Potential of EPIC/ALMANAC for Crop Growth Simulation in Semiarid Environments of NE Brazil

Thomas H. Hilger (1), Joachim Herfort (1), Inacio de Barros (2), Thomas Gaiser (3), Luciano M.F. Saboya (4), Luis G. R. Ferreira (5) and Dietrich E. Leihner (1)

(1) Universität Hohenheim, Institut für Pflanzenproduktion und Agrarökologie in den Tropen und Subtropen (380), 70593 Stuttgart, Germany, t-hilger@uni-hohenheim.de, Fax: +49[0]711-4592304 (2) Universität Hohenheim, Institut für Pflanzenernährung, (3) Universität Hohenheim, Institut für Bodenkunde und Standortskunde, (4) Universidade Federal do Tocantins, Tocantins, Brazil, (5) Universidade Federal do Ceará, Ceará, Brazil

Abstract

Crop modelling are valuable tools in research, training and teaching, yield and area forecasting, land use planning, and decision-making. They synthesise existing knowledge in a common framework and explore the consequences of known or hypothetical mechanism at higher levels of integration. EPIC and its follow-up version ALMANAC were selected for simulating the crop production in semi-arid regions of Northeast Brazil within the Brazilian-German research program *WAVES*. The objective of this study was to test both models under NE Brazil conditions. In conclusion, both models are appropriate for simulating crop production in Northeast Brazil but model calibration is necessary.

Keywords: Al toxicity, erratic rainfall distribution, crop management, crop modelling, model calibration

Introduction

In general, crop simulation models are designed for an improved understanding of the influence of season, location and management on crop growth processes, for deriving recommendations concerning crop management, for investigating environmental and sustainability issues, for yield and area forecasting, and for land use planning and decision-making (Jones and Kropff, 1996; Jones et al., 1996; Jorgensen, 1986; Penning de Vries, 1983). Crop models are also used to gain a better understanding of how ecosystems interact with a rapid changing environment as they can synthesise existing knowledge in a common

framework and explore the consequences of known or hypothetical mechanism at higher levels of integration (Goudrian et al., 1999). Thus, they can be valuable tools in research, teaching and training, business and policy-making (Sinclair and Seligman, 1996).
The joint German-Brazilian research program on *Water Availability and Vulnerability of Ecosystems and Society in the Northeast of Brazil (WAVES)* aims at analysing the interactions between water availability, natural resources and human activities in semiarid areas of Northeast Brazil and predicting their possible responses to climate change by an interdisciplinary approach. A second goal of the program is to develop an integrated regional model as a tool for evaluating strategies of a sustainable rural development in the Brazilian federal states of Piauí and Ceará under changing climatic and socioeconomic conditions.
In this context, crop modelling plays an important role as agriculture is the mainstay for the majority of the rural population. In Northeast Brazil, however, agricultural production is strongly handicapped by adverse site conditions such as low levels of soil fertility, erratic rainfall distribution and recurrent sporadic droughts. The latter are possibly associated with the *El Niño Southern Oscillation* (ENSO) phenomenon. In years with unfavourable rainfall, migration from the rural areas of Northeast Brazil to the Amazon basin and the urban centres increases substantially, leading to strong environmental impacts and social tensions in the Brazilian society.
The *Environmental Policy Integrated Climate* (EPIC) model and its follow-up version the *Agricultural Land Management Alternatives with Numerical Assessment Criteria* (ALMANAC) model were selected for simulating the crop production in the integrated Models of WAVES. The objective of the research presented here was to test both simulation models in semiarid environments of NE Brazil.

Materials and Methods

Site description

The German-Brazilian research program WAVES focuses on the Northeast Brazilian federal states Piauí and Ceará. Both states belong to the polygon of droughts. The drought polygon covers about 82 and 92%

of the state territories of Piauí and Ceará, respectively (Fig. 1). In this area, rainfall distribution varies strongly in time and space and in many years the rainy season is disrupted by dry spells which may last up to three weeks and more (Conti, 1995). These dry spells mainly occur in periods most sensitive to crop growth and lead to reduced yields or even total crop failure.

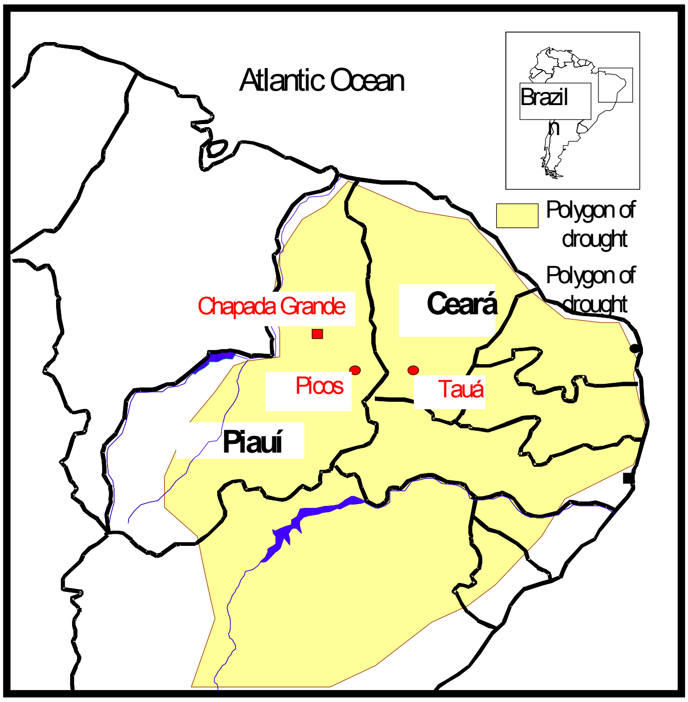


Figure 1. NE Brazil and the polygon of droughts

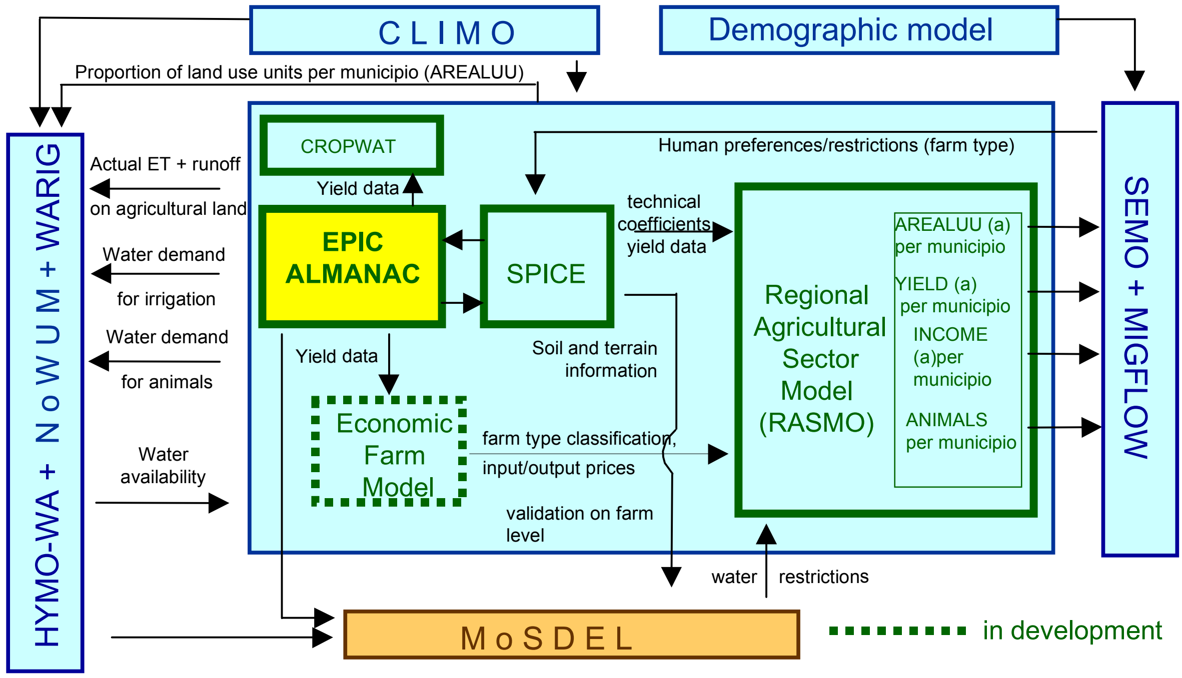
In addition, the crop production of this area is limited by adverse soil conditions. In Piauí, the soils are often strongly weathered (<5% weatherable minerals) and very acid (pH 4.0). They often present toxic levels of free Al ions (Al saturation of CEC: >85%) and the potential cation exchange capacity (CEC) is low due to the presence of low activity clays. In contrast, more fertile soils are found in Ceará which are less weathered and present higher pH values. Nevertheless, salinity and water availability are important constraints of crop production in this area.

Data collection

For this study, data from field trials at representative sites in Piauí - Chapada Grande (6°30´S 42°20´W; 400 m above mean sea level; Humic Ferralsol) and Picos (7°1´S,41°37´W; 545 m a.m.s.l.; Alumi-haplic

Acrisol) - and in Ceará – Tauá (6°25´S, 40°25´W, 450 m a.m.s.l., Eutric Fluvisol) and Fortaleza (3°45´S, 38°32´W, 25 m a.m.s.l., Haplic Acrisol) were collected for model testing.
Field trials with rice, maize, and cowpea were established in various environments by using traditional and improved crop varieties Traditional and improved cropping practices such as burning, mulch and fertilizer application, weeding, sole and mixed cropping, various planting densities and patterns were also included in the test program. Apart from soil and climate data, yield components, dry matter production and leaf area development were determined for comparisons of observed and simulated data. Data on rice were collected in 1986 and 1987, and on maize and cowpea in 1994, 1998 and 1999. The 1987 and 1998 growing seasons were strongly affected by *El Niño*.

Model structure and statistical analyses
The simulations were run with EPIC v. 0941 and its derivative ALMANAC v. 1364 by using a cowpea crop file recently developed by the Federal University of Ceará (UFC) and the existing maize and rice crop files. Both models are linked to the integrated models developed by WAVES - the Semi-arid Integrated Model (SIM) and the Model for Sustainable Development of Land Use (MoSDEL). SIM allows a dynamic simulation, its resolution is the municipality and it works on the macro scale (state level = Piauí and Ceará, approximately 400,000 km²), whereas MoSDEL is GIS-based with a resolution of 100 m x 100 m and it works on the meso scale (focus area = Picos, approximately 3,000 km²).
Crop parameters and potential crop production data required by SIM are estimated by using either the FAO *Crop and Water Requirement* (CROPWAT) method or EPIC and ALMANAC. Output data of the agricultural submodels are up-scaled by use of the ***S****oil and Land Resource Information System for the States of* ***Pi****auí and* ***Ce****ará* (SPICE) (Gaiser et al., 2000). An overview of the interfaces between the various WAVES sub-models and the particular models of the research area Agroecosystems is given in Figure 2.
Statistical analyses were carried out by using SPSS.



Note: **ALMANAC** = Agricultural Land Management Alternatives with Numerical assessment Criteria; **CLIMO** = Climate Model; **CROPWAT** = Crop and Water Requirement; **EPIC** = Environmental Policy Integrated Climate model; **HYMO-WA** = large-scale Hydrological Model; **MIGFLOW** = Migration Flow; **NoWUM** = Nordeste Water Use Model; **SEMO** = Socioeconomic Model; **SPICE** = Soil and Land Resource Information System for the States of Piauí and Ceará; **WARIG** = Water Availability in the Rio Guaribas Watershed

Figure 2. Overview of the integrated models of WAVES and its interfaces; Semiarid Integrated Model (SIM; blue: all submodels, green: agricultural submodels of SIM) and Model for Sustainable Development of Land Use (MoSDEL; brown)

Results and Discussion

Model structure analyses

Among 13 crop models, EPIC and ALMANAC were selected for simulating the crop production within the interdisciplinary Brazilian-German research program WAVES in semi-arid regions of Northeast Brazil as the crop files of both models allow to simulate the growth and yield performance of about 80 crops, half of them can be grown in the tropics. In 1996, the harvested area of the economically important crops for Piauí and Ceará, represented by the EPIC/ALMANAC crop files, were 20% for the Litoral, 74% for the Sertão, 76% for the Meio-Norte, and 83% for the Cerrado in the states of Piauí and Ceará (Tab. 1).

Tab. 1. Economically important crops in the four ecological zones of the research area Piauí and Ceará and its percentage (%) of harvested area

	Litoral	Sertão	Meio-Norte	Cerrado
Maize	8,6	36,7	31,3	28,2
Beans	8,4	31,2	19,6	12,8
Rice	0,7	3,7	23,0	41,3
Cashew	64,3	14,6	12,4	2,9
Cassava	5,7	2,3	7,0	3,3
Sugar cane	2,6	0,8	2,3	0,2
Coconut	5,6	0,1	0,1	0,0
Bananas	1,8	2,0	0,4	0,6
Fodder grasses	0,7	1,2	0,7	0,5
Cotton	0,0	1,5	0,1	0,2
Mango	0,4	0,2	0,3	0,2
Melon	0,2	0,0	0,1	0,0
Tomatoes	0,0	0,2	0,0	0,0
Others	1,0	5,5	2,7	9,8

Source: (IBGE, 1998)

Furthermore, both models consider Al toxicity and the availability of more than one nutrient in the soil - nitrogen and phosphorus. Phosphorus is a major limiting factor for crop growth in Piauí.

Finally, ALMANAC is able to consider up to ten plants in a single simulation run and, thus, it reflects both competition by weeds and mixed cropping, the latter being an important characteristic of traditional crop production in NE Brazil.

The daily rainfall distribution was well simulated by the weather generator from recorded monthly data. The occurrence of dry spells within the rainy season was also well predicted by the weather generator of the models. With regard to solar radiation, a good correlation between simulated and measured data was found for the rainy season only whereas solar radiation during the dry season was under-estimated, leading to reduced yields in the simulation runs (Fig 3). When using the recorded solar radiation data as input data (SR1994) instead of the weather generator (SRWXGEN), a much better simulation result was obtained (Fig 4).

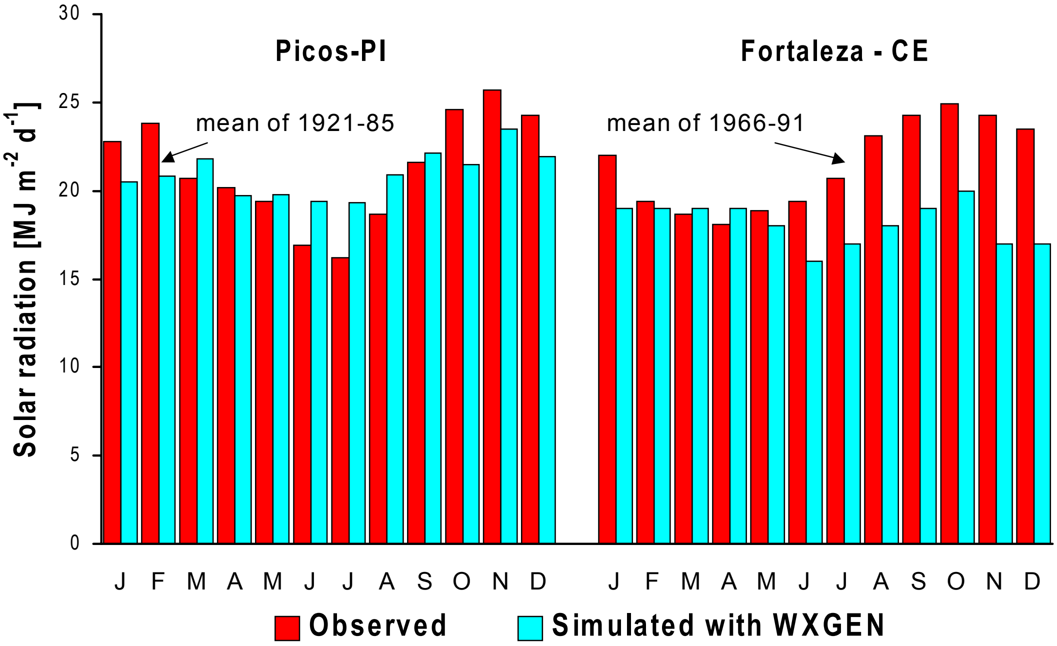


Fig. 3. Comparisons between observed (long-term mean) and simulated solar radiation (EPIC weather generator WXGEN). Picos (Piauí) and Fortaleza (Ceará), NE Brazil

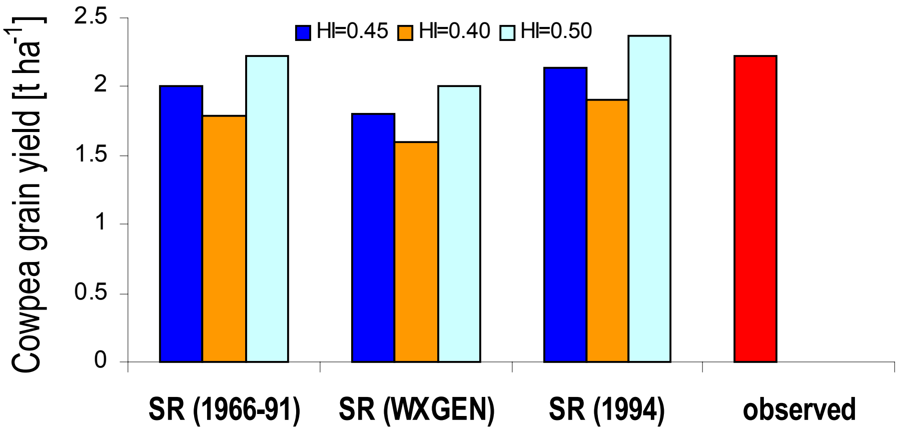


Fig. 4. Simulated cowpea grain yield as affected by harvest index and origin of solar radiation input data. Fortaleza, Ceará, NE Brazil. Cowpea variety Epace 10 was grown from October to December 1994 under irrigated and completely fertilised conditions.

Simulation runs with EPIC/ALMANAC

In Piauí, the first simulation runs with the original maize and rice files and the recently developed cowpea file showed low correlations between simulated and observed data in a comparison of all treatments (rice: R^2=0.35; maize: R^2=0.38; cowpea: R^2=0.33). The fit of regression increased when some of the treatments were excluded from the regression analyses. In the case of rice, fit of regression significantly improved when burning and mulching was excluded, whereas fertiliser application and final spacing had to be excluded for improving fit of regression in the case of maize and cowpea (rice: R^2=0.86; maize: R^2=0.74; cowpea: R^2=0.82). Comparing data from Piauí and Ceará, however, showed contrasting results for improved cropping practices (Figs. 5 and 6). In Ceará, growth and yield of cowpea was well predicted even under improved crop management. Even the simulated and observed maize data corresponded much better at this site when compared to Piauí. These results indicated that EPIC/ALMANAC performs well at more fertile sites represented by the test sites in Ceará, but it may completely fail to predict the positive fertilizer response of maize and cowpea under less favourable site conditions as they were found in Piauí.

For improving the simulation results, the structure of both models was analysed. The analyses of the crop files and the output data showed a high sensitivity of the models to both soil fertility and acidity related parameters. The simulation results of Picos indicated a strong relationship between soil pH, root formation and the number of days with water stress (Fig. 7).

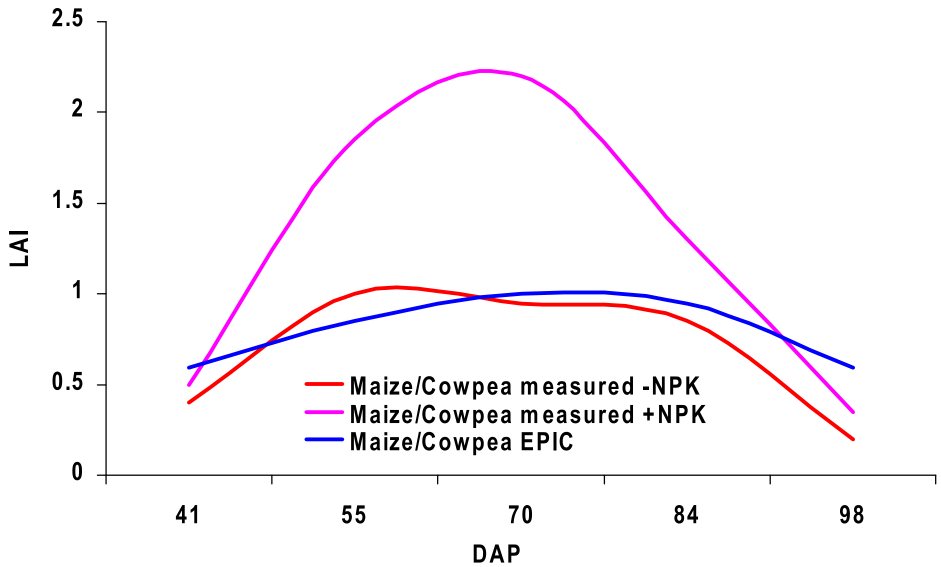


Fig. 5. Simulated (EPIC/ALMANAC) and observed LAI (Delta T SunScan Canopy Analysis System) of intercropped maize and cowpea. Data were collected between March 3 and April 29, 1998 at Picos PI, NE Brazil.

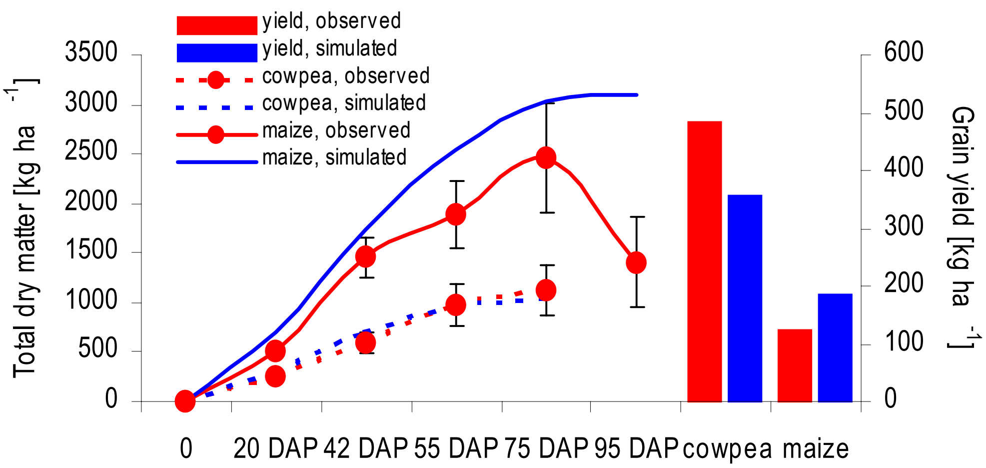
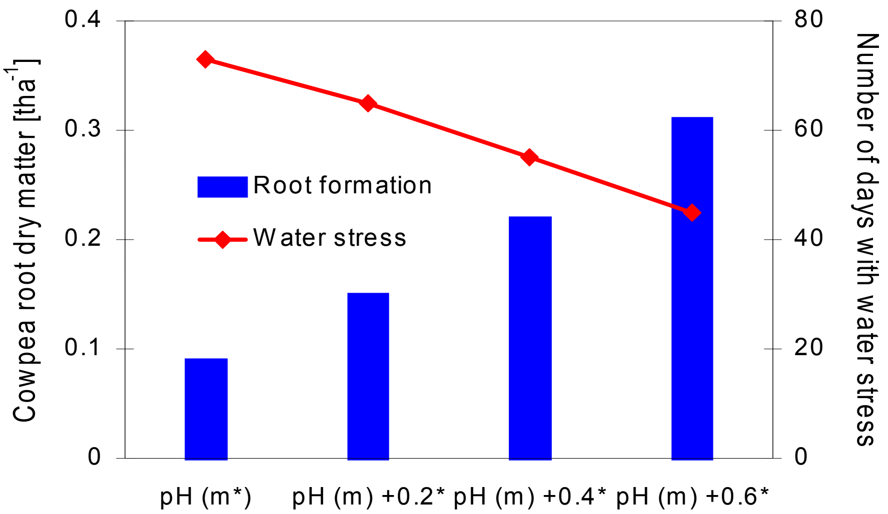


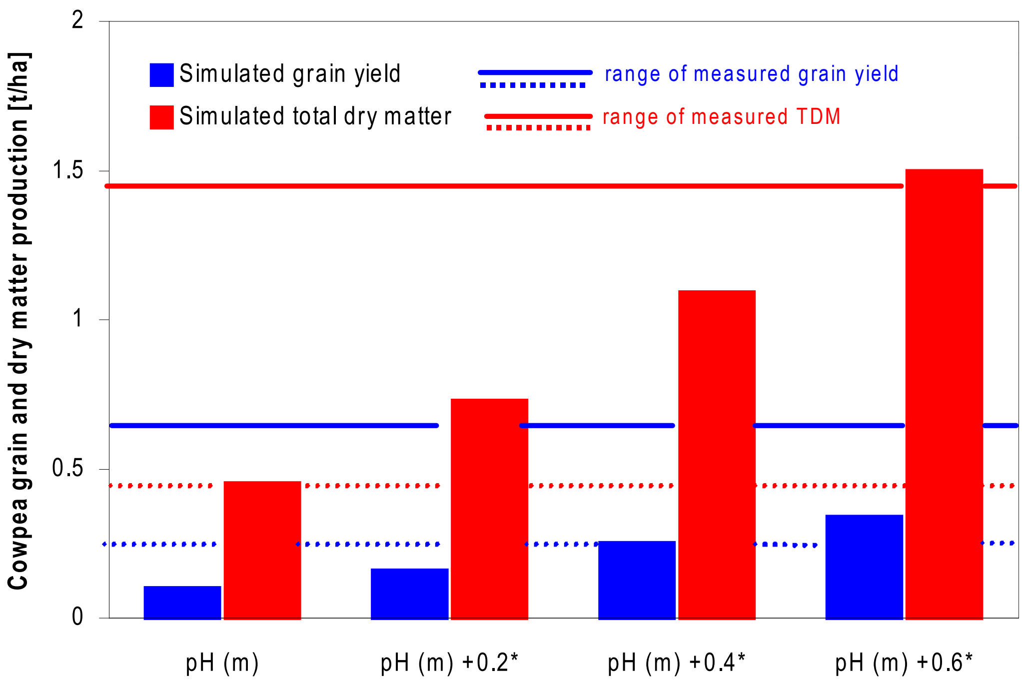
Fig. 6. Simulated and measured TDM and grain yield of maize and cowpea (Treatment 1: weeding and NPK application). Data were recorded in 1999 at Tauá CE, NE Brazil.



Note: m = measured value; pH 4.1 * increment by which measured pH value was raised

Fig. 7. Simulated cowpea root formation and corresponding number of days with water stress as affected by increasing the soil pH. Field data were recorded between 1998 and 1999 at Picos PI, NE Brazil.

Simulation runs with cowpea by using the measured pH in the representative soil profile showed that the model considered water availability as the only limiting factor for crop growth, although field data revealed a positive growth and yield response of cowpea to fertilizers even under the water-limited growing conditions of 1998 despite a poor soil fertility level. A sensitivity analysis of the model revealed that an increase of the soil pH improved the water availability, leading to more reliable simulation results (Fig. 8).



Note: m = measured value; pH 4.1 * increment by which measured pH value was raised
Fig. 8. Simulated cowpea grain yield and total dry matter production as affected by increasing the soil pH. Field data were recorded between 1998 and 1999 at Picos PI, NE Brazil.

Another problem of the models in their present version is that both models calculate the limiting factors according to Liebig's minimum law. This approach, however, is not adequate if more than one factor is limiting crop growth as in the case of Piauí. Improving the calculation of limiting factors by using, e.g., the optimum law, adapting the Al tolerance index of the used crop files to local varieties, and assessing the spatial variability of the soil pH are, therefore, considered as the key factors for improving the reliability of the models.

Conclusions

Both models showed promising results, particularly when traditional crop management was used. However, improved crop management was only well estimated on the more fertile test sites. Both models partly failed to simulate crop growth and yield performance with regard to burning, mulching, increased planting density and fertilizer applications on less favourable sites which represent about 40% of the agricultural area cultivated in Piauí. The sensitivity of the models to soil pH modifications is very high and both models seem to under-estimate the potential of local varieties to cope with adverse site conditions, particularly with acid soils.

The structure of both models is appropriate for simulating crop production in Northeast Brazil. Model calibration, however, is urgently recommended and the calculation of limiting factors has to be improved particularly.

References

Conti JB (1995): Proposta de metodologia de estudo aplicada ao Nordeste Brasileiro. Tese de Livre-Docente apresentada ao Departamento de Geografia da Faculdade de Filosofia, Letras e Ciências Humanas da Universidade de São Paulo. São Paulo-SP.

Gaiser T, Ferreira LGR, Hilger T, Römheld V and Stahr K. 2000. The land resources information system SPICE as a tool for integration of the reults of the research area „agroecosystems“. In: Printz A (Ed.). Proceedings of the 3rd International WAVES Workshop held at Freising-Weihenstephan, March 13-16, 2000, pp46-49. TU München, Freising, ISBN 3-00-006630-6

Goudriaan J et al. 1999. Use of models in global change studies. In: Walker B, Steffen W, Canadell L, and Ingram J (Eds). The Terrestrial Biosphere and Global Change - Implications for natural and managed ecosystems. Synthesis Volume. IGBP Book Series No. 4. Cambridge University Press, Cambridge (UK), 439 pp.

IBGE (1998). Censo Agropecuário 1995/96. IBGE, Rio de Janeiro.

Jones JW and Kropff MJ. 1996. Developing Concepts and Methods for ICASA Systems Tools and Applications, ICASA.

Jones JW et al. 1998. Decision Support System for Agrotechnology Transfer: DSSAT v. 3 In: Tsuji GY, Hoogenbloom G, Thornton PK (Eds.). Understanding Options for Agricultural Production. System Approaches for Sustainable Agricultural Development Vol. 7.

Jorgensen SE. 1986. Developments in Environmental Modelling. Fundamentals of ecological modelling Vol. 9. Elsevier, Amsterdam. 389 pp.

Penning de Vries FWT. 1983. Modelling of growth and production In : Lange OL, Nobel PS, Osmond CB and Ziegler H (Eds.) Physiological plant Ecology IV. Springer, Berlin. pp 117-147.

Sinclair TR and Seligman NG. 1996. Crop modelling: From infancy to maturity. Agron. J. 88. pp 698-704