temperature from 1961 to 1990; the average annual precipitation is 551 mm and temperature 9.7°C (Fig. 1). No dry period is predictable, although rain-free intervals of 20 to 40 days may occur once or twice during the growing season [10]. Therefore, irrigation is required for many crops grown in the area.

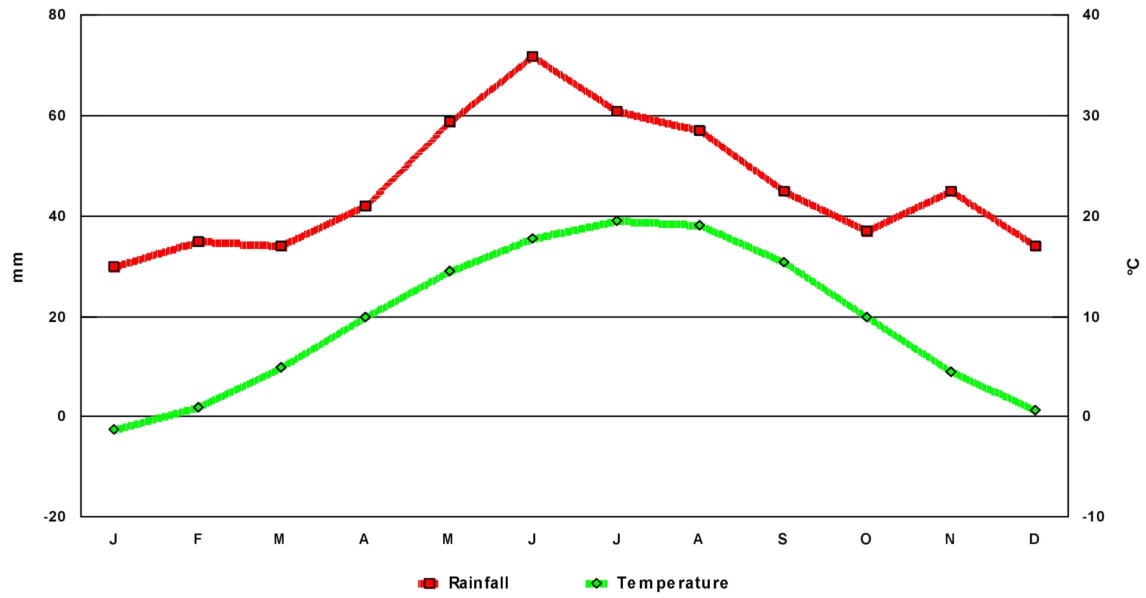

FIG. 1. Climatic diagram of the study area from 1961 to 1990.

2.2. Measuring devices

Soil-moisture determinations were made with tensiometers (tensionics), gypsum blocks, and the neutron probe (SOLO 40). Small lysimeters and suction cups were employed to measure N leaching. In order to eliminate influences of fences or windbreak hedges, the measuring devices were installed at least 7 to 8 m from the edge of the field. The distance from wind-protection appliances was at least 50 m.

The ceramic suction cups had a diameter of 20 mm, a length of 80 mm, and an average pore size of 1.0 to 1.5 µm (Fig. 3a). They were connected with 1-mm diameter tubing, about 10 m in length, to a collecting bottle within a measuring unit [11]. The water samples were translocated to the measuring unit by maintaining continuous suction in the tubes (Fig. 2). Due to the small diameter of these tubes, only about 8 mL of water were stored in each tube at any time. The ceramic suction cups were installed horizontally into undisturbed soil and samples collected weekly. Two suction cups were installed at each location.

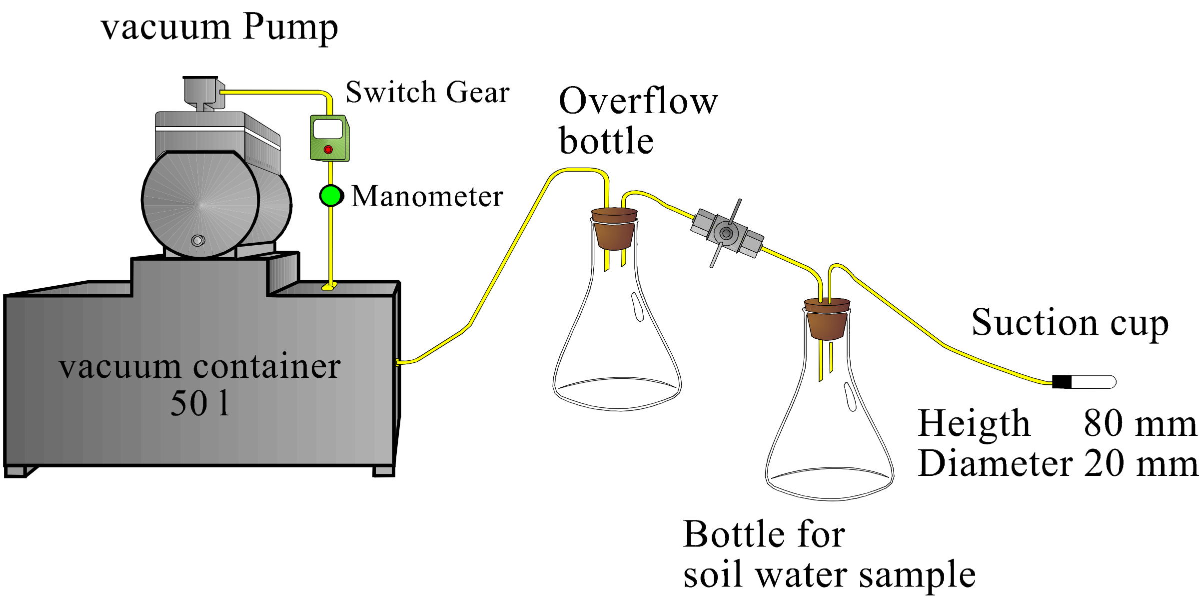

FIG. 2. Suction cup and the vacuum system.

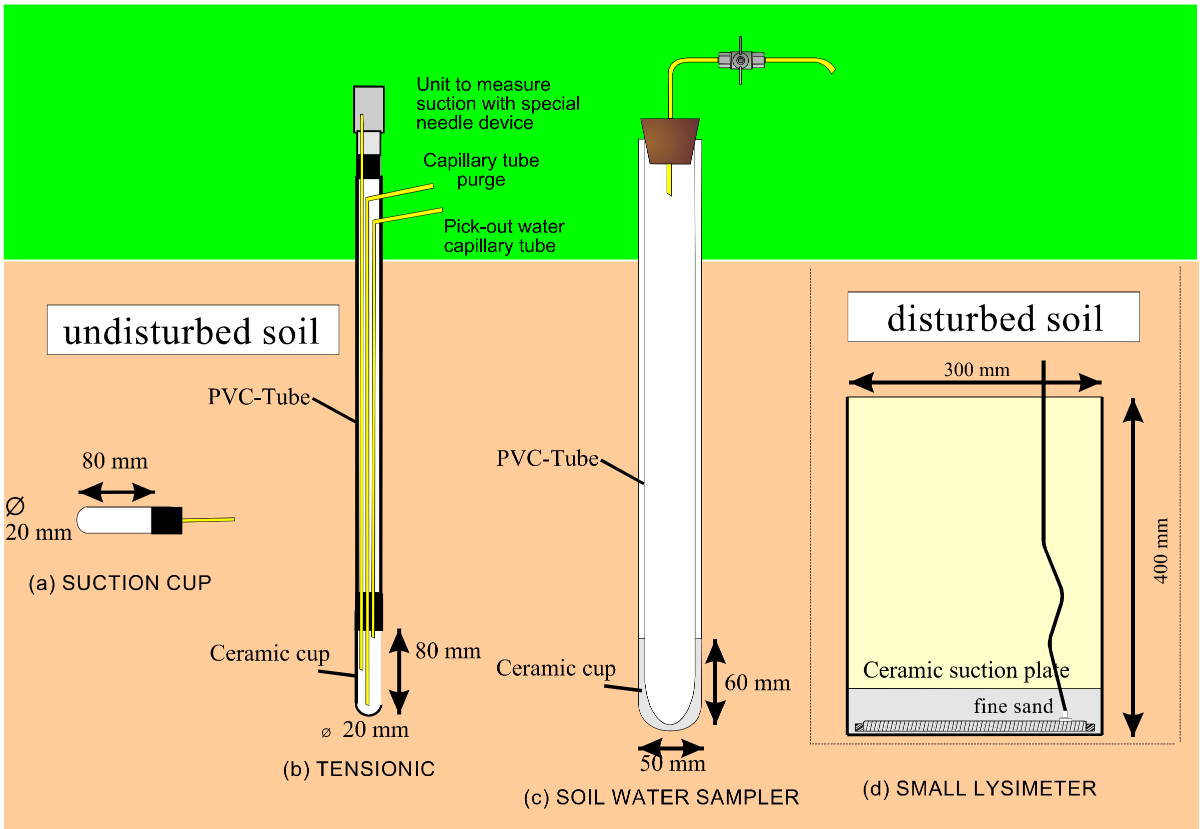

FIG. 3. Devices for measuring suction, percolation and nitrate concentration in the soil.

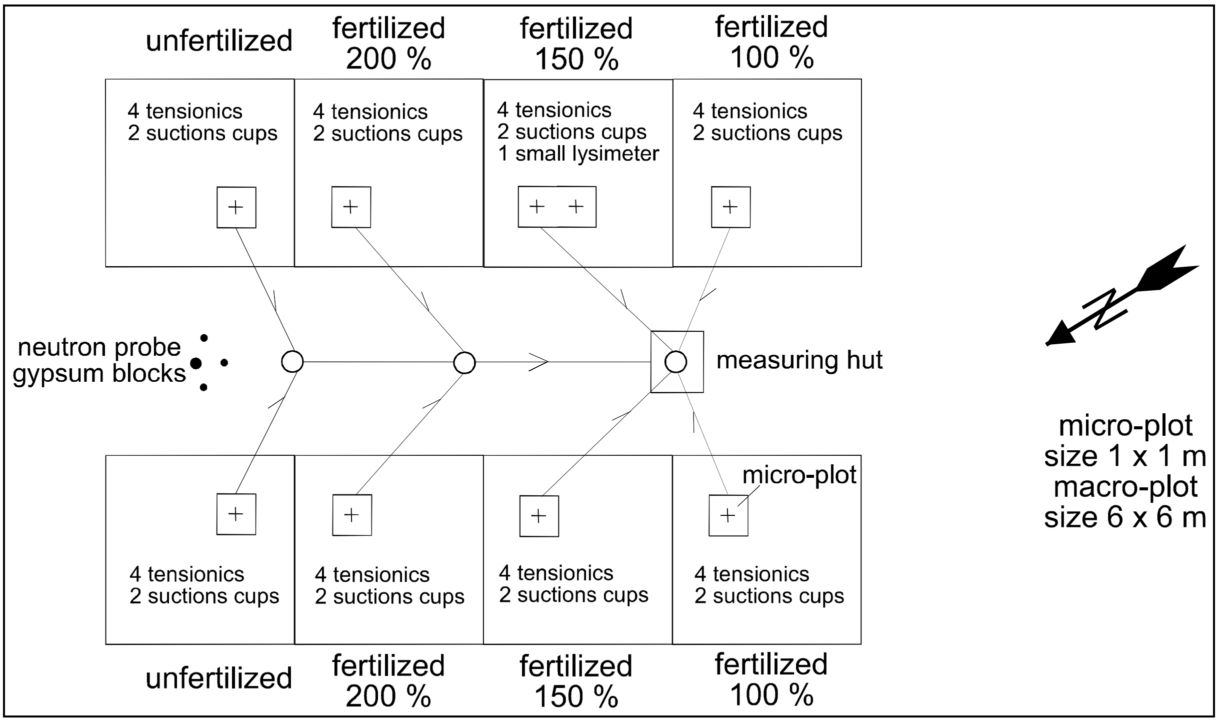

FIG. 4. Plan of the experimental site.

TABLE III. TILLAGE OPERATIONS FROM 1995 TO 1998

Winter wheat 1995 / 96	13. Oct	Planting of wheat	**Soybean 1997**	24. Apr	Row planting
	11. Apr	60 kg/ha N-fertilizer		16. Jun	60 kg/ha N-fertilizer
	09.May	60 kg/ha N-fertilizer		13. May	25 mm Irrigation
	13. Jun	60 mm Irrigation		03. Sep	Harvest
	23. Jul	Harvest	**Winter barley 1997 /98**		Planting of barley
				23.Sep	65 kg/ha N-fertilizer
Cover crop	03. Aug	Planting of cover crop		19. Feb	55 kg/ha N-fertilizer
	05. Nov	Incorporation of cover crop		04. May	Harvest
				25. Jun	

The tensionics consisted of high-flow ceramic cups, 20 mm in diameter, with a plug containing three capillary tubes sealed with adhesive bonding (Fig. 3b). Two of these tubes reached to the bottom of the ceramic cup, one for the hydraulic load, and the other to extract the solution. The third terminated at a higher level in the cup, for system purging and return to the cup. The porous cups were initially filled with distilled water. The nitrate concentration of the surrounding soil solution is reached by ionic or molecular diffusion usually within 10 days [12, 13]. They were installed in undisturbed soil.

Each soil-water sampler consisted of a PVC tube, diameter 50 mm. A porous ceramic cup, with a 0.2-MPa air-entry value, was attached to one end (Fig. 3c). The other end of the tube contained a stopper with an attached rubber tube to allow removal of the sample. The rubber tube had a clamp to retain suction after evacuation. These were placed also in undisturbed soil.

The small lysimeters, installed at a depth of 105 cm, consisted of a high-flow ceramic suction plate within a PVC tube, diameter 30 cm, height 40 cm, with a closed base. A tube connected the suction plate to the measuring unit where the samples were collected. The suction cups and lysimeters were evacuated with a pump that operates at 0.05 MPa suction, and water samples were collected every week

(Figs. 3d and 5). The 0.05-MPa suction was chosen as the collecting bottles were located about 2 m above the soil surface so, even at field capacity, the suction was sufficient to push water into the sampling bottles.

To measure nitrate concentration, three different types of ceramic cup, i.e. ceramic suction cups, tensionics, and soil-water samplers, were installed. Nitrate concentration was also measured using the small lysimeter. In order to install a suction cup, it was necessary to dig a hole equal to its diameter, which has the advantage of causing minimum soil disturbance. The installation of the small lysimeter [11], which has a diameter of 30 cm, requires removing soil layers carefully and returning them in order.

To provide comparative data, ceramic cups were installed at 15, 45, 75 and 105 cm in an apple orchard. To measure percolation, the small lysimeter was installed at 105 cm, below the effective root zone of approximately 90 cm depth. Therefore, all the water that percolated below 90 cm was contributing to the groundwater. In order to appraise the effects of the disturbance in the soil structure caused by the installation of the lysimeter, the qualitative analyses of the seepage water collected by the lysimeter and suction cups, which were installed in the undisturbed area, were compared.

Three levels of N fertilizer were applied by fertigation or broadcasting, and nitrate concentrations in the soil profile were determined. Labelled fertilizer (5% ^{15}N a.e.) was applied weekly from mid-April to the end of June 1995 by fertigation at rates of 5 and 10 kg N ha^{-1}, and broadcast on the first and fifth weeks at 20 kg N ha^{-1}. Tensionics require a minimum of 10 days for ionic or molecular diffusion, therefore, the sampling interval was selected as every 14 days [12].

To investigate the efficiency of N-fertilizer application, a project involving winter wheat (‘Capo’) with four rates of fertilizer application was undertaken at the Institute’s experimental site at Gross-Enzersdorf. This work was carried out within an on-going long term N-research project that has been in progress since 1990. It consisted of three levels of fertilizer and an unfertilized control, with two replicates (Fig. 4). Fertilizer was applied at 100% (equal to the amount of N expected in the grain, 120 kg ha^{-1}) 150% and 200% (Table II). Winter wheat was planted in the fall of 1995. To capture residual mineral N after harvest of 1996, a cover crop miture of mustard (‘Maxi’), valley vervenia (‘Angela’) and buckwheat (‘Bamby’) was grown between August and November 1996. In 1997, soybean (‘Nebraska,’ maturity group 000) was planted followed by winter barley (‘Montana’). The winter wheat had two fertilizer applications during spring and was irrigated once. Tillage details are provided in Table III.

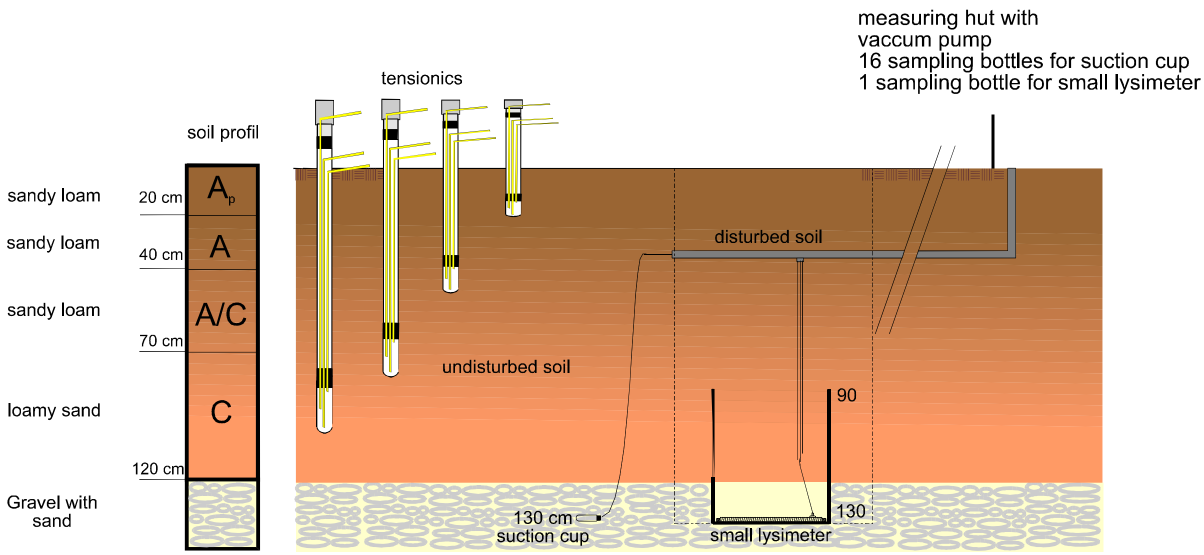

FIG. 5. Cross-section of the experimental site.

In the spring of 1996, ^{15}N-enriched (2.5% a.e.) fertilizer was applied to the winter wheat. In the subsequent years, unenriched fertilizers were applied. However, ^{15}N-enrichment determinations were made in 1996 for the cover crop, and in 1997 and 1998 for soybean and winter barley, respectively.

Figure 4 shows the location of the eight micro-plots (^{15}N-enriched fertilizer) and macro-plots (unenriched fertilizer). In addition, the figure shows the location of the neutron probe and gypsum blocks for measuring water content. Each micro-plot had four tensionics and two suction cups (Fig. 5). The lysimeter was installed in the plot fertilized at 150% (Fig. 4). Water samples from the sixteen suction cups and the lysimeter were collected weekly.

All water samples collected from the field were brought to the laboratory and nitrate concentrations measured spectrophotometrically. The soil-water samples were treated by the diffusion method [14] in preparation for $^{14}N/^{15}N$ ratio determinations with an on-line Carlo Erba automated Dumas-combustion system connected to a VG-SIRA mass spectrometer at the International Atomic Energy Agency's Laboratory in Seibersdorf, Austria.

3. RESULTS AND DISCUSSION

Large numbers of soil samples were collected from the study area and physical and chemical properties determined (Table IV). The soil was a typical czernosem, sandy loam to a depth of 70 cm and loamy sand from 70 cm to 120 cm. No gravel was present to 120 cm, but gravel and sand were present at greater depths. In the upper layers, the organic matter content was 2%. The pH for all depths was in the range from 7.0 to 7.5 and Ca content was about 25%..

TABLE IV. PHYSICAL AND CHEMICAL SOIL PARAMETERS

Soil depth (cm)	S a n d 2000–50 µm	S i l t 50–2 µm	C l a y < 2 µm	Organic matter (Vol%)	Available water (Vol%)	kf-Value (m/d)
0–20	33.2	45.1	21.7	2.6	14.3	75
20–40	34.0	43.2	22.8	2.3	15.3	2
40–70	33.1	42.8	23.1	0.8	14.7	17
70–120	46.9	38.5	14.6	0.3	13.4	2

Water content was measured at several depths by neutron probe, gypsum blocks, and tensiometer, mostly on a weekly basis. Determinations made at 20, 50, 80 and 100 cm revealed that each device showed similar patterns (Fig. 6 a–d). After a rainstorm. the 20-cm data from the gypsum blocks and neutron probe showed predictable rising trends. At the 20th week, approximately, when no rainfall had been recorded during the preceding days, both devices showed rapid downward trends indicating drying of the soil and, accordingly, the tensiometer showed increases in suction. Similar observations were made for other depths. However, for unknown reasons, from approximately the 22nd week, the gypsum blocks showed a rising water content (Fig. 6c), in contrast with the neutron probe, which indicated declining moisture, and the tensiometer's increasing suction. Such differences may have been due to the measurement devices being located at slightly different depths, and soil variability may have played a role. Also, the profiles assayed were different: the data provided by the neutron-probe at 20 cm provided an average for 10 to 30 cm, whereas the gypsum block measured the water content at 20 cm. Furthermore, these measurements are indirect and need calibration.

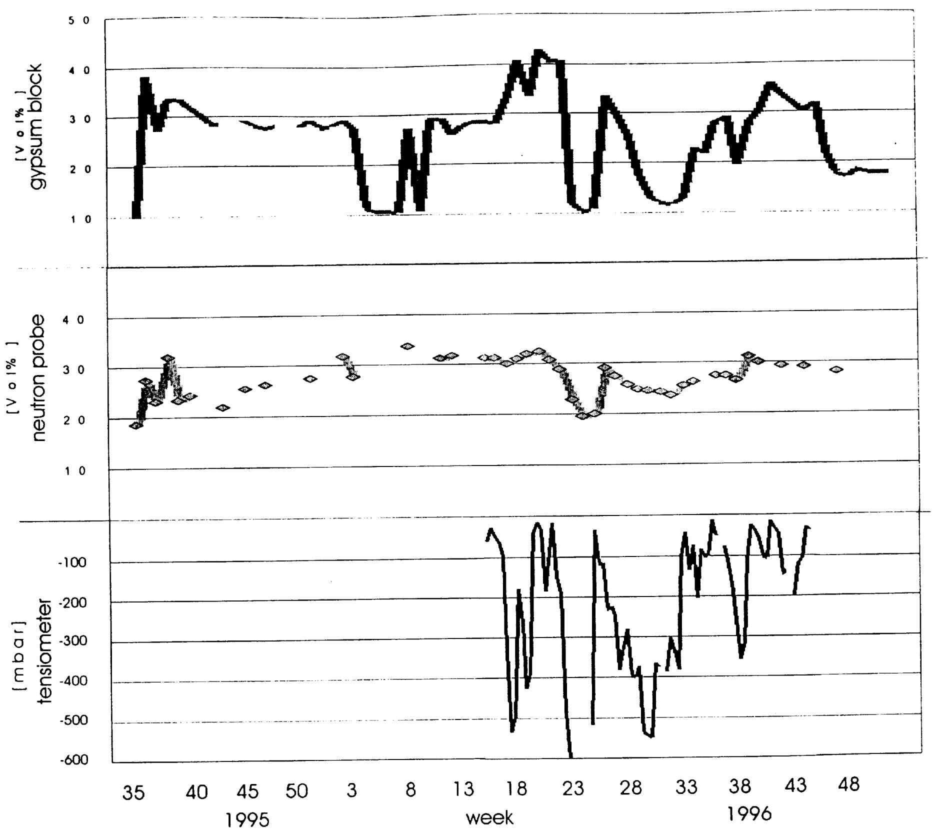

Fig. 6a. Water content and suction at 20 cm depths of soil profile.

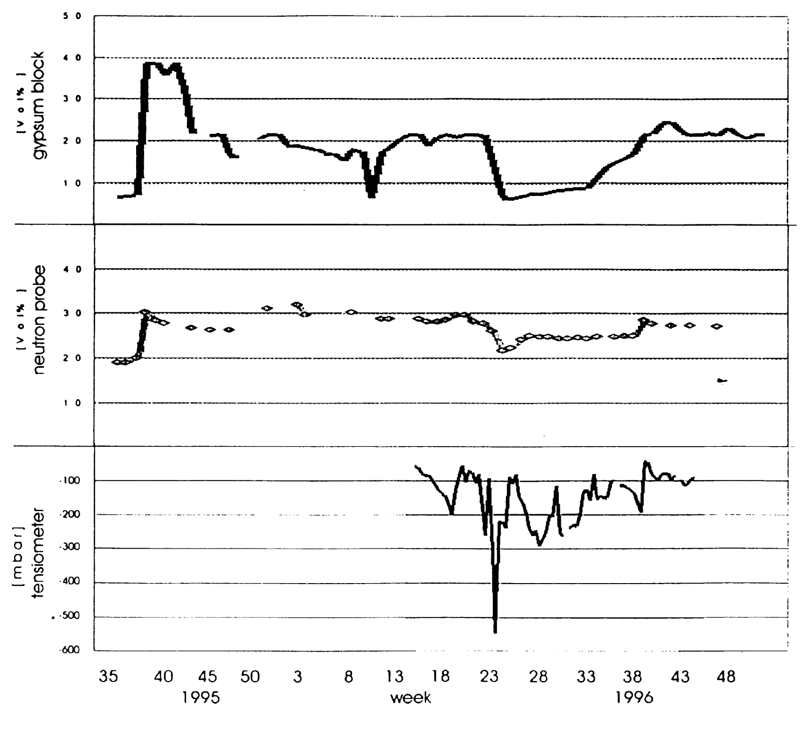

Fig. 6b. Water content and suction at 50 cm depths of soil profile.

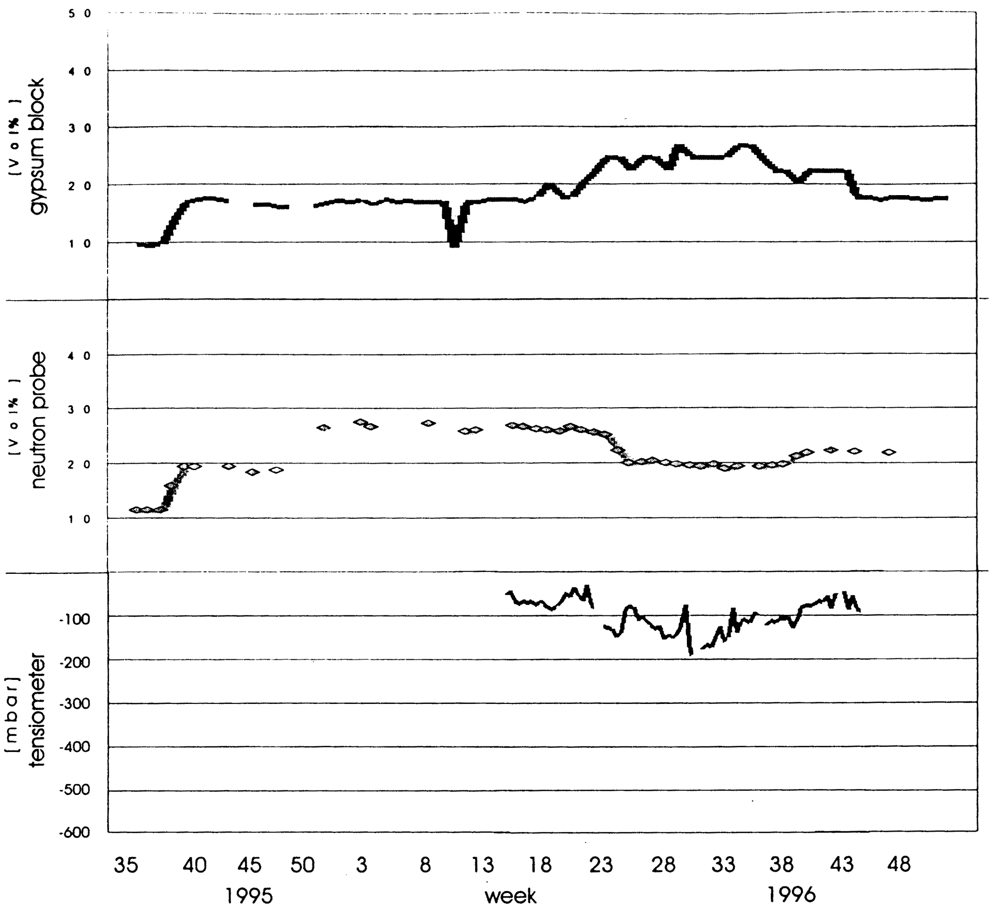

Fig. 6c. Water content and suction at 80 cm depths of soil profile.

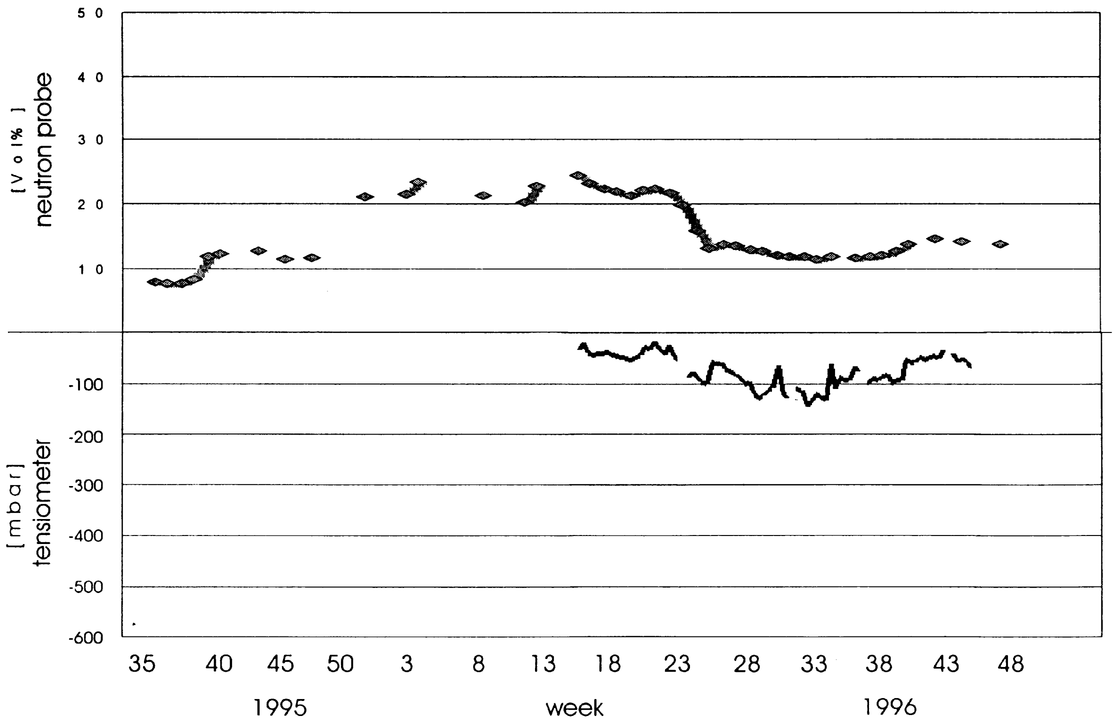

Fig. 6d. Water content and suction at 100 cm depths of soil profile.

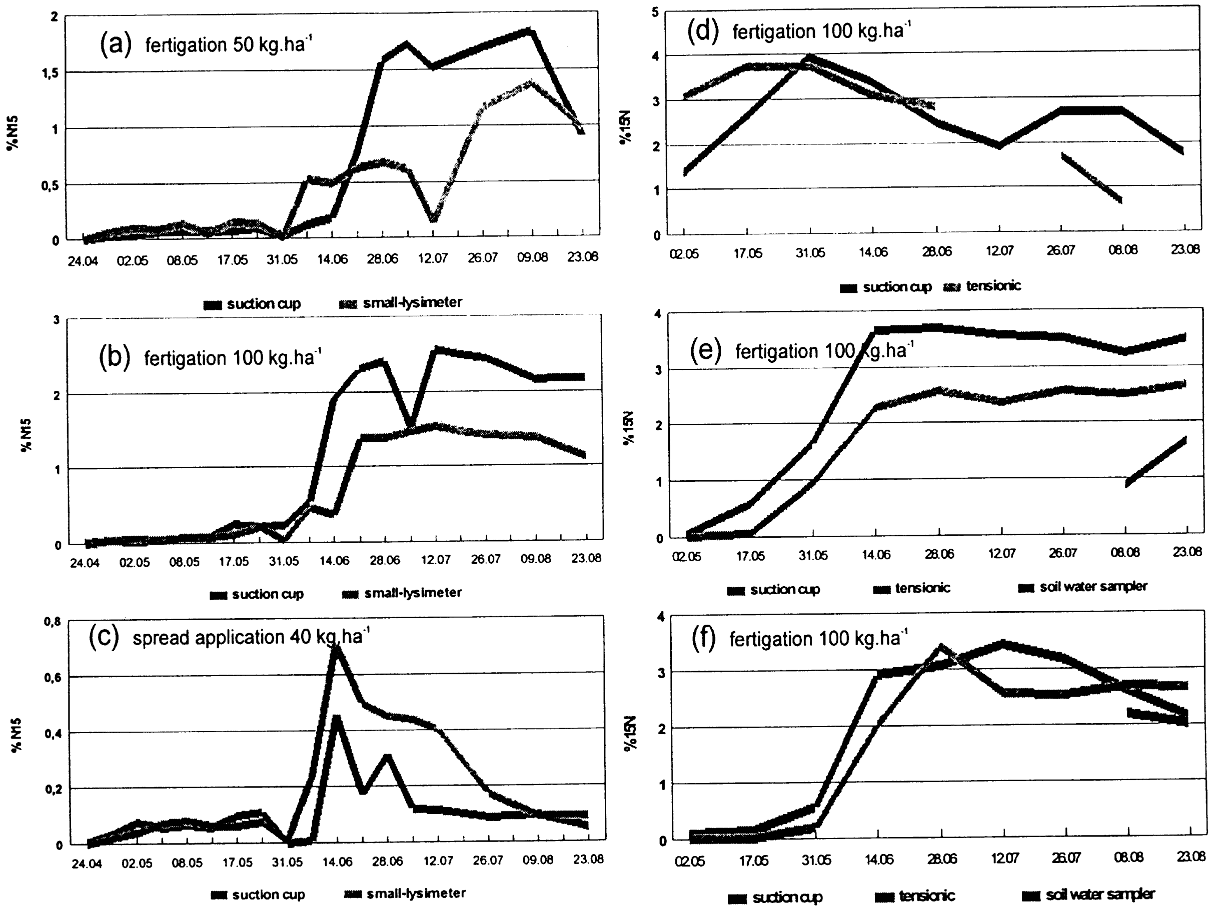

Fig. 7. Average ^{15}N-concentrations in soil water from different devices.

Figure 7 shows ^{15}N-enrichment data at different depths for samples collected by various devices installed in the apple orchard fertilized at different rates of N from mid-April to the end of August 1995. During the first 2 months, at 105 cm, ^{15}N-concentrations from the suction cups and lysimeters were similar (Fig. 7a–c). Subsequently, rapid increases in concentration were observed. Figure 7d–f shows the comparison of ^{15}N-concentration from suction cups, tensionics and soil-water samplers; clearly, all of the measuring devices were successful in assaying ^{15}N-concentration in the soil profile. The minor differences in the data may have been due to the flow through macro-pores or to within-plot variability of the soil.

Concerning N leaching in the orchard, the best results were obtained with broadcast application: the maximum ^{15}N-concentration at 105 cm depth was only 0.7% (Fig. 7c). The highest concentration that was obtained with 50 kg N ha^{-1} applied as fertigation was 1.7%, whereas 100 kg N ha^{-1} as fertigation produced a value of 2.5% for the same depth.

Rainfall on the study area was recorded at a local hydrology station, and percolation was measured with the lysimeters installed below the root zone. During the investigation period (September 1995 to December 1996), 860 mm of rainfall and 96 mm of percolation were recorded. In the spring, large amounts of moisture were present throughout the soil profile due to winter rainfall, shown by neutron-probe measurements at several depths (Fig. 6). The percolation started after the rainfall in week 8 of 1996, and continued to increase, largely due to rainfall during weeks 13 to 15. The large amounts of percolation during this period was partly due to low water requirements of the winter wheat. Rainfall in the subsequent weeks was diminished. At the same time, the water requirement of the crop was higher,

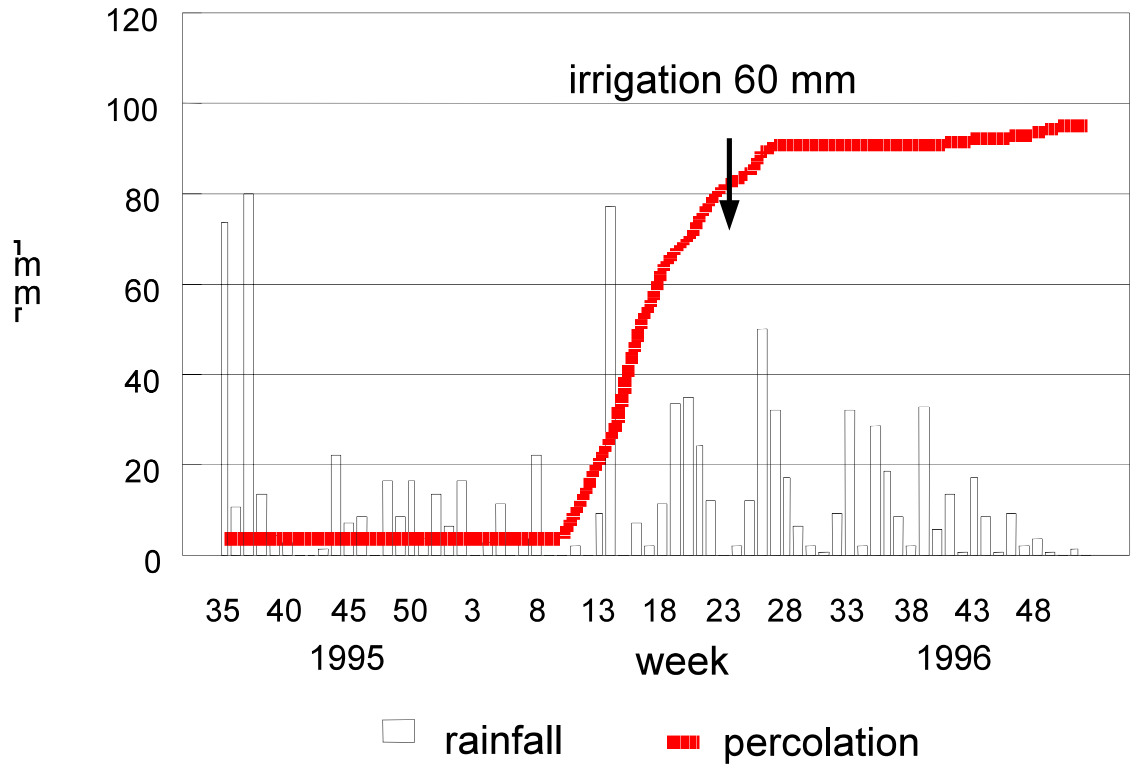

Fig. 8. Average rainfall and percolation measured using lysimeter.

therefore, 60 mm of irrigation was applied. This resulted in an increase in the water content of the soil profile to a depth of 50 cm, as shown by neutron-probe measurements (Fig. 6a, b). However, moisture deeper in the soil declined from week 15 onwards (Fig. 6c, d), indicating that all of the applied water was consumed by the crop.

All the devices used to measure ^{15}N-concentration gave similar results. Therefore, nitrate concentrations were measured at a depth of 130 cm using suction cups for the investigation of 1995–96, when winter wheat was grown followed by a cover crop. For each fertilizer application, four measurements were made (Fig. 4). Nitrate concentrations increased with the amount of fertilizer applied (Fig. 9). However, the weighted average nitrate concentration remained the same. The unfertilized plots had a nitrate concentration of 111 mg L^{-1}, slightly more than double the European Union guidelines for groundwater. In fertilized plots, the average nitrate concentration was 215 mg L^{-1} for 100% fertilization, 352 mg L^{-1} for 150% and 477 mg L^{-1} for 200%. The nitrate concentration in unfertilized plots also rose slightly after the 8th week of 1996, due to mineralization of soil organic matter.

The ^{15}N-concentrations of samples collected in suction cups ranged between 0.005% to 0.01% from a possible maximum of 2.5%. These low values showed that only a small part of the fertilizer applied during spring, for all treatments, percolated through the soil profile. For plots with 100% and 150% fertilizer treatments, only a few measurements of ^{15}N were possible as rainfall was light at the end of 1996 (Fig. 8). The total amount of fertilizer consumed by winter wheat and the cover crop ranged from 35 to 44% of total N-fertilizer applied (Table V), indicating that a significant amount of fertilizer remained in the soil that could leach with subsequent percolation.

The grain yields of winter wheat varied between 3.07 and 5.23 t ha^{-1}, depending on N applied (Table V). In the unfertilized plots, 21 and 63 kg N ha^{-1} were recovered in straw and grain, respectively. In the fertilized plots, 60 to 73 kg N ha^{-1} were found in the straw, and 111 to 116 kg N ha^{-1} in the grain. A 60-kg N ha^{-1} increase in the amount of fertilizer applied resulted in an increase of only 5 kg N ha^{-1} in

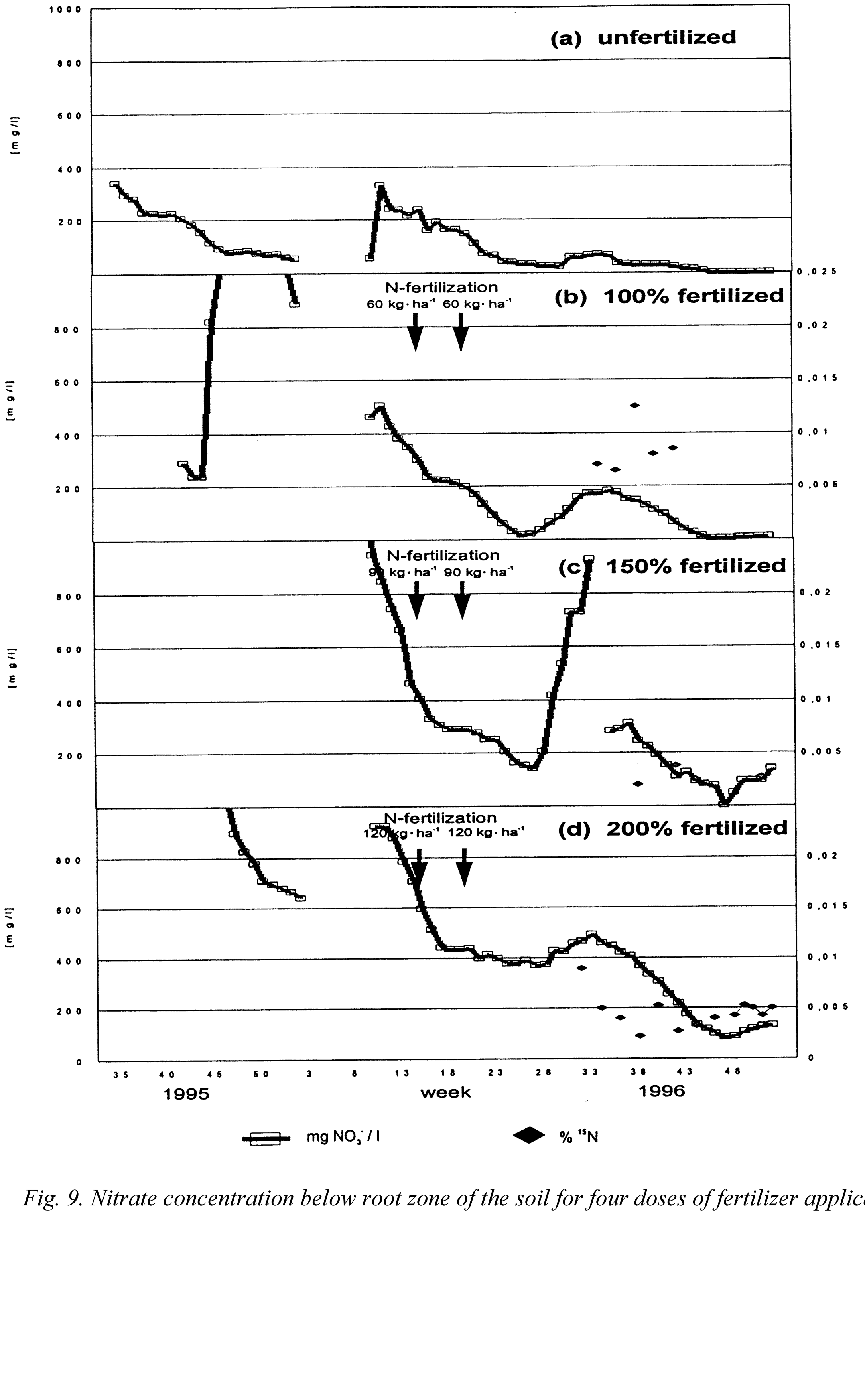

Fig. 9. Nitrate concentration below root zone of the soil for four doses of fertilizer application.

TABLE V. YIELD AND NITROGEN UPTAKE FROM SOIL AND FERTILIZER DURING 1996–1998

treatment		Yield [t.ha^{-1}]		Total N [kg.ha^{-1}]			fertilizer N [kg.ha^{-1}]			Total N / fertilizer N	Total fert. / fertilizer N*)
		straw	grain	straw	grain	Total	straw	grain	Total		
Winter Wheat 1995/96	0% N	5.75	3.07	21	63	84					
	100% N	8.52	5.23	62	111	172	19.4	30.7	50.1	29.1%	41.8%
	150% N	9.46	5.14	60	116	177	28.6	49.7	78.3	44.3%	43.5%
	200% N	9.18	5.12	73	113	187	37.2	41.3	78.6	42.1%	32.7%
Cover Crop 1996	0% N	1.19		25		25					
	100% N	1.94		51		51	0.7		0.7	1.4%	0.6%
	150% N	2.24		52		52	1.2		1.2	2.4%	0.7%
	200% N	3.53		118		118	2.9		2.9	2.4%	1.2%
Soybean 1997	0% N	3.98	1.46	15	60	75					
	100% N	5.68	2.15	22	98	120	2.1	1.6	3.7	3.1%	3.1%
	150% N	5.41	2.08	26	99	125	4.7	3.5	8.2	6.6%	4.5%
	200% N	5.57	2.02	36	102	138	6.6	5.6	12.2	8.8%	5.1%
Winter Barley 1997/98	0% N	4.83	2.08	16	27	43					
	100% N	9.61	5.09	41	99	140	1.3	0.7	2.0	1.5%	1.7%
	150% N	5.98	4.91	36	114	150	1.9	0.9	2.9	1.9%	1.6%
	200% N	12.20	5.81	79	128	208	3.4	1.5	5.0	2.4%	2.1%

*) depending on the nitrogen fertilization in 1996, 120 kg.ha^{-1} for 100%, 180 kg.ha^{-1} for 150%, 240 kg.ha^{-1} for 200%,

TABLE VI. TOTAL NITROGEN AND PART OF FERTILIZER IN SOIL IN kg.ha^{-1}

Depth/time	Total nitrogen in soil July 1996	Nitrogen from fertilizer in soil July 1996	Nitrogen from fertilizer in soil November 1996
Fertilization 100%			
0–30	5,850	19	15
30–60	3,670	7	7
60–90	2,193	5	4
Total	11,713	31	27
Fertilization 150%			
0–30	6,060	43	23
30–60	4,753	11	11
60–90	2,588	9	1
Total	13,400	62	35
Fertilization 200%			
0–30	6,280	32	31
30–60	4,870	16	11
60–90	2,345	4	9
Total	13,495	52	51

plant uptake. A further increment in fertilizer application to 240 kg N ha^{-1} increased plant uptake by only 15 kg N ha^{-1}, which explains the higher concentrations in Fig. 9; however, grain yield decreased.

The measured and calculated [15] values for crop uptake from fertilizer varied from 50 to 79 kg N ha^{-1}. Uptake from soil in unfertilized plots was 84 kg N ha^{-1}, and 122 kg N ha^{-1} from the fertilized plots. With the highest fertilizer rate (200%, 240 kg N ha^{-1}) only 33% of plant N was from fertilizer, whereas with 120 and 180 kg N ha^{-1}, the values were 42% to 44%. Also, through the use of the cover crop, a lot of N was captured for possible subsequent benefit to a grain crop, ranging from 25 kg N ha^{-1} on unfertilized plots to 118 kg N ha^{-1} with 200% fertilization, most of which came from the soil. The part from fertilizer was only 0.6% for 100% fertilization, 0.7% for 150% fertilization and 1.2% for 200% fertilization.

Subsequent crops, soybean and winter barley, were fertilized with unlabelled fertilizer (Table III). As with wheat, total-N values were greater for the higher rates of fertilizer. From the fertilizer applied to winter wheat in spring 1996, 3.7 to 12 kg N ha^{-1} were taken up by soybean. In 1998, the ^{15}N-fertilizer uptake by winter barley was 2.0 to 5.0 kg ha^{-1}, which represented 1.7 to 2.1% of the amount applied. The total fertilizer uptake by crops, in 1998, during vegetative growth ranged between 41% (99 kg N ha^{-1} for the 200% treatment) and 50% (91 kg N ha^{-1} for 150%). With the 100% treatment (120 kg N ha^{-1}) the total crop uptake was 57 N kg ha^{-1} , which was 47%.

Soil-N contents of 0.02% to 0.14% indicated approximately 12 to 13.5 t N ha^{-1} in the 90-cm root zone. Of this pool, 1 to 2% may be crop-available through mineralization. At the same time, part of the mineral N may be retransformed and immobilized. To determine what fraction of the organic N came from fertilizer, ^{15}N-analyses were made on soil samples collected from three soil depths. The samples were taken after the harvest of winter wheat and after the harvest of the cover crop. The amount of N from fertilizer decreased with depth (Table VI), indicating that only a small part of the applied fertilizer penetrated to deeper soil layers. Similar conclusions are also made for Fig. 9. In total, 27 to 65 kg N ha^{-1} N from fertilizer were immobilized in the soil, 22% to 36% of what had been applied. This amount may be used by other crops.

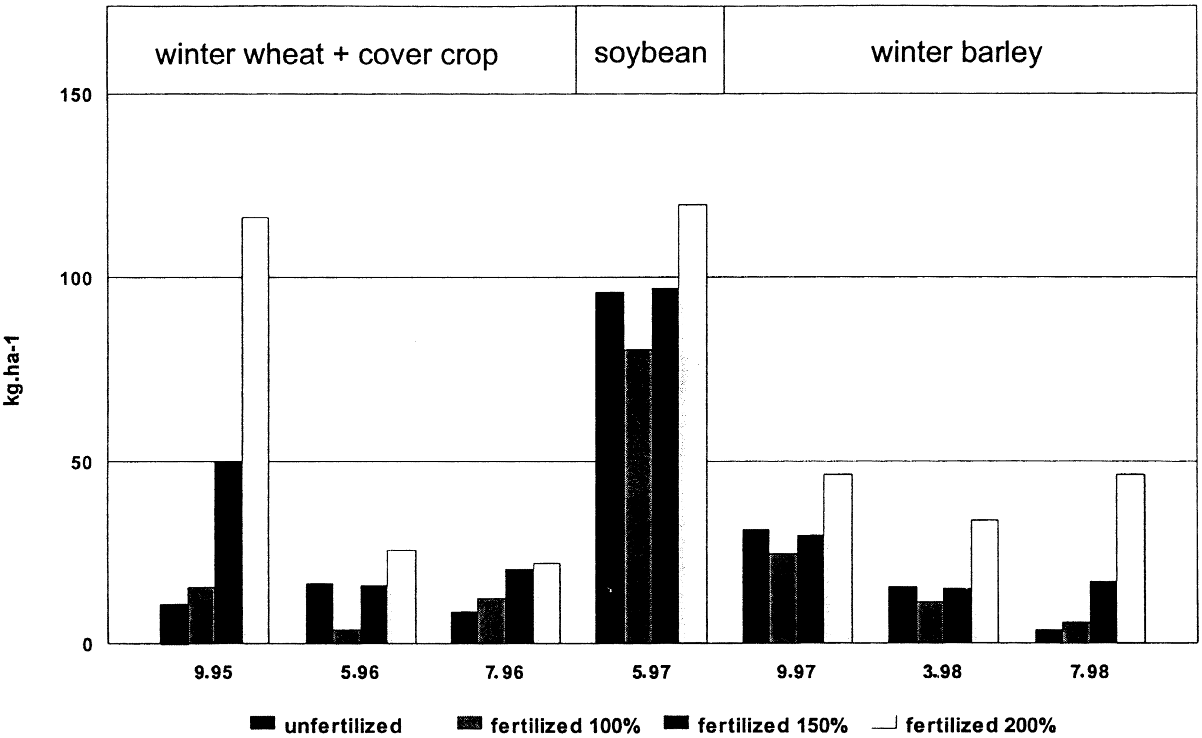

Fig. 10 Plant available nitrogen for the rooting depth of 90 cm.

The measurements of the plant-available N in the rooting depth gave the possibility of adjusting the N fertilization depending on the plant requirement. Using the N_{min}-method, actual plant-available N content in the soil was obtained on a given day, which was directly dependent on N-fertilization (Fig. 10). Due to the poor growth of plants in unfertilized plots and high mineralization rates, the plant-available N was often higher than that derived from the soil in the 100% fertilized plots. The large amount of N in the unfertilized plots may lead to higher N leaching to groundwater.

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EFFECT OF RATE, TIMING AND PLACEMENT OF NITROGEN ON SPRING WHEAT IN FARMERS' FIELDS IN THE YAQUI VALLEY OF MEXICO

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Abstract

The objective was to validate, in farmers' fields in the Yaqui Valley, N-management practices that had resulted, under experimental conditions, in reduction of trace-gas emissions while maintaining grain yield and quality. Trials were variously established in five different farmers' fields. The local management practice was compared with a new alternative, under various rates of N. The farmers managed all aspects of the trials, except for fertilizer application. The new N-management practice resulted in higher yield, protein and fertilizer recovery. The SPAD chlorophyll meter was found to be a promising tool for predicting grain-protein concentration. The method of application, broadcast vs. banding, did not affect fertilizer-N recovery. We conclude that it is possible to improve N-uptake efficiency in wheat grown in the Valley by delaying most of the N application close to the time of the first auxiliary irrigation.

1. INTRODUCTION

High levels of inputs, including N fertilizer, are used on irrigated spring wheat in developing countries. The inefficient use of this fertilizer can affect farmer income and have environmental consequences, such as nitrate leaching and emission of trace gases.

In the Yaqui Valley of Sonora, Mexico, wheat is produced with high inputs of N fertilizer (250 kg N ha^{-1}). Therefore, losses to the environment are potentially significant. A multi-disciplinary group of scientists at CIMMYT and Stanford University has been investigating N-uptake efficiency in irrigated wheat systems in the Yaqui Valley, from agronomic, environmental and economic perspectives. Experiments established at a research station compared local farmers' rotations and management practices with alternatives that included reducing the amount of N applied and changing the timing of its application. Farmers apply 75% of 250 kg N ha $^{-1}$ a month before planting, zero at planting, and the rest at six weeks after planting, designated 75–0–25.

The best alternative practice reduced the amount of N to 180 kg ha^{-1}, one-third applied at planting and two-thirds 6 weeks later, designated 0–33–66; emissions of nitrous and nitric oxide were cut by half, although yields and grain quality were maintained. There was a saving of US$55–76 ha^{-1}, equivalent to 12–17% in after-tax profits [1]. Since fertilization is the highest production cost in the Yaqui Valley, such an incentive may induce farmers to alter their N-management strategies.

The on-farm trials have been established over the last two years in a total of twenty eight locations. The results reported in this paper are from a subset of five of those experiments that were established the first year. The main objective of this paper is to show one possibility in the analysis of fertility trials over locations. The results and conclusions from this paper may not necessarily be the same as those of the final report that will include all the locations.

TABLE I. CROP ROTATION AND SOIL TEXTURE OF FIVE FARM LOCATIONS

Trial	Rotation	Soil Texture	Crop
K801	Maize-Wheat	Clay	Altar C84
K802	Cotton-Wheat	Sandy Clay Loam	Altar C84
K804	Cotton-Wheat	Clay	Altar C84
K805	Wheat - Wheat	Clay	Altar C84
K814	Cotton-Wheat	Sandy Clay Loam	Rayon F89

TABLE II. TREATMENTS USED IN THE EXPERIMENTS ESTABLISHED IN FARMERS' FIELDs

Treatment[1]	Proportion and Timing[2]	Method[3]
1. 0 Control	0-0-0	broadcast
2. 75	75-0-25	broadcast
3. 150	75-0-25	broadcast
4. 225	75-0-25	broadcast
5. 300	75-0-25	broadcast
6. 75	0-33-66	broadcast
7. 150	0-33-66	broadcast
8. 225	0-33-66	broadcast
9. 300	0-33-66	broadcast
10. 150	0-33-66	band
11. 225	0-33-66	band
12. 225	0-0-100	band
13. Farmers' sample[4]		

1 The total rate of N applied in kg/ha.
2 The three numbers represent the percentage of the total rate applied at three times; pre-plant, planting and 1st irrigation (about 45 to 55 days after planting).
3 There were two methods of application as a broadcast over the field or as a band in the furrows.
4 This sample was collected from the farmers field in plots adjacent to the experiment.

TABLE III. MEAN SQUARES FOR GRAIN YIELD (GY), YELLOW BERRY (YB), TOTAL NITROGEN IN THE ABOVEGROUND BIOMASS (NTOT), GRAIN PROTEIN (GP) AND CHLOROPHYLL READING IN FLAG LEAVES (CHL). ALL VARIABLES ANALYZED HAD MISSING VALUES

Sources of variation	**df[1]**	**GY**	**YB**	**df**	**NTOT**	**GP**	**df**	**CHL**
Loc	4	7564086**	5443**	4	12634**	30.312**	4	260.43**
Rep (Loc)	10	200428	486**	10	447	1.115**	10	3.75
NTrt	12	12077843**	4350**	12	16605**	16.441**	12	149.78**
Farmer Lin.	1	64040139**	21764**	1	75082**	71.002**	1	700.30**
Farmer Quad.	1	4944054**	361	1	602	0.007	1	9.220
New Lin.	1	71958485**	28807**	1	112376**	111.413**	1	970.742**
New Quad.	1	20741398**	2044**	1	8820**	4.448**	1	157.671**
Farmer vs New	1	8407080**	2560**	1	15660**	14.405**	1	136**
Loc x NTrt	48	328603	414**	48	423	0.6630**	48	7.596
Error	112			111			102	

*,** Significance at the 0.05 and 0.01 probability levels, respectively.
[1] df = degrees of freedom

Therefore, this information should be taken as an example of data analysis and not of the final conclusions of the study. This study, on farmers' fields, was undertaken with the following objectives:

- To compare the alternative 0–33–66 N-management practice with the farmers' 75–0–25,
- To estimate the N contribution from the soil,
- To test the SPAD chlorophyll meter as a diagnostic tool for predicting grain protein at maturity.

2. MATERIALS AND METHODS

Five N-management trials were variously established in farmers' fields in the Yaqui Valley of Mexico, near Cd. Obregon, Sonora, during the 1996–97 cropping cycle (Table I). Each trial was composed of thirteen treatments (Table II) with various rates, times and methods of N application, arranged as a randomized complete block design with three replications. A combined analysis of variance across locations was used to analyze the five experiments. The analysis of the N treatments was divided into several single-degree-of-freedom comparisons (SDFCs) (Table III). Four of the SDFCs were used to test the linear and quadratic effects of the farmers' method and the new practice. The other SDFC examined the average effect across rates of the two approaches.

The fields on which the experiments were established were identified before the farmer applied fertilizer. The total experimental areas were then marked and soil samples collected at 0 to 15, 15 to 30 and 30 to 60 cm depths. The farmers were asked not to apply fertilizer in the marked area for the rest of the crop cycle. Each experimental unit was 8 m long and six beds wide; the width of each bed was 80 cm. The harvest area was comprised of the center two beds and center 3 m, an area of 4.8 m^2. The only nutrient other than N that limits wheat yields in the Yaqui Valley is P, therefore, all experiments were fertilized with 20 kg P ha^{-1} as triple superphosphate (0–46–0). Except for the fertilizer application in the experimental area, the farmer was responsible for all other management decisions and operations.

All the experiments were planted within the optimum planting dates for the area (15/11 to 15/12). Four of the experiments were planted with the semi-dwarf durum wheat 'Altar C 84' and one was planted with the semi-dwarf bread genotype 'Rayon F 89.'

In general, the experiments were well managed. In a few instances, weeds were observed in some plots, but were removed manually before becoming a significant problem. At heading, twenty flag leaves were collected from each experimental unit, and three readings with a Minolta SPAD chlorophyll meter were taken along each. The flag-leaf samples were oven-dried (75^{o}C, 48 h) and analyzed for total N. At physiological maturity, the harvest area was cut at ground level and bundled. A sub-sample of 100 spikes was collected at random from the harvest area and oven-dried as above. This sub-sample was used to determine yield components and moisture content of the bundle. The bundles were sun-dried and passed through a stationary thresher. Grain yields were weighed, and 40- to 60-g sub-samples collected and oven-dried at 105^{o}C for 24 h to adjust total yield to zero moisture. A sub-sample of 100 stems was threshed separately and the straw and the grain saved and analyzed colorimetrically for %N (Technicon Auto Analyzer II, Tarrytown, NY, Industrial Method no. 154-71 W, February 1973). The dry weights of grain and non-grain biomass (total biomass – grain) were multiplied by their respective N concentrations to calculate above-ground total N. A sub-sample of 400 grains was taken from the grain-yield sample to determine the fraction of kernels with yellow berry.

3. RESULTS AND DISCUSSION

The combined analyses of variance for grain yield showed highly significant effects due to location and N treatment (Table III). On the other hand, the interaction between location and N

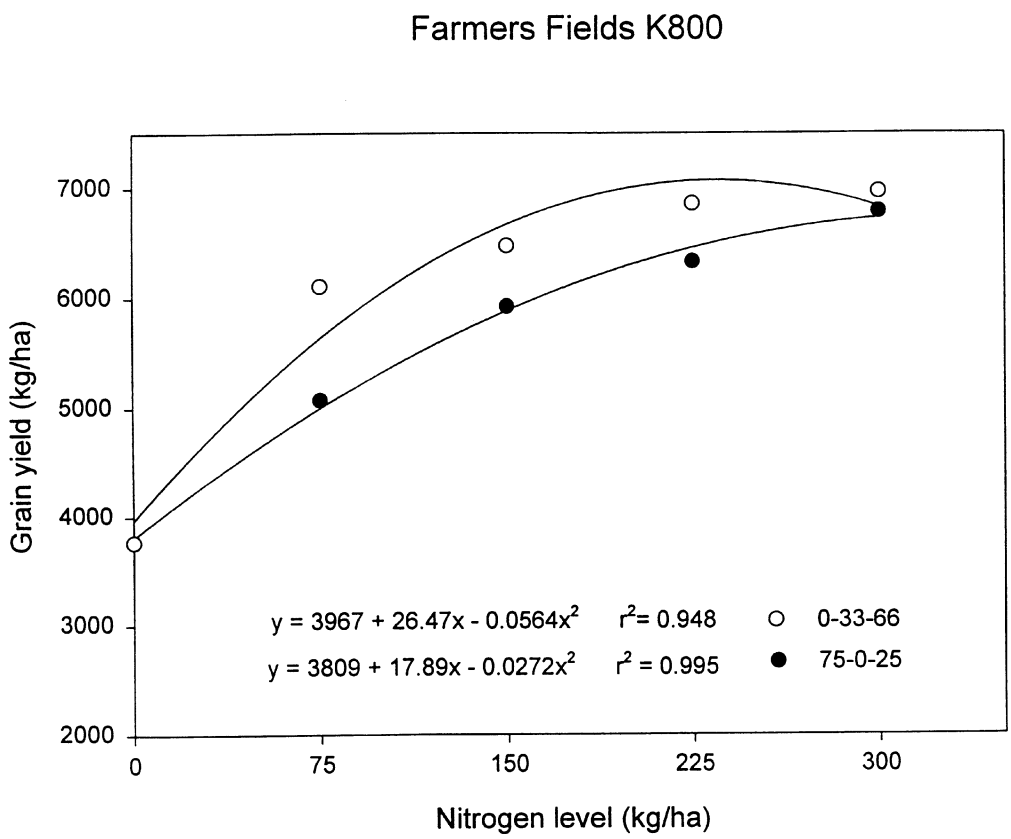

FIG. 1. Effect of five rates and two timings of N application on grain yield.

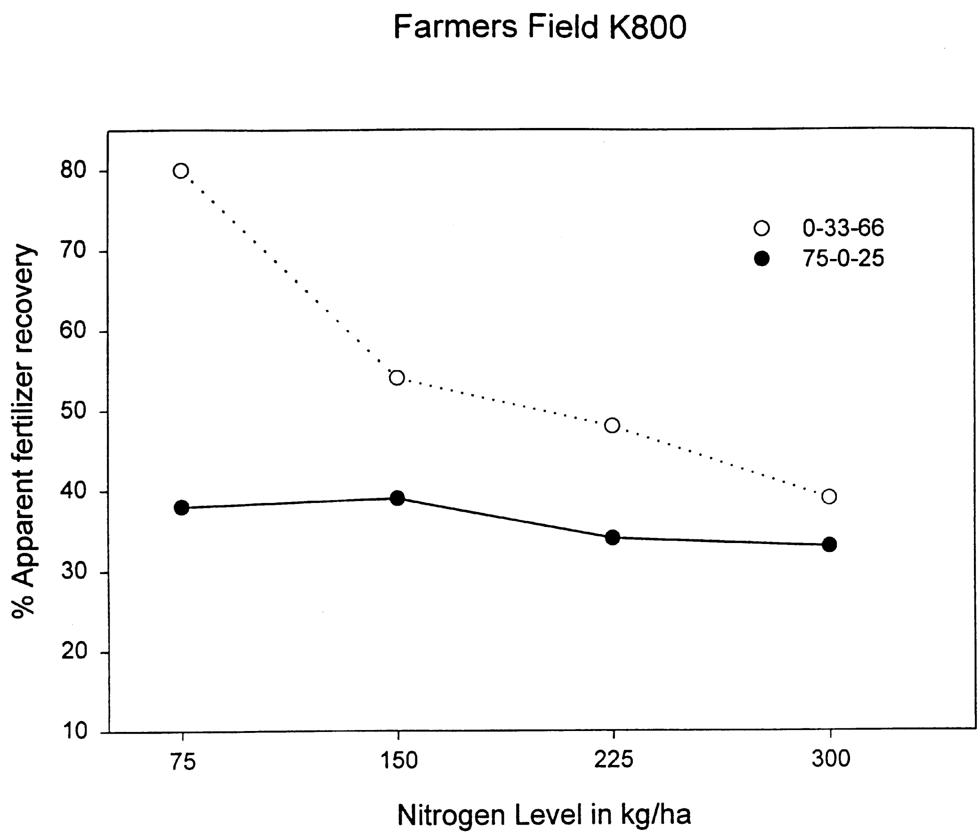

FIG. 2. Effect of five rates and two timings of N application on percent grain protein.

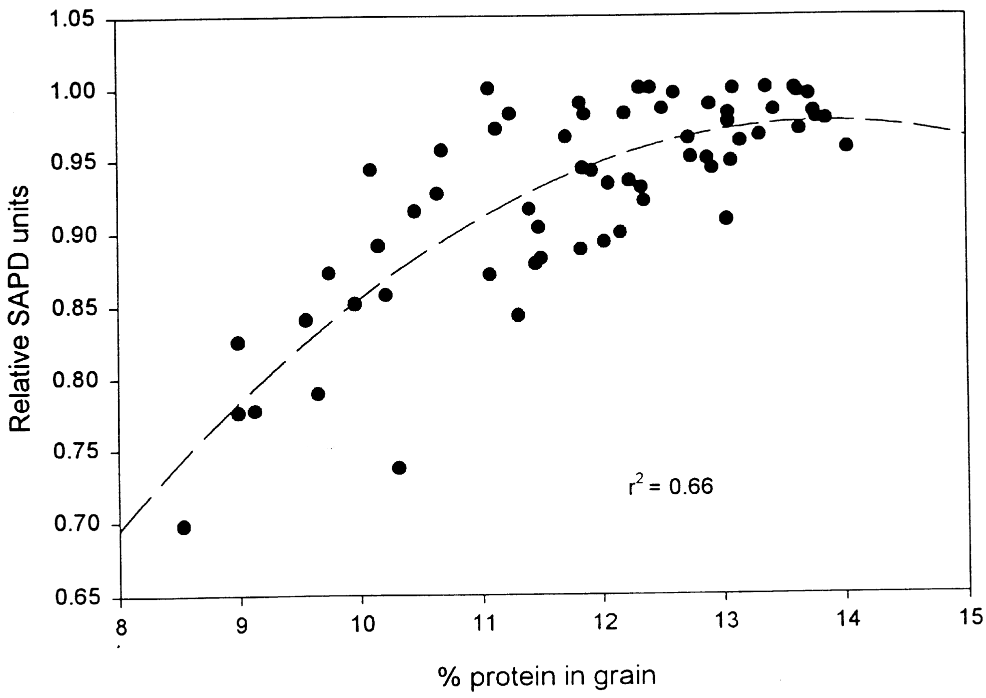

FIG. 3. Effect of five rates and two timings of N application on the percent apparent fertilizer recovery.

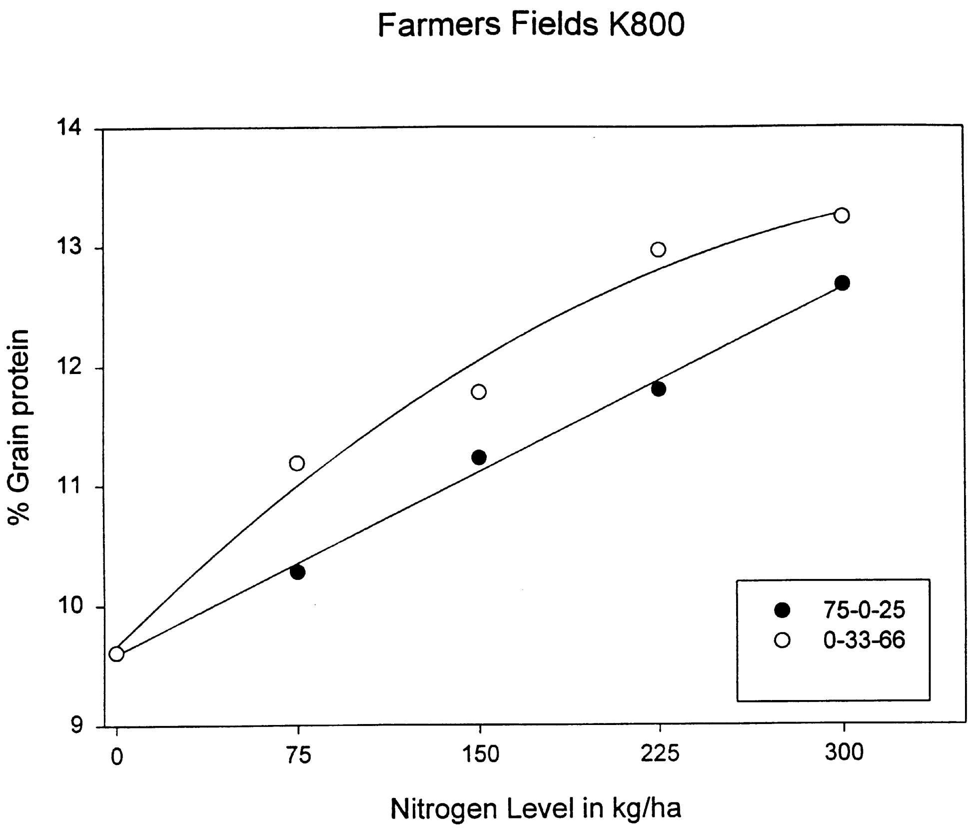

FIG. 4. Relationship between total aboveground nitrogen in the plant in plots without N fertilizer application and grain yield.

TABLE IV. TREATMENTS USED IN THE EXPERIMENTS ESTABLISHED IN FARMERS' FIELDS

Treatment[1]	Proportion & Timing[2]	Method[3]	Grain Yield	S. Dev.
1. 0 Control	0-0-0	broadcast	3765	920
2. 75	75-0-25	broadcast	5072	969
3. 150	75-0-25	broadcast	5918	707
4. 225	75-0-25	broadcast	6329	680
5. 300	75-0-25	broadcast	6782	757
6. 75	0-33-66	broadcast	6104	783
7. 150	0-33-66	broadcast	6471	474
8. 225	0-33-66	broadcast	6858	558
9. 300	0-33-66	broadcast	6963	654
10. 150	0-33-66	band	6591	766
11. 225	0-33-66	band	6967	594
12. 225	0-0-100	band	6648	643
13. Farmers'[4]			6720	674
Mean				6230
C.V.				9.66

1 The total rate of N applied in kg/ha.

2 The three figures represent the percentage of the total rate applied at three times; pre-plant, planting and 1st irrigation.

3 There were two methods of application as a broadcast over the field or as a band in the furrows.

4 This sample was collected from the farmers field in plots adjacent to the experiment.

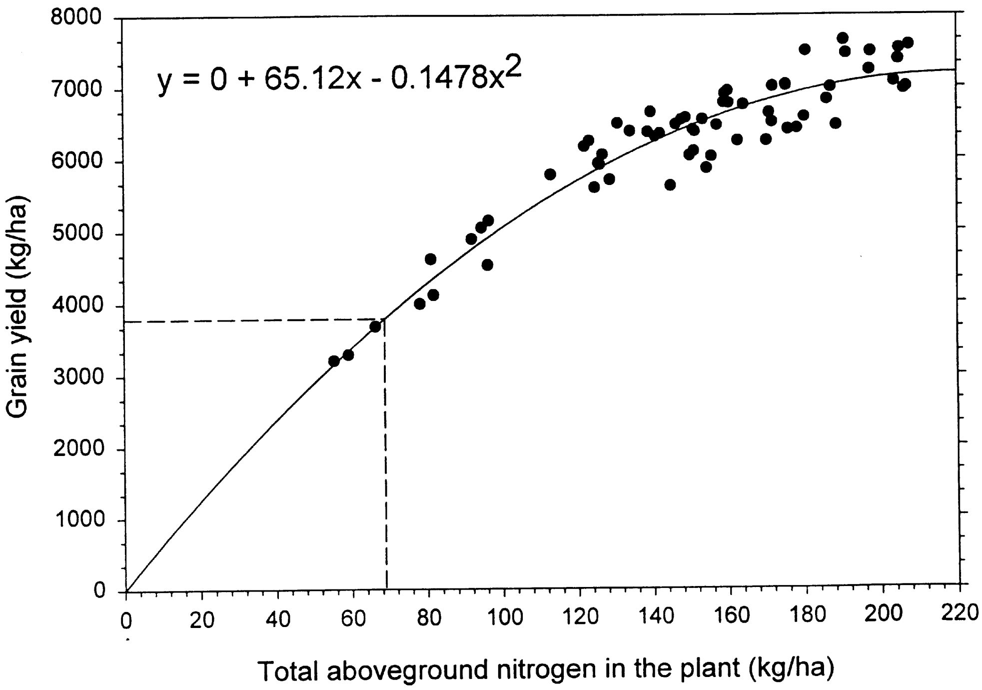

FIG. 5. Relationship between total aboveground nitrogen in the plant in plots without N fertilizer application and grain yield.

treatment was not significant. Therefore, discussion of the results focuses on the average of the N treatments across all five locations. In the farmers' practice, as well as in the new, the linear and the quadratic effects were highly significant, indicating the N responses with both approaches had linear and quadratic components (Fig. 1). The average effect across N rates was significantly higher with the new practice than with the farmers' (Table III).

Apparent fertilizer-N-uptake values were calculated for all fertilizer treatments. The new method showed higher recoveries than did the farmers' practice, particularly with the lower rate of N, which partially explains the higher yield obtained with 0–33–66 than with 75–0–25. The apparent recovery of N from 75 kg ha^{-1} in the 0–33–66 treatment was high at 79% [2]; the recovery values across N rates for the 75–0–25 treatment were lower and remarkably constant (Fig. 2), suggesting that large quantities of N were lost or made unavailable to the crop when the fertilizer was applied 3 weeks before planting. Normally, fractional N recovery decreases as N rate increases[2], as was observed in the 0–33–66 practice, whereas the low recoveries with 75–0–25 were not affected by the rate of N application. We found that losses of N as nitrous oxide and nitric oxide were cut by half with the 180 kg N ha^{-1}/0–33–66 practice compared to the farmers' 250 kg N ha^{-1}/75–0–25 [1]. However, this was not enough to account for the very large difference in recovery. We speculate that ammonia fixation may occur in these soils, immobilizing significant levels of N when it is applied well in advance; alternatively ammonia volatilization may explain some of these differences. This aspect requires more research.

The agronomic and economic optima were calculated for each of the response curves: the 0–33–66 practice resulted in savings of N fertilizer compared to 75–0–25. The agronomic optima were 329 and 234 kg N ha^{-1} for the 75–0–25 and the 0–33–66 practices, respectively. Economic optimum was calculated using a fertilizer:grain-price ratio of 3804/1350, i.e. 2.8 (10 pesos = US$1). The price of urea at the beginning of the crop cycle was 1,750 pesos t^{-1}, which was then divided by 0.46 to transform it to a unit-of-N bases. Some examples of the fertilizer:grain-price ratio of other countries are: India (2.1), Nepal (2.1), Egypt (2.1), Pakistan (2.5), USA (3.5), Turkey (3.6), Hungary (4.4), Brazil (4.6), Australia (5.5), Argentina (5.8) and Chile (8.8) [3], therefore, the ratio in the Yaqui Valley is relatively low. The optimum economic rate for the 0–33–66 practice was 210 kg N ha^{-1}, about 25% or 68 kg N less than with the 75–0–25 practice. This saving in fertilizer is similar to what we found previously [1].

Grain-protein concentration is a measure of quality for bread and durum wheat. The issue of wheat quality has become important in the Yaqui Valley, largely because most production is of durum for export. Therefore, a reliable diagnostic test is needed to give the farmer an indication of the final protein concentration at a time when it can still be modified. Foliar or soil application of N around the time of heading can have significant impact in grain protein [4–6]. It has been reported also that total N in the flag leaf at heading may be used to predict final protein concentration in the grain of wheat [7]. There was a significant correlation between chlorophyll reading and total N in the flag leaf at heading (r = 0.74**, n = 63), suggesting that the SPAD meter is a useful estimator of total N. The correlation between percent protein in the grain and chlorophyll reading was high when calculated within each field, however, when run across all five locations, a quadratic model fit the data better, but with a low $r^2 = 0.32$. A relative chlorophyll value was calculated, based on the maximum reading from each location, to standardize the data. This adjustment improved the relationship between SPAD readings and percent grain protein to an $r^2 = 0.66$ (Fig. 3). We need to do additional calculations to determine the critical value.

It is often stated that there is a negative correlation between grain yield and grain-protein concentration. However, when the range in grain yields was associated with different rates of N, we observed a positive correlation, r = 0.75**, n = 65. For grain protein concentration, the responses of the two management practices under the different N rates were somewhat different. The response of the 75–0–25 practice was linear, whereas that with 0–33–66 was slightly curvilinear, but significant (Table III, Fig. 4). The average protein concentration across rates was higher for the 0–33–66 practice. Yellow berry, also an important measure of quality, had a highly significant negative correlation with grain-protein concentration (r = -0.88**). Therefore, 0–33–66 had a lower incidence of yellow berry than did 75–0–25.

Comparisons of treatments, 7 vs. 10 and 8 vs. 11, evaluated broadcast vs. band applications; there were no significant differences (Table IV), i.e. no effect due to placement of N under the conditions tested.

When we plotted grain yield vs. total above-ground N in the plant, a quadratic response was obtained that starts at the origin (Fig. 5). The average yield of the control plots from all locations was 3,765 kg ha^{-1}. Extrapolating this to the X-axis gives about 68 kg N ha^{-1}, the average amount of N supplied by the soil to the crop. Doing the same at the 1,000 kg ha^{-1} grain yield, the equivalent value on the X-axis is about 16 kg N ha^{-1}, i.e. the amount of N needed to produce 1 t of grain yield. However, due to the curvilinear nature of the response, the amount of N needed to produce 1 t of grain increases as the yield increases. For the highest average yield for the Valley, 6,000 kg ha^{-1}, the amount of N needed to produce it was 130 kg N ha^{-1}. By dividing that value by six to get the amount of N needed per ton of yield, the value is 22 kg N ha^{-1}, which is 37.5% more than at the 1-t yield level. It is possible that some fields and treatments had significant amounts of N available post-anthesis. Such N seldom has an effect on grain yield, however, if available, the plant absorbs and stores it in the grain and straw. In our conditions, it is common to find higher concentrations of N in the grain and straw at the higher levels of yield.

4. CONCLUSIONS

(1) Grain yield showed a curvilinear response to N rate under both the 75–0–25 and the 0–33–66 strategies.

(2) The new practice, 0–33–66, which supplies N in closer synchrony with the plant's needs, was more efficient than the farmers' 75–0–25 method, in the following respects:
– Grain yield response per unit of fertilizer applied,
– Percent apparent fertilizer recovery,
– Protein concentration in the grain and incidence of yellow berry.

(3) There were no differences in grain yield between the broadcast and the band methods of N application.

(4) Although the number of locations was relatively small, it gives a first indication about the amount of residual soil N in farmers' fields, i.e. 68 kg N ha^{-1}.

(5) The SPAD meter used at heading showed potential as a diagnostic tool to predict protein concentration in the grain at maturity.

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CHLOROPHYLL METER FOR ESTIMATING NITROGEN STATUS OF IRRIGATED WHEAT

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Abstract

Chlorophyll-meter readings, generated from the leaves of irrigated wheat at particular growth stages, were normalized to the data obtained with locally recommended rates of fertilizer N, in Chile China, India and Mexico. Normalizing permitted comparisons of crop-N status across growth stages, locations, cultivars, and years. Relative yields and meter readings at growth-stage Z-50 are presented; they revealed similar trends for India, China, and Chile, however, for Mexico, the combination of soil, wheat cultivar, and climate resulted in much less response to N fertilization in the meter data. The implications are discussed. The SPAD meter proved to be a good tool to monitor and evaluate the N status of irrigated wheat.

1. INTRODUCTION

Because of the strong relationship between leaf-N concentration and chlorophyll content, the Minolta SPAD-502 meter provides a convenient monitor of crop-N status by measuring the light absorbed by chlorophyll. Thus, useful inferences about crop N-status are possible.

The chlorophyll-meter technique is nondestructive, fast, and easy compared to traditional plant-sampling and analytical procedures. The readings are generated by measuring the transmission of red light (650 nm) and near-infrared (NIR) light (940 nm) through the leaf blade, with the premise that light not captured by chloroplasts is detected by the sensor. Therefore, the more light detected, the lower is the potential photosynthetic rate, and the greater the crop stress.

Photosynthetic activity can be influenced by many factors, but when all plant-growth components are held constant except one, then the chlorophyll meter provide a relative measure of that factor, e.g. N fertility of the soil. Previous research with corn, wheat, cotton, and several other crops has shown a strong positive correlation between leaf-N concentration and chlorophyll-meter reading (see Bibliography). The relationship weakens at excessively high levels of N fertilization because crops frequently continue to take up N (i.e. luxury consumption) even though other nutrients or crop-growth factors limit photosynthesis and thus cause the meter readings to reach a plateau. When more than one factor limits growth, then interactions are likely. This is especially true for water stress and N, both of which are required in large quantities by high-yielding crops.

It is not possible to independently record data from the red and NIR bands using the SPAD meter. Rather, the meter output is a ratio of the two. Theoretically, red light is sensitive to chlorophyll activity whereas NIR light is insensitive to chlorophyll and sensitive to biomass. Electronics within the meter use NIR data to correct for factors related to biomass such as leaf thickness and density of cells. This normalization strategy attempts to minimize the need for calibration of the meter for each stage of growth, cultivar, etc. Nevertheless, scientists are cautioned about using meter data in situations where multiple factors may affect chlorophyll activity.

Plant stresses that affect chlorophyll and biomass differently from N may cause problems with interpretation of SPAD-meter data. For example, water stress affects cell turgidity, which affects NIR reflectance from leaves. Therefore, scientists are cautioned about making interpretations about crop-N nutrition based on SPAD data when moisture status is a variable.

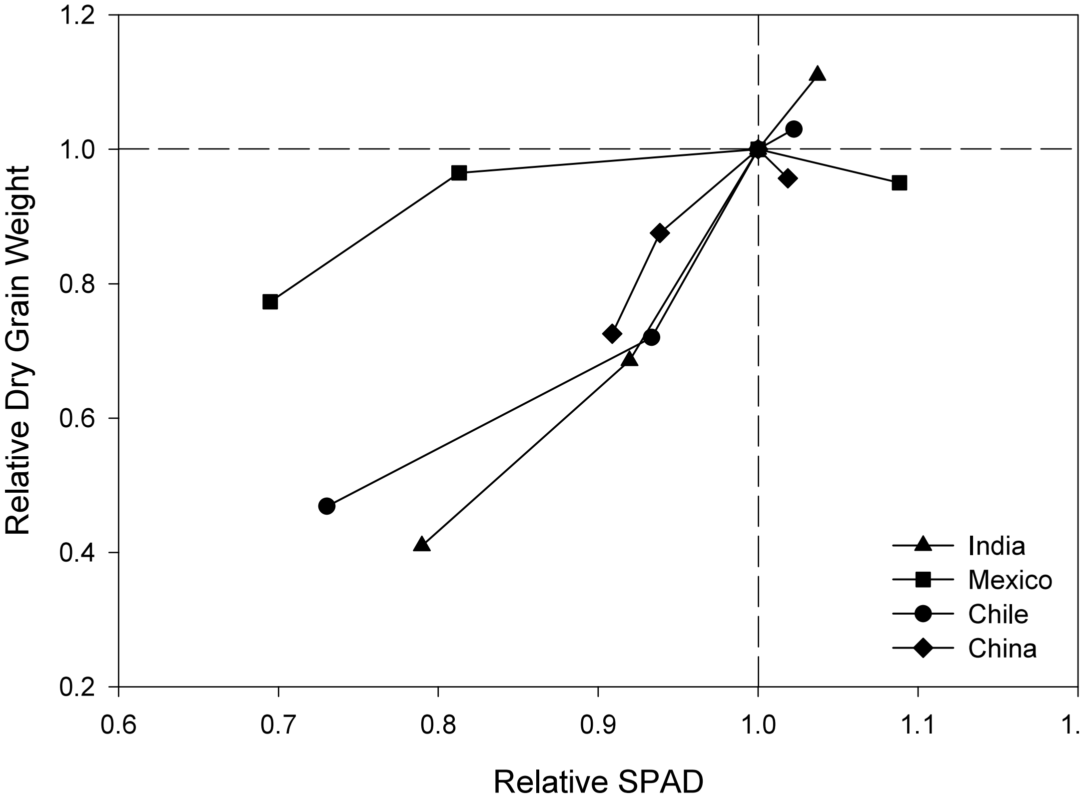

FIG. 1. Relationships between relative chlorophyll meter readings (SPAD) at the Z-50 growth stage and irrigated wheat yields at four locations.

2. SUMMARY OF DATA

The use of the chlorophyll meter to monitor crop-N status was a voluntary component of this co-operative research project. Not all Contractors were able to meet the cost of the instrument, approximately US$1300. Chlorophyll-meter numbers were generated at several locations at prescribed growth stages (i.e. Z-20, Z-30, Z-39, and Z-50).

This report was compiled from results entered into the master data set as of October 15, 1998. Yield and chlorophyll-meter data from all locations were normalized (i.e. at each location, referenced to the value for the $N_{1.0}$ fertilizer treatment, the recommended rate). Adequate yield and chlorophyll-meter data were generated by Contractors in China, India, Chile, and Mexico, for further analysis. Not all data sets were complete across years and N rates.

Relative grain yield and chlorophyll-meter values from India, China, and Chile followed similar trends, which is remarkable considering the vastly differing prevailing conditions. Data in Fig. 1 were normalized within year and then averaged for each N rate across years. Each data point represents the mean of three replications or more at each site for two or more years. The relationship for India indicates that the recommended N rate was not adequate to produce near maximum yields. The same trend was evident for Chile, but to a lesser extent. Mexico and China showed slight reductions in yield with the $N_{1.5}$ treatment. These lower yields were attributed to lodging late in the growing season, which occurred after the chlorophyll-meter data were collected at Z-50 growth stage).

The wide range in relative SPAD values at Z-50 for the Mexico site would normally be associated with an equally wide range in yields. The crop may have acquired significant amounts of N after chlorophyll-data collection; possibilities include abundant mineralization brought on by favorable water and temperature conditions or that the water used for irrigation contained significant concentrations of nitrate. In either case, the Mexico data indicate that wheat can recover from N stress after the Z-50 growth stage. Additional research may be justified to explore this observation; ^{15}N-enriched fertilizer would be useful for such as study, applied in a time-series to N-deficient plants.

The environmental and management implications of these observations are substantial. Nitrogen stress at Z-50 in Chile, China, and India reduced grain yields by about 2.4% for each 1.0% decline in meter reading. Depending on the cost of fertilizer and the value of wheat grain, one can readily determine the loss in profitability associated with a deficiency in N. In cases where N fertilizer turns out to be a way for producers to minimize the risk of yield losses, water management becomes a critical issue. The combination of excess N and non-uniform or excess irrigation can put the environment at risk from nitrate leaching.

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