Modelling the agricultural and environmental consequences of non-uniform irrigation on a maize crop at field scale

Laurent Bruckler, Francois Lafolie, Stephane Ruy, Bruno Mary, Jean Marc Granier, D. Baudequin, Patrick Bertuzzi

St. Paul

ARS 780

MODELLING THE AGRICULTURAL AND ENVIRONMENTAL CONSEQUENCES OF NON-UNIFORM IRRIGATION ON A MAIZE CROP AT FIELD SCALE.

Laurent Bruckler[a], François Lafolie[a], Stéphane Ruy[a], Bruno Mary[b], Jacques Granier[c], Denis Baudequin[c] and Patrick Bertuzzi[a],

[a] INRA, Unité de Science du Sol d'Avignon, Domaine saint paul, Site Agroparc, 84914 Avignon Cedex 9, France.
[b] INRA, Unité d'Agronomie de Laon-Péronne, rue Ferdinand Christ, F02007 Laon Cedex., France.
[c] CEMAGREF, Groupement d'Aix-en-Provence, BP 31, Le Tholonet, 13612 Aix-en-Provence Cedex 1, France.

ABSTRACT

Among crop systems, intensive irrigation probably represents one of the greatest threats to the quality of groundwater. Irrigation uniformity is a key factor in increasing water and nitrogen efficiencies by crops and consequently limiting water and nitrate percolation. The objective of this work is to predict at field scale, plant growth and water fluxes under non-uniform irrigation conditions using the NIWASAVE model. It links an irrigation water distribution model with the STICS crop growth model. It provides a description of irrigation distribution, crop development and growth, water and nitrogen balances and N cycle in the soil. Simulations were applied during 21 cropping years to a maize crop irrigated with a moving gun. The spatial coefficients of variation were less than or equal to 18%, 9%, 20%, and 36% for cumulative irrigation, actual evapotranspiration, drainage below the root zone and yield, respectively. Temporal effects due to natural climatic variability dominated and spatial effects of irrigation only increased the variance of the fluxes and biomass without greatly modifying the mean patterns. For nitrogen, cropping and intercropping periods were analyzed and two fertilization rates (180 and 280 kg N ha^{-1}) were considered. The spatial coefficients of variation were less than 37%, 8%, 25% and 34%, for cumulative N uptake, mineralized N, inorganic N left in the soil at harvest and leached N, respectively. The simulations run with or without reinitialization every year of inorganic N and water content at sowing gave similar results, except in certain years. There were significant differences between high and low fertilization treatments, especially for leaching. Other sources of variation such as soil type, soil hydrodynamic properties or irrigation and fertilisations strategies must also be analysed to provide more general conclusions.

Keywords : irrigation/non-uniformity/water balance/nitrogen balance/modeling/maize.

INTRODUCTION

A major challenge in agriculture is developing management techniques that optimize crop production while ensuring environmental quality. Intensive crops with high irrigation input probably represent one of the greatest threats to the quality of groundwater (Shufford *et al.*, 1977; Silvertooth *et al.*, 1992). One of the most efficient means of minimizing contamination of groundwater resources is through guidelines in water and fertilizer use. The uniformity of water distribution is one of the key factors for obtaining more efficient use of water by crops and limiting percolation below the root zone (Dagan and Bresler, 1988; Ben-Asher and Ayars, 1990ab). Nevertheless, variability in water depth in the field remains one of the most

org. par Univ. Minnesota, St. Paul

important characteristics of irrigation practices (Amali et al., 1997; Mateos, 1998). This is due to several factors such as local topography, pressure loss along the laterals, nozzle characteristics, or wind velocity during irrigation (Mateos, 1998).

Despite of the existing literature, some points have not been sufficiently analyzed. First, most of the studies deal with individual or regularly distributed sprinklers, while data for moving guns are scarce. Second, most of the papers analyze the impact of irrigation non-uniformity on the water budget, but the linkage between water and nitrogen is not fully described, although it is one of the most important issues (Bruckler et al., 1997). Third, only simplified approaches such as crop production functions or actual to potential yield ratio are used to describe crop growth and biomass production. Indeed, models giving a realistic representation of physical and biological processes occurring in the soil-plant system are necessary to provide consistent agricultural responses (Leenhardt et al., 1998). Such models must be able to take into account agricultural practices such as sowing and harvest dates, soil temperature, root growth, cultivar, organic matter management and fertilization practice. Consequently, the main objective of these papers is to link irrigation non-uniformity for an irrigation system (moving gun) with a crop model constructed as a simulation tool capable of working under agricultural conditions and of providing outputs relative to both yield and the environment.

THE NIWASAVE MODEL

The NIWASAVE model links an irrigation water distribution model that calculates irrigation rates for given, spatially distributed locations in the field, with the STICS model that runs at the same locations and simulates the crop-soil system. The NIWASAVE model provides daily and cumulative output variables for crop and soil.

First, the model computes the irrigation distribution at the field scale as a function of equipment and climatic conditions. The irrigation equipment is characterised by the operating water pressure which determines the water flow, the type and orientation of nozzle, and the grid-layout in the case of sprinklers, or distance between successive passages in the field for guns (Augier et al., 1995). The water distribution at the soil surface is measured under field conditions in the absence of wind and simulated by using drop trajectory calculations. Wind direction and velocity then modify the water distribution at the soil surface (Kosuth et al., 1994). Evaporation during drop trajectory is not considered (Augier et al., 1997), but the overlapping of the water distribution over the whole field is calculated. The NIWASAVE model uses a database which numerically describes the water distribution for any given irrigation equipment (guns in our case) and for various wind directions (10° angle step) and speeds (1ms $^{-1}$ velocity step).

Second, the NIWASAVE model computes crop development and growth, yield components, water and nitrogen balance using the STICS model (Brisson et al., 1998). STICS is a dynamic model with a daily time step that simulates the soil–crop system within a year or for a succession of years. The climate is characterised by standard data (solar radiation, minimum and maximum temperature, rainfall, potential evapotranspiration) and the crop is characterised by its aboveground biomass, leaf area index, the number of grains and the biomass of harvested crop organs. Root length distribution in the soil profile is calculated every day according to shoot growth simulation. A phenological model calculates the development stages, particularly the time when organ filling occurs. Water and nitrogen stresses are calculated using three indices which can reduce the leaf area index and the radiation use efficiency shortage of water and/or nitrogen. The soil is considered as a succession of horizontal layers in which water and nitrate transport and uptake are simulated, whereas production of nitrate by mineralization occurs mainly in the plough layer. Since the

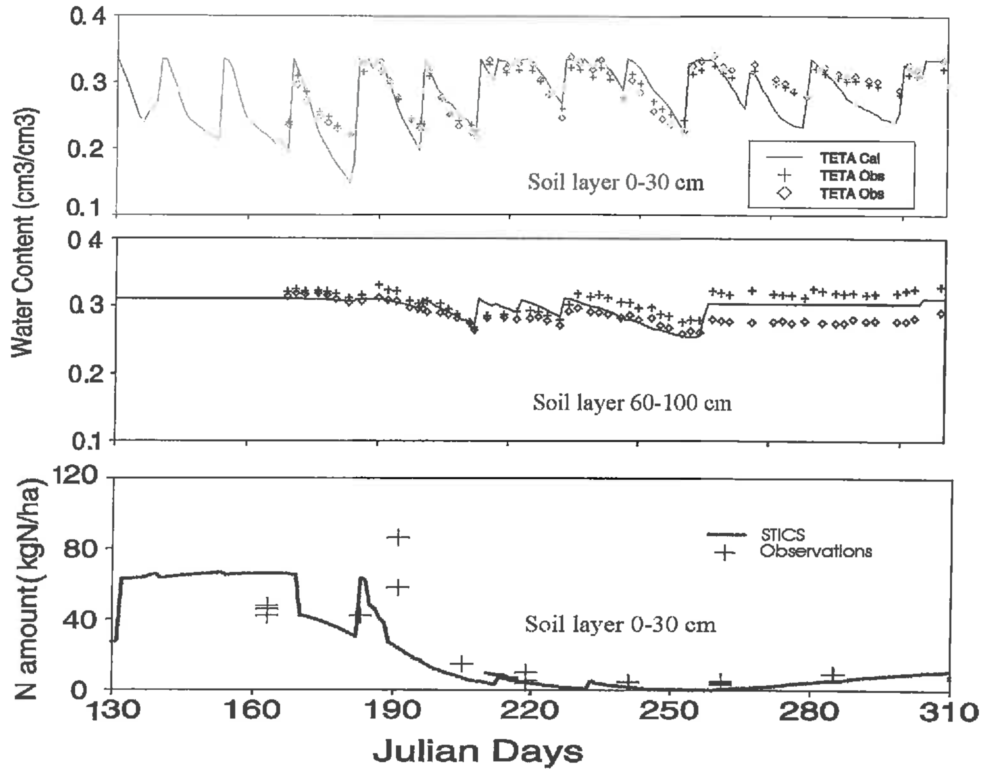


Figure 1 Comparison between measured and calculated soil water contents and soil nitrogen storages during a maize crop.

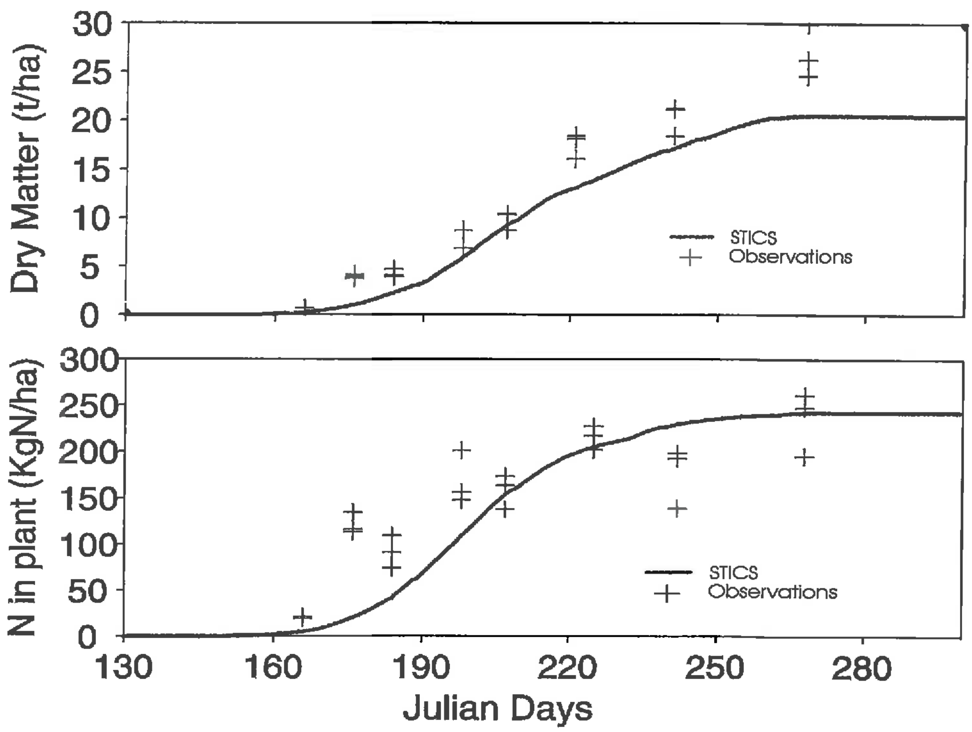


Figure 2 Comparison between measured and calculated plant dry matters and N contents during a maize crop.

nitrogen balance partly depends on the carbon balance, both are calculated together. Although the model computes the carbon, water and nitrogen balances, some specific processes like ammonia volatilisation and soil denitrification are not treated.
The two components of the NIVASAVE model were validated by field experiments during the overall period of a maize crop. Some selected results for the STICS component are presented in Figures 1 and 2. Figure 1 displays results for the soil compartment. It compares mean and estimated soil water content and nitrogen storage for an irrigation condition equal to 150 % of the climatic demand. Figure 2 displays results of the crop component: measured and simulated dry matter and N for the same irrigation condition.

MATERIALS AND METHODS

For the simulations, the used soil was a loamy clay soil with a 22% clay content, a field capacity of 0.22 kg kg^{-1} and a permanent wilting point of 0.12 kg kg^{-1}. The initial water content at the sowing date was field capacity, and the bulk density of the soil profile was 1450 kg m^{-3}. The soil was divided into five layers (0 – 0.30 m; 0.30 – 0.50 m; 0.50 – 0.65 m; 0.65 – 0.80 m; 0.80 – 0.95 m). The first layer initially contained 50 kg N ha^{-1} and the second layer 20 kg N ha^{-1}. The three deepest layers were assumed to contain no mineral N. The organic N content in the first layer was set at 1.0 g kg^{-1} soil.
Plant development was described by successive stages (germination, emergence, maximum leaf area index, beginning of grain filling, senescence, end of grain filling, ripeness and harvest), each stage being reached for a given thermal time calculated with a 6°C thermal base. Maize (cv Cecilia) was assumed to be sown on April 20 (day 111) and harvested no later than December 1 (day 335). Crop residues were assumed to be incorporated in the soil on December 3 (day 337).

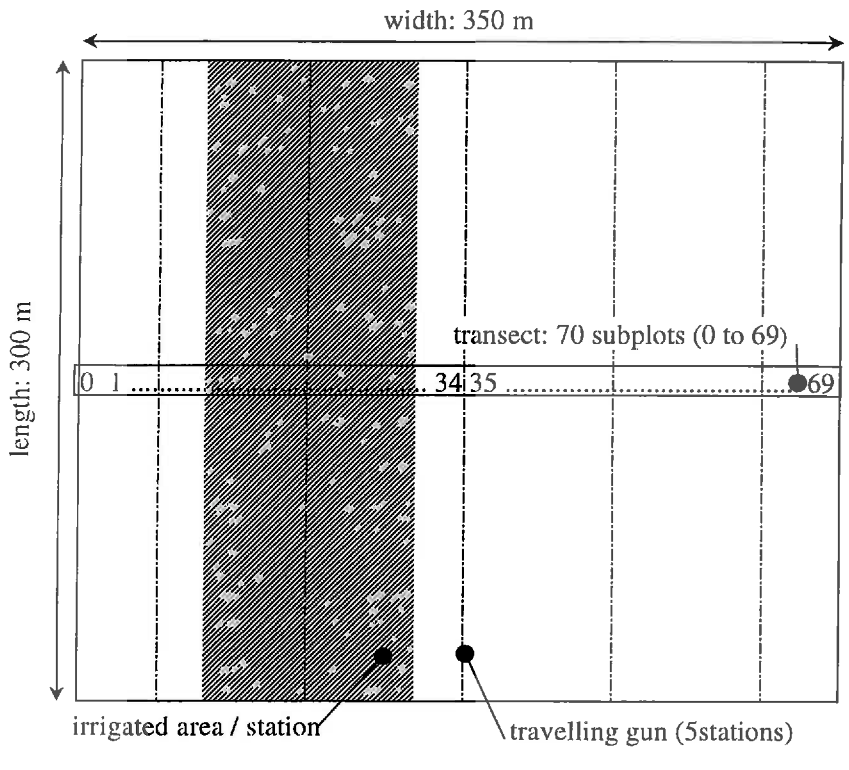


Figure 3 : The experimental setup for the simulation.

Irrigation occurred between June 7 (day 158) and September 24 (day 267), corresponding to a 500-1800 degree day interval. Irrigation was assumed to be carried out with a travelling gun in a 300 m long and 350 m wide field, oriented 340° north. Because the spacing between two consecutive waterings with the travelling gun was 70 m with one passage per day, the irrigation period for the entire field was 5 days. Consequently, irrigation frequency was 5 days or more during the cropping period, and an 8 day irrigation frequency was chosen. Each dose of irrigation was 40 mm, irrigation was postponed to the next day if it rained at least 15 mm, and cancelled if it rained more than 35 mm. The first irrigation began when the amount of water in the soil was reduced by more than 45 mm. For the amount of fertilization, we compared an N application rate of 180 kg N ha^{-1} with a rate of 280 kg N ha^{-1} (reference scenario). N application was split into 30 kg added on the sowing date (day 111), and the remaining added on day 172.The climatic data base comes from the experimental site of L'Etoile (Drôme, France). It starts from 1975 (January 1) and ends in 1995 (December 31), corresponding to 21 crop cycles and 20 intercropping periods. To provide graphic outputs versus space, a transect was chosen perpendicular to the direction in which the gun travelled and located at 100m from the border of the field (Figure 3). The transect was divided into 70 elementary sections of 5 m. Each section considered as uniform for irrigation dose and crop growth.

RESULTS AND DISCUSSION

The water balance

Annual climatic conditions showed high variability. Global radiation, Penman potential evapotranspiration and rain were located in the [4800 – 5400 MJ m^{-2} y^{-1}], [850 – 1200 mm], and [500 – 1300 mm] range, respectively. Mean rainfall was 888 mm and the standard deviation 215 mm for the overall period (CV = 24%). Figure 4 illustrates the temporal and spatial variability of irrigation, cumulative evapotranspiration and drainage. All these terms of the water balance exhibit a significant temporal variability among year. For irrigation the structure of the spatial variability is quite independent of the year. The passage of the gun always maintained dry zones on the border of the field, and overlapping zones at regular intervals. It is regarded as moderate (coefficient of variation on an annual basis less than or equal to 18% for the 21 years). Spatial variability of evapotranspiration is lower than for irrigation. Coefficients of variation are in the range [0.3 – 9%]. Crop uptake not only depends on irrigation depth, but also on climatic demand and on the ability of the root system to extract water. Spatial coefficients of variation of drainage vary from 1 to 20% among years. It also appears moderate. No direct relationship was found between irrigation and drainage. In our simulations, drainage becomes significant (typically exceeding 100 mm) when rain exceeds 400 mm.

We also defined a relative value for each term of the water budget or for yield at the field scale. This relative value was defined as the dimensionless ratio of the actual spatial mean to the calculated value at a virtual location for which the theoretical irrigation dose is assumed to be truly and uniformly applied. During the cropping period, values for the relative irrigation, evapotranspiration and drainage as defined above vary from 0.87 to 0.98 (mean of 0.93), 0.95 to 1.00 (mean of 0.96), and 0.86 to 1.16 (mean of 1.00), respectively. Hence, although spatial variability of water fluxes induced by non-uniform irrigation exists, the spatial mean at field scale is close to the value representing a uniform irrigation depth. Spatial variability appeared not to influence strongly the field mean of the water balance, as compared to the perfectly uniform case.

Figure 4 **Spatial distribution along a transect of (a) irrigation, (b) actual evapotranspiration, (c) drainage in the cropping period during the 21 years simulated. Each line corresponds to one year, the dashed lines indicate the position in which the gun travels.**

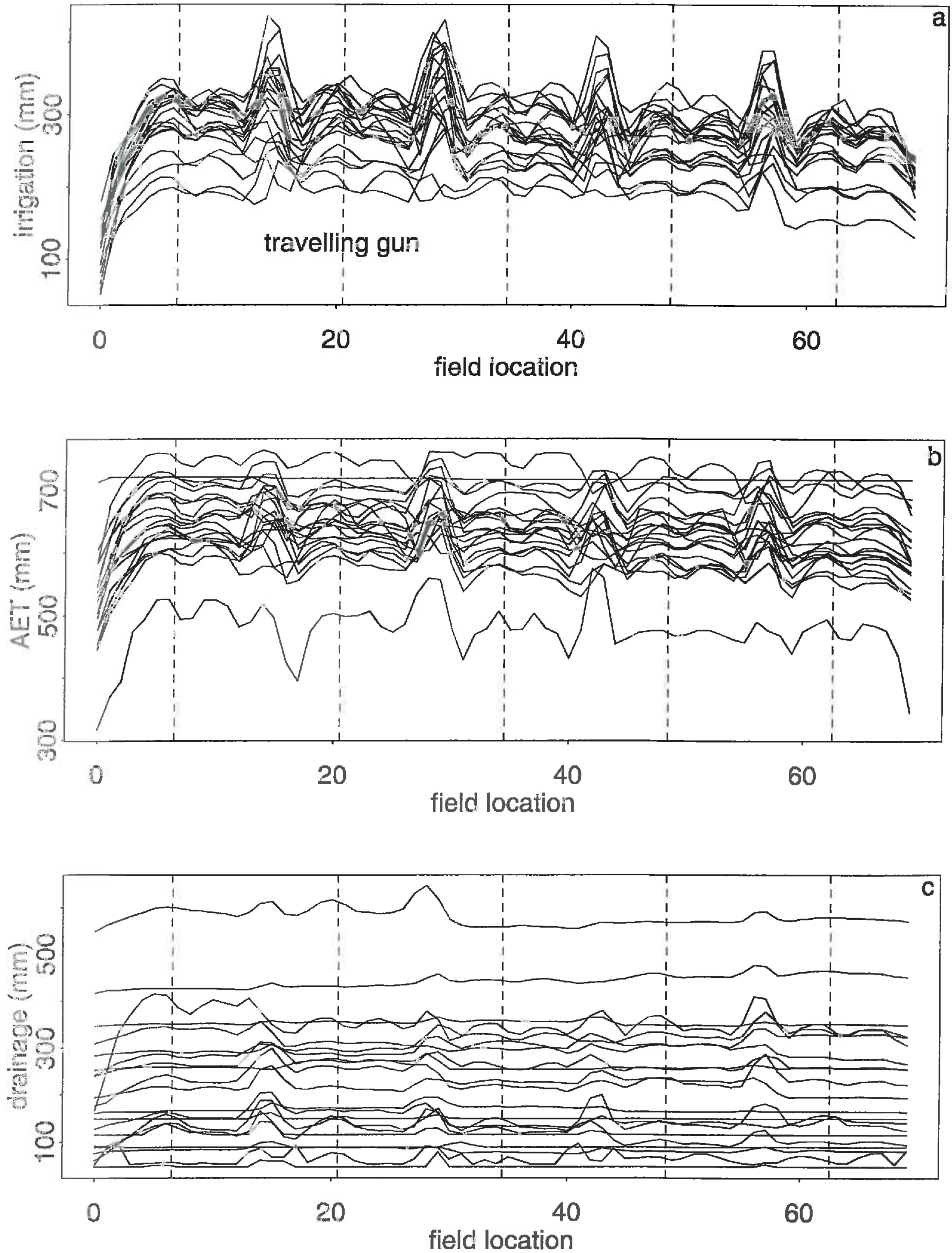
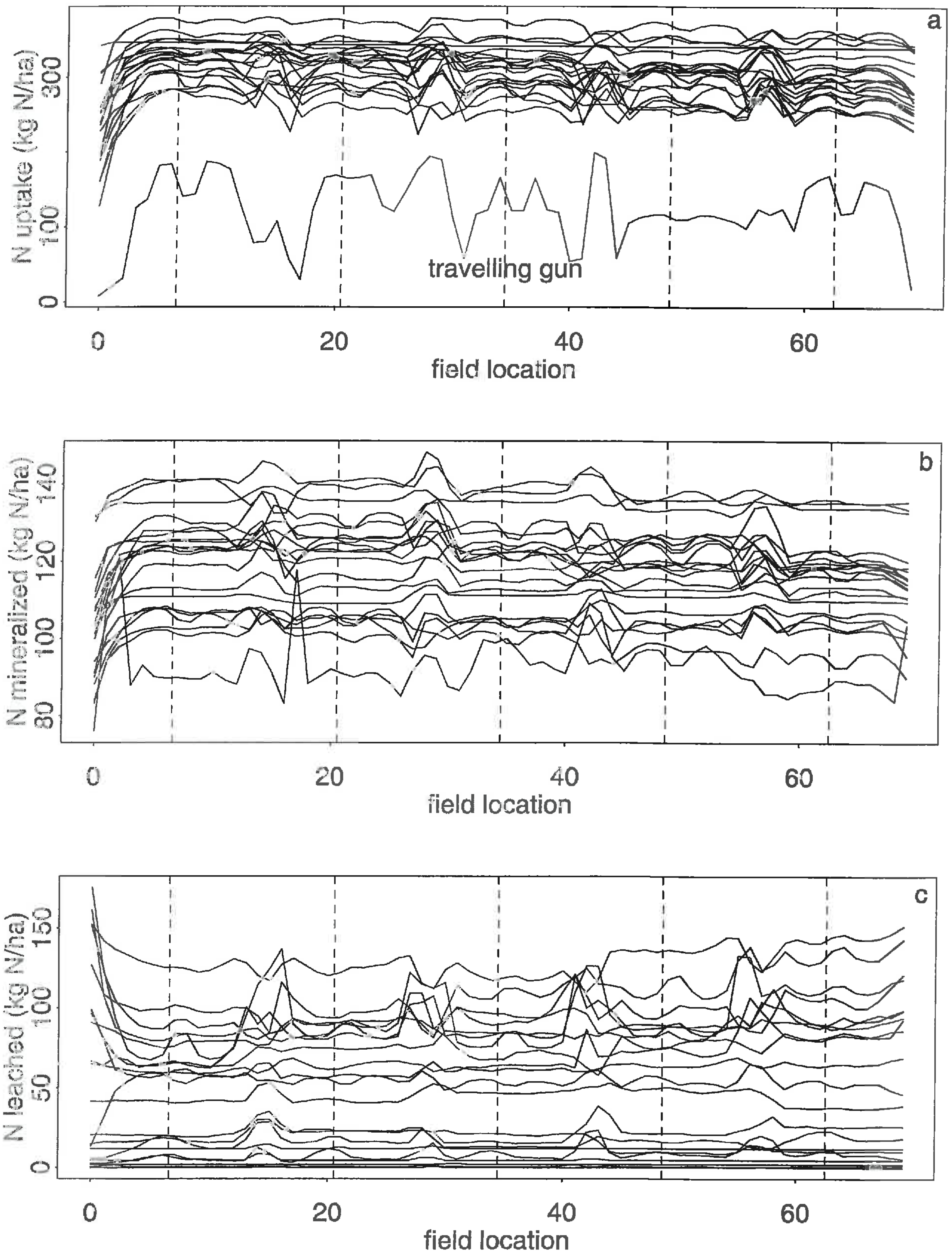


Figure 5 **Spatial distribution along a transect of (a) N plant uptake, (b) mineralised N, (c) leached N in the cropping period during the 21 years simulated. Each line corresponds to one year, the dashed lines indicate the position in which the gun moves.**



The nitrogen balance

During the cropping period, N uptake by the crop was 300 kg ha^{-1}, and variation between years was small. This suggests that nitrogen uptake was generally not limited by irrigation conditions, except in 1989. Spatial variability in crop N uptake (Figure 5) was generally low, and of the same order of magnitude between years (mean value of 19 kg ha^{-1}), except in 1989. These results are in agreement with the spatial variability in evapotranspiration (coefficient of variation between 0.1 and 9%), indicating that N uptake was correlated to crop transpiration and dry matter production. The spatial variability of N mineralization was also low: Coefficients of variation were in the [1 – 8%] range. Temporal effects dominated except in overlapping zones due to successive gun movements where the wet soil favoured mineralization (Figure 5). N leaching varied from 0 to 130 kg ha^{-1}, the coefficients of variation from 3 to 34%. In dry years, leaching was nil or limited throughout the field, and the variability low, as expected. In wet years, leaching occurred at some specific locations or on the whole field, depending on the source of water (uniform rain or non-uniform irrigation), thus leading to various situations of leaching at field level. Temporal variations in leaching among years dominated whereas the distribution of nitrate leaching along the transect highlighted the overlapping zones (Figure 5). Variations in leaching were correlated with drainage variations but spatial variability in leaching was greater, especially in wet years. Leaching becomes significant when drainage exceeds 150 - 180 mm, which roughly corresponds to soil water content at field capacity.
Relative N mineralization is close to 1 (0.98) with low temporal variability between years (CV = 3%). This may be attributed to: the fact that mineralization is mainly sensitive to variations in climatic conditions (air temperature, for example) and microbial activity, factors that were regarded uniform for the whole field.

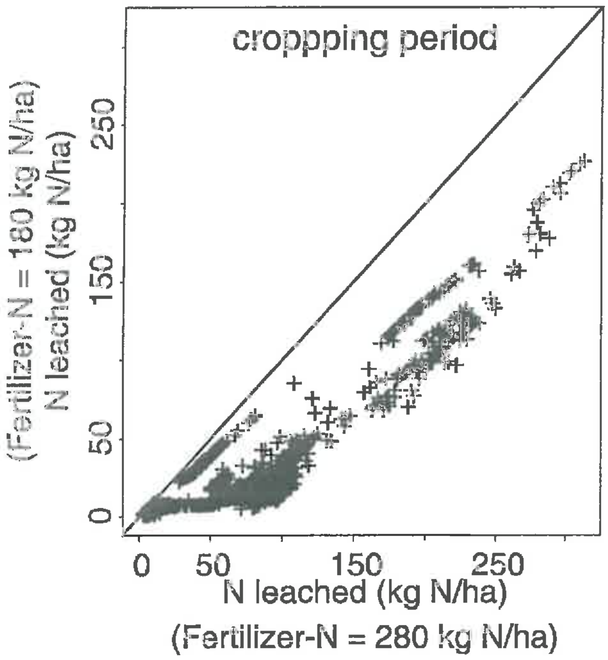


Figure 6 Comparison of leached N with the high (280 kg N ha-1) and the low (180 kg N ha-1) fertilization rate during the 21 years simulated

For N leaching, the mean ratio exceeds 1 (1.13), and showed greater variability between years (standard deviation 0.12) than crop uptake (standard deviation 0.07), or mineralization (standard deviation 0.03). This results from the strong impact of overirrigated zones in the field. Reducing N fertiliser rate from 280 kg ha`1 to 180 kg.ha^{-1} markedly differed in N leaching (Figure 6). The water balance components (irrigation, actual evapotranspiration, and drainage) were identical for the two fertilisation rates, thus indicating that interactions between nitrogen and water were negligible. Total biomass and yield were similar for both situations showing that nitrogen availability did not limit plant growth even at the lower N rate. N uptake by the crop was only slightly lower at the lower fertilisation rate. Globally, the pattern of the N fluxes and the order of magnitude of the nitrogen balance terms were generally similar for the two treatments, except for N leaching.

CONCLUSION

Numerical experiments and modeling are useful alternatives to experimental approaches to compare different irrigation and fertilization management over long periods, and to take into account spatial variability in the soil-plant-atmosphere system. Experimental approaches cannot consider all conditions of soil water, soil fertility and crop growth induced by the diversity of soil, climatic conditions, and agricultural practices. As irrigation distribution, biomass production, and environmental consequences of various agricultural practices strongly interact, it is essential to combine them in a single model like the described NIWASAVE model in order to simultaneously analyze agricultural management consequences in terms of both yield and environmental quality. Given the obtained results, this model appears a useful tool in analyzing water use by crops under spatially heterogeneous conditions. Nevertheless, this approach does not explore all possible agricultural practices, climatic and soil conditions. Many other sources of variation such as type of soil, soil hydrodynamic properties or irrigation strategies must be tested to arrive at more general conclusions.

REFERENCES

Amali S., Rolston D.E., Fulton A.E., Hanson B.R., Phene C.J., Oster J.D., Soil water variability under subsurface drip and furrow irrigation, Irrig. Sci. 17 (1997) 151-155.

Augier P., Deumier J.M., Guillard E., Spray improvement and water economy, Ingénieries EAT 3 (1995) 13-22.

Augier P., Kosuth P., Deumier J.M., Lacroix B., Bonnemort C., Management of irrigation heterogeneity and impact on crop yield and water losses, Colloque AFEID-COFIRA-SIMA, Paris, 25/02/1997, 1-20.

Ben-Asher J., Ayars J.E., Deep seepage under nonuniform sprinkler irrigation. I. Theory, J. Irrigation and Drainage Engineering 116 (1990a) 354-362.

Ben-Asher J., and Ayars J.E., Deep seepage under nonuniform sprinkler irrigation. II. Field data, J. Irrigation and Drainage Engineering 116 (1990b) 363-373.

Bresler E., Dagan G., Variability of yield of an irrigated crop and its causes. 1. Statement of the problem and methodology, Water Resour. Res. 24 (1988) 381-387.

Brisson N., Mary B., Ripoche D., Jeuffroy M.H., Ruget F., Nicoullaud B., Gate P., Devienne-Baret F., Antonioletti R., Durr C., Richard G., Beaudoin N., Recous S., Tayot X., Plenet D., Cellier P., Machet J.M., Meynard J.M., Delécolle R., STICS: a generic model for the simulation of crops and their water and nitrogen balances. I. Theory and parameterization applied to wheat and corn, Agronomie 18 (1998) 311-346.

Bruckler L., de Cockborne A.M., Renault P., Claudot B., Spatial and temporal variability of nitrate in irrigated salad crops, Irrig. Sci. 17 (1997) 53-61.

Dagan G., Bresler E., Variability of yield of an irrigated crop and its causes. 3. Numerical simulation and field results, Water Resour. Res. 24 (1988) 395-401.

Kosuth P., Augier P., Deumier J.M., Lacroix B., Effect of wind on yield and watering heterogeneities with sprinklers, 17th regional conference on irrigation and the efficient and ecologically appropriate drainage of irrigation water in European countries, Varna, BGR, 12-16/05/1994, 47-62.

Leenhardt D., Lafolie F., Bruckler L., Evaluating irrigation strategies for lettuce by simulation: 1. Water flow simulations, Eur. J. Agron. 8 (1998) 249-265.

Mateos L., Mantovani E.C., Villalobos F.J., Cotton response to non-uniformity of conventional sprinkler irrigation, Irrig. Sci. 17 (1997) 47-52.

Shufford J.W., Fritton D.D., Baker D.E., Nitrate-nitrogen and chloride movement through undisturbed field soil, J. Environ. Qual. 6 (1977) 255-259.

Silvertooth J.C., Watson J.E., Malcuit J.E., Doerge T.A., Bromide and Nitrate Movement in an irrigated cotton production system, Soil Sci. Soc. Am. J. 56 (1992) 548-555.