Int. Agrophysics, 1996, 10, 171-184

ACCESS-II: A DETAILED MODEL FOR CROP GROWTH AND WATER CONDITIONS

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Accepted May 21, 1996

Abstract. ACCESS-II contains a detailed model of crop growth and soil water use, for use within small areas and with detailed soil and cropping data. The principles behind the detailed model are described. Validation studies of water movement are shown at two sites in England, and of crop growth in Southern France, together with an example of the impacts of climate change on crop growth.

Keywords: model, soil water use, crop growth, climate change

INTRODUCTION

Studies of the impact of climate change on crop growth and productivity rely heavily on the use of models to predict the likely impacts of conditions which are not currently observed. Whereas the results of any model extended beyond its observational base are always speculative, the use of physically-based models derived from well established theory offers a route for making predictions of the impact of climate change on cropping systems. Where the models are shown to be well-founded and effective at predicting current conditions, then they can be used with some confidence. Consequently, climate change studies involve significant efforts in the development and testing of models, as a necessary first stage before the testing of hypotheses relating to changed climatic conditions [27].

The ACCESS suite of models, which is designed to offer a tool for the study of climate change impacts on crop growth and potential [28,29] is no exception, as the major focus of the ACCESS project has been the development, integration and testing of suitable models of all the components necessary for operational implementation. The ACCESS models thus consider both the growth of crops and the interaction with the soil in response to meteorological inputs, whether they represent present or altered climatic conditions.

The ACCESS models operate at two spatial scales [35], depending on the needs of the user. At all stages, the overlying philosophy has been to give the user of the models the flexibility to address a range of issues at a variety of scales. The user is thus given the option to choose the degree of modelling complexity. ACCESS-I is designed to operate on a wide spatial scale, using soil parameters that can be easily measured or estimated from pedotransfer functions and soil surveys, and is capable of relatively rapid operation. By contrast, ACCESS-II is a mechanistic model that requires additional data to give more detailed results. It is thus intended primarily to be used at a single site. Because it operates on multiple soil layers and a daily time step, ACCESS-II is computationally more expensive. It requires full soil data (including the moisture characteristics) and detailed crop growth parameters. The detailed modelling of ACCESS-II can be used to support the less-detailed, but spatially more distributed, modelling of ACCESS-I.

ACCESS-II

Overview

The ACCESS-II model has been developed from the MOBIDIC model of Leenhardt [24] and the EPIC model of Williams *et al.* [40]. It consists of linked daily plant growth and daily soil water balance sub-models. However, many detailed changes have been made to the models, and additional components included. This paper presents the details of the ACCESS-II model, and its implementation within the ACCESS project. The overall structure of the model (Fig. 1) is clear: it takes detailed inputs about the 'driving' meteorological inputs and the crop management parameters; and from them predicts the performance of the crop and ultimately predicts crop yield. In order to do this, the model must consider the state of the crop, and its development. Because of its crucial role in defining the amount of water available for crop growth, the soil water balance is of major concern, and so the ACCESS-II model includes two separate techniques for predicting the distribution of water within the soil and the user makes the choice depending on the level of information available to the investigation.

Crop growth stress, which is used to restrain the rate of crop growth, is the ratio between actual and potential transpiration. In this way the interaction between crop growth and the soil water balance is made explicit. The effect of this stress on the eventual crop yield is mediated through a crop-specific harvest index which is calibrated by phenological stage. ACCESS-II adopts a daily time step for modelling the crop and soil water states, and reproduce both a complex soil profile and multiple land uses within complex cropping rotations.

Crop water use

In ACCESS-II, Reference (Potential) Evapo-Transpiration (ET_0) is regarded as input data which is calculated outside the model using a standard method. This parameter is separated into evaporation and transpiration, using a Beer-Lambert law analogy [17,34] to calculate potential evaporation:

$$PE = ET_o e^{-cLAI} \quad (1)$$

where, *LAI* is the Leaf Area Index (leaf surface area per unit of ground surface), and *c* is a

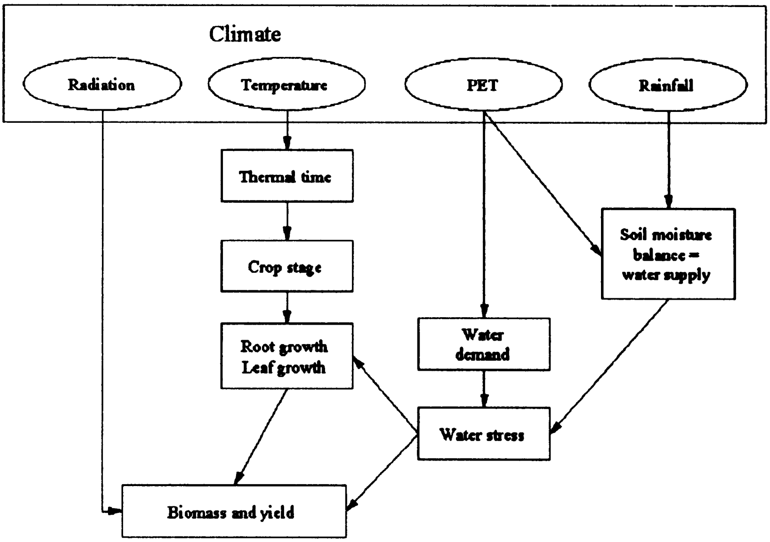

Fig. 1. Conceptual diagram of ACCESS-II

coefficient linked with plant structure. We use the method of Van Keulen [38] to estimate the actual evaporation (*AE*), modified after Rambal and Comet [24] and by Leenhardt [32]:

$$AE = PE\left(0.0075 + 1.2e^{-0.3/X}\right) \qquad (2)$$

where, X is the quantity of water (θ_i) in the first horizon normalised over the range between saturation (θ_s) and residual water content (θ_r):

$$X = \frac{\theta_i - \theta_r}{\theta_s - \theta_r}. \qquad (3)$$

Using this equation implies that evaporation is linked only with the moisture status of the first horizon. If this horizon is dry, the evaporation may be less than 1 % of the potential value. However, this method is acceptable only if the first horizon is thin. For this reason, the first two layers in the calculations within ACCESS-II are half the thickness of the others (2.5 cm /2.5 cm / then 5 cm...).

The water that the first horizon is able to transmit to the atmosphere (*AE*) must be furnished by the different layers. A factor, *f(i)*, which is proportional to the quantity of water that could be extracted of the ith layer, is calculated from the water content and depth:

$$f(i) = X_i\left(x^{\varepsilon z_i} - e^{\varepsilon z_{i-1}}\right) \qquad (4)$$

where, z_i is the top of the layer (cm); z_{i+1} is the bottom of the layer (cm); ε is a coefficient (value near to 0.125).

The quantity of water that is then extracted from the each layer is taken in proportion to this function. Because evaporation and water content are strongly linked, the time step for calculation is reduced to 1/6 of day, and the water contents updated at this frequency.

Actual transpiration (*AT*) is calculated using the method of Rambal and Comet [32], which represents transpiration using an electrical analogy:

$$AT = \left(\psi_f - \psi_i\right) / \, Res \qquad (5)$$

where, ψ_f is the unknown water potential of the plant cover; ψ_i is the water potential of the ith horizon; *Res* is the overall resistance to transfer. The contribution of each layer to transpiration is in proportion to the root density (rd_i) in each.

The unknown plant cover potential, ψ_f, is derived by noting that transpiration can also be given as:

$$AT = \left[1 / \left(1 + \frac{\psi_f}{ta}\right)^n\right] PT \qquad (6)$$

where, *ta* and *n* are two parameters defined for each crop. Combining the two relations gives:

$$\left[1 / \left(1 + \frac{\psi_f}{ta}\right)^n\right] PT =$$

$$SUM_i\left[\frac{\left(\psi_f - \psi_i\right) rd_i}{Res}\right]. \qquad (7)$$

The value of ψ_f can then solved numerically, and AT_i is calculated for each horizon. These calculations need the values of ψ_i, the soil water potentials in the different layers. As the model simulates the evolution of the water content, these soil water potentials are derived from moisture retention curves for each soil layer (pF curves). In ACCESS-II, two possibilities are available for defining these curves:

i) definition of the curve, for each horizon, using up to ten experimental points given as input data. In this case, the value of the potential is calculated by interpolation between the two nearest points;

ii) use of the van Genuchten [37] representation of the soil potential function. The four parameters needed are given as input data for each layer.

Each of the two methods has advantages and drawbacks. The first method seems to be simpler, but in implementation, the corresponding algorithm is slightly more complex. The second one is simpler, but the user must verify the shape of the curve before proceeding.

The need for pF curves is probably the main constraint in using ACCESS-II.

Crop growth

The crop growth component of the ACCESS-II model comes from the EPIC software developed by the USDA [40]. We chose EPIC for two main reasons: firstly the software simulates the growth of a large range of crops, including those of interest in this project; secondly EPIC has been thoroughly evaluated for European conditions by INRA-Toulouse, over a period of several years. EPIC was calibrated for the Languedoc-Roussillon by Cabelguenne *et al.* [8,9], and additionally modified to include crop phenophases. This modified model was linked with the MOBIDIC model of Leenhardt [25] by Bellivier [3], and at the same time, sensitivity analyses were conducted [23], and the possibility of the improvement of root extraction was considered [36]. Crop sowing and harvesting dates are defined in a crop diary, so that the model can be used to simulate long rotations of multiple crop types which can include multiple crops within a year.

The model assumes crop growth is dependent upon a cumulative heat unit, *HU* above a basal temperature, T_o:

$$HU_j = \sum_{i=0}^{j} HE_i \qquad (8)$$

$$HE_i = T_i - T_o \quad \text{when } T_i > T_o \qquad (9)$$

$$HE_i = 0 \quad \text{when } T_i \le T_o. \qquad (10)$$

These values are used to calculate relative thermal time for each day, j, syp_j:

$$syp_j = \frac{HU_j}{HU_{\max}}. \qquad (11)$$

Crop growth takes place between thermal time zero (which is crop emergence) and maturity. The important innovation of Cabelguenne *et al.* [8,9] is to subdivide the growth period into up to four phenological phases, in which the effects of stress can be parameterised separately. Table 1 illustrates the stages for four major crops that have been the modelled as part of the ACCESS project.

Table 1. Crop phenophases and lengths in relative thermal time for four crops modelled in ACCESS-II

Crop	Nature of phenophase	Duration (syp)
Winter wheat	emergence	0.40
	stem elongation	0.21
	flowering	0.13
	maturation	0.26
Maize	emergence, vegetative stage	0.35
	flowering	
	grain filling to desiccation	0.24
	(50 % water content)	
	grain filling to desiccation	0.24
	(32 % water content)	0.17
Soya	vegetative phase	0.30
	flowering to pod elongation	0.20
	pod filling	0.15
	grain swelling	0.35
Sunflower	emergence to first bud	0.221
	first bud to start of flowering	0.226
	start of flowering to end of flowering	0.137
	end of flowering to maturation	0.416

During each day of crop growth, the potential rate of growth as defined by thermal time, is reduced by a series of stress functions, relating to water and thermal stress. In the original EPIC model additional stress functions were provided to account for nutrient stresses, but these factors are not included in ACCESS-II.

In ACCESS-II, biomass is calculated in relation to the available quantity of solar energy. Half the global radiation is considered as active on the vegetation, and only a proportion of this is intercepted by the vegetation. To calculate this part the Beer-Lambert law is used:

$$PAR = PAR_0\left(1 - e^{-cLAI}\right) \qquad (12)$$

in which the intercepted and active radiation (*PAR*) is a function of the total photosynthetically active radiation (PAR_o), the crop Leaf Area Index (*LAI*) and a structure coefficient, *c*. The validity of this approach using the Beer-Lambert law is discussed, for example, by Varlet-Grancher *et al.* [39], and it is generally thought that the method is acceptable only if the canopy is closed (the leaves begin to touch or overlap).

Biomass synthesis is proportional to the intercepted energy, an observation which is supported by numerous field experiments which consider the whole growing period, although on a daily basis this assumption is less good. A simple proportionality constant represents the efficiency of the transformation between energy and biomass [26]. It can subdivided by crop phenophase [10,31,33], effectively creating phase specific conversion coefficients (Table 2). In principle, the accumulated biomass should be divided into the different parts which go to make the leaves, the roots, the stems and the yield. However, in ACCESS-II the growth of the different organs are computed separately, using empirical relationships between the growth of each organ. Relative root length is given as a linear function of thermal time and crop maximum value (Table 2). The maximum length is reached with a relative time less than 1, after which growth stops. This cannot be greater than the attainable soil depth or smaller than the crop height [18]. The distribution of roots within the profile was then calculated using the method developed by Leenhardt [24] from the CORNGRO model [12], in which the relative root density is computed from a third order polynomial. This method of calculation is simple, and takes into account an average form of a root system, but it is not adapted for simulations of plant growth in conditions that are far from the optimum water supply. For this reason, Trocme [36] reviewed the simulation of root growth and function, although his suggestions have not yet been incorporated into ACCESS-II.

Table 2. Example parameters for principle crops considered in ACCESS-II

Parameter*	Winter wheat	Maize	Soya	Sun-flower
warwa (phase 1)	2.7	2.0	2.125	2.125
warwa (phase 2)	2.7	5.2	2.5	2.875
warwa (phase 3)	2.7	6.4	1.75	2.875
warwa (phase 4)	2.7	6.4	1.375	1.125
LAI_{max}	7	5.0	6	6
rlad	0.80	0.40	1.60	1.50
syp_o	0.50	0.54	0.60	0.55
T_b	12	22.5	25	25

**warwa* - phase specific vlaues of biomass/energy conversion (g/MJ); *rdmx* - maximum root length, m; LAI_{max} - maximum Leaf Area Index; *rlad* - rate of senescence; syp_o - time of senescence (relative thermal time); T_b - optimal temperatures.

In ACCESS-II, leaf growth, characterised by the value of *LAI*, is not related to biomass, but only to time measured on the thermal time calendar. The relation between relative *LAI* measured and relative time, is calculated from the Heat Unit Factor (*HUF*):

$$HUF = \frac{syp}{syp + e^{a-bsyp}} \tag{13}$$

where, *a* and *b* are crop coefficients.

The daily increase of *LAI* is in proportion to the daily increase in *HUF*, up to a crop defined maximum value. However, when the thermal calendar reaches the beginning of senescence, the *LAI* is calculated differently:

$$LAI_i = LAI_o \left(\frac{1 - syp_i}{1 - syp_o} \right)^{rlad} \tag{14}$$

where, LAI_i is the *LAI* for day *i*; LAI_0 is the *LAI* for the first day of senescence; syp_o is the Heat Unit Index at the beginning of senescence, and *rlad* is the rate of senescence for the crop considered. With all these parameters, it is possible to compute a curve describing leave growth and senescence in a manner which fits experimental data, although this may require several calibration runs.

ACCESS-II includes calculation of the water stress, which then affects the plant performance. Water stress is defined simply as the ratio: *AT/PT*. Following the EPIC program, the daily biomass is reduced in proportion to the water stress value. However, this stress function could well be more complex, and is the subject of ongoing research.

The yield is a proportion, *HUI*, of the above ground biomass which is, in turn, calculated from the whole biomass after subtracting the biomass allocated to roots. Cabelguenne and Debaeke [6], Cabelguenne *et al.* [7] and Debaeke *et al.* [15,16] introduced the idea that the Harvest Index (*HI*) has a value that diminishes, to a degree which depends on the phenophase, if the plant suffers from water stress.

The Harvest Index, *HI*, is reduced each day by the amount *hi*, which is calculated from the daily value of the water stress, *WS*, (defined as the ratio of actual to potential transpiration) compared with a threshold *WSLIM* depending on the crop phenophase, where:

$$hi = psw\ pirinf\ (1 - WS) \quad WS > WSLIM \tag{15}$$

$$hi = psw\ pirsup\ (1 - WS) \quad WS < WSLIM \tag{16}$$

where, *psw* is a parameter depending on the crop phenophase; *pirinf* is a parameter giving the impact of *psw* if *WS* is <*WSLIM*; *pirsup* is a parameter giving the impact of psw if *WS* is >*WSLIM*. Values for these parameters were established at INRA-Toulouse (Table 3), but these are only examples and must be evaluated again for other climates. The positive values correspond to periods in which a small water stress can be favourable. Water stress also affects leaf growth, and ACCESS-II adopts the EPIC system in which leaf growth is reduced as the square root of the *WS* index. Root growth is not, in the current implementation of ACCESS-II, linked with water stress, and the development of a suitable link is identified as a task for the future.

Crop performance is also affected by thermal (heat) stress. In ACCESS-II, as in EPIC, a Thermal Stress *TS* is introduced:

$$TS = \sin\left(1.5707\,\frac{t_{soil} - t_g}{t_b - t_g}\right) \tag{17}$$

where, t_{soil} is the average daily soil surface temperature, calculated from air temperature; t_g is the base temperature for the crop (input parameter); t_b is the optimal temperature for the crop (input parameter). The effect of this stress is the same as the water stress, and for each time step, the largest stress factor is identified, and this is used to affect crop performance in the same way as described for the water stress. The stress factors are thus not additive.

Soil water component

The critical role of soil water in crop growth is mediated through its restriction on crop transpiration, accounted for in the model by the water stress function. It is thus essential to keep an accurate record of the storage of water within the soil. The soil water modules of both ACCESS-I and ACCESS-II were thus a major development area for this study. However, considerable variations exist in the quantity of data that are available for dealing with the soil water storage. In particular,

T a b l e 3. Values of parameters for the effect of stress on the crop harvest index, for different crops and phenophases (from Cabelguenne *et al.*, [9]).

Parameter	Phase	Winter wheat	Winter wheat old varieties	Maize	Maize old variety	Soya	Sunflower
psw	1	+0.0005	+0.0005	0.000	0.000	-0.000	0.000
	2	-0.0012	-0.0012	-0.020	-0.020	-0.003	+0.004
	3	-0.0071	-0.0071	-0.010	-0.010	-0.002	-0.002
	4	-0.0036	-0.0036	0.000	0.000	-0.003	-0.002
wslim	1	1	0.95	1	0.85	1	1
	2	1	0.95	0.80	0.85	1	0.7
	3	1	0.95	0.80	0.85	1	1
	4	1	0.95	1	0.85	0.8	1
pirsup	1	1	0	1	1	1	1
	2	1	0	1	1	1	2
	3	1	0	1	1	1	1
	4	1	0	1	1	1	1
pirinf	1	1	1.5	1	1.7	1	1
	2	1	1.5	1	1.7	1	1
	3	1	1.5	1	1.7	1	1
	4	1	1.5	1	1.7	2	1

the full solution to the equations of unsaturated water movement (the Richards' equation) require full information of the soil hydraulic functions, which are not readily available for many soils. Consequently, two versions of the soil water component model were developed and included in the ACCESS-II model: the simple ARFEJ model, and a full solution to the Richards' equation.

A simple model of soil water movement is offered by the ARFEJ model [19] incorporated in the MOBIDIC model of Leenhardt [24]. Water is assumed to move between layers in proportion to its excess above field capacity:

$$Q=(\theta-\theta_{FC})\left(1-\mathrm{e}^{\frac{-K_{sat}}{d(\theta_s-\theta_{\min})}}\right) \qquad (18)$$

where, *d* is the thickness of the soil layer, and θ_s and $\theta_{\min}$ are the water contents at saturation and air dried. All the terms beyond the first in the equation are constant for any soil layer, so the equation becomes a simple linear function of water above field capacity. Physically-based modelling of soil water movement within ACCESS-II is provided by numerical solution of the unsaturated flow equation, more commonly known as the Richards' equation. The form of this equation for one-dimensional vertical flow in a homogeneous, isotropic porous medium is:

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left[K\left(\frac{\partial h}{\partial z}+1\right)\right]-S(h,z) \qquad (19)$$

where, θ is volumetric water content; *h* is pressure head; *K* is hydraulic conductivity; *t* is time, and *z* is vertical position defined as positive upwards [33]. *S(h,z)* is a sink term which can account for water uptake by roots. Practical application of this equation required the use of an implicit finite difference method. ACCESS-II runs on a daily time step. The time step required for the Richards' equation solution needs to be an order of magnitude smaller, and the time step is varied during the simulation, dependant upon the fluxes within the profile, using a scheme proposed by Belmans *et al.* [4]. The Richards' equation model requires a description of the soil moisture release characteristic and hydraulic conductivity curves. In ACCESS-II, the relationships given by Clapp and Hornberger [13] are used for this purpose.

Boundary conditions

If the top layer is unsaturated then water (rainfall-evaporation) enters the profile at each time step and is redistributed by the model. If the top layer becomes saturated then any excess is first held on the surface up to an amount equal to the surface storage capacity (set to 2 mm). Any excess water above this is then lost as surface runoff. Two options are available for the lower boundary condition - free drainage, and sealed. In the case of free drainage, water leaves the bottom layer of the profile as deep seepage at a rate equal to the conductivity of the compartment at that time step, i.e., under a unit hydraulic gradient. If the sealed base is chosen then no water can pass through the base and the profile will tend to fill up with water from the bottom up. This will result in the formation of a water table, which, if drains are present, may produce drainflow.

RESULTS

Validation of the soil water component

Model validation is concerned primarily with testing whether the model predictions are an adequately accurate representation of the reality the model purports to simulate. It thus seeks to confirm that the model can be used for the purposes for which it was derived. Validation of the ACCESS-II model soil-water component is thus concerned to ask whether the predictions of the model are sufficiently accurate to allow the model to be used with confidence for climate change studies. The first stage in evaluating the ACCESS-II model was to compare the water movement sections against data collected from current climatic situations using data from a clay soil at Brimstone Farm in Oxfordshire.

Clay site

The test for the ACCESS-II model on a clay site used data from the Brimstone Farm experiment, in Oxfordshire, England (UK national grid SU247945), which was established in 1978 as a joint AFRC/ADAS experiment and intensively monitored ever since [11,20,21]. The soil of the Brimstone Farm is of the Denchworth series [14], which typically has 55-60 % clay. Effective drainage, which is required for the utilisation of this soil for arable agriculture, is achieved by the use of mole drainage which both introduces close-spaced drainage channels and increases the macroporosity. The soil is typical of many cereal growing areas of central England. Critical soil parameters are given in Table 4. The model adopted an impermeable lower boundary condition with artificial drains at 55 cm depth and 2 m spacing.

The soil moisture content predictions of ACCESS-II using the Richards' equation model are shown in Fig. 2, together with the observational data points from the neutron probe (NP) data. The observations follow the pattern of the data moderately well, and in particular reproduce the behaviour that at depth, the moisture content of the soils remains virtually constant, reproducing the behaviour observed at other sites by Armstrong and Arrowsmith [1]. Sample predicted and observed profile moisture contents for both the Richards' equation and the ARFEJ model (Fig. 3) show that the main problem is that

Table 4. Critical soil parametrs for Brimstone Farm, Oxfordshire, U.K.

Horizon	Top of layer (cm)	Bottom of layer (cm)	Max. water content (g/g)	Field capacity (g/g)	Saturated hydraulic conductivity (cm/day)	Texture
1	0	30	0.634	0.564	131	Clay
2	30	50	0.468	0.430	0.24	Clay
3	50	90	0.468	0.430	0.64	Clay
4	90	110	0.205	0.116	0.31	Clay

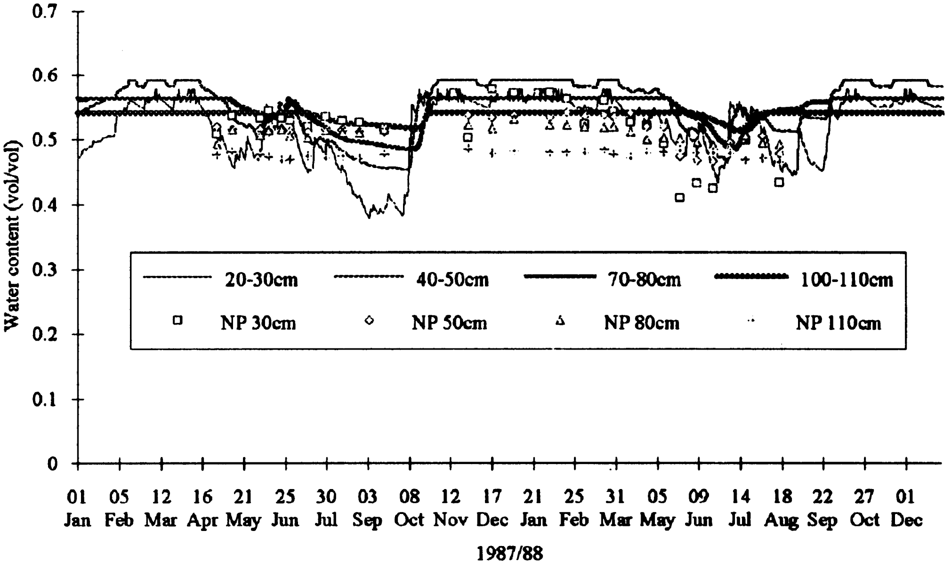

Fig. 2. Comparison of observed and predicted soil moisture contents using the ACCESS-II Richards' equation, in a clay soil, Brimstone Farm, UK.

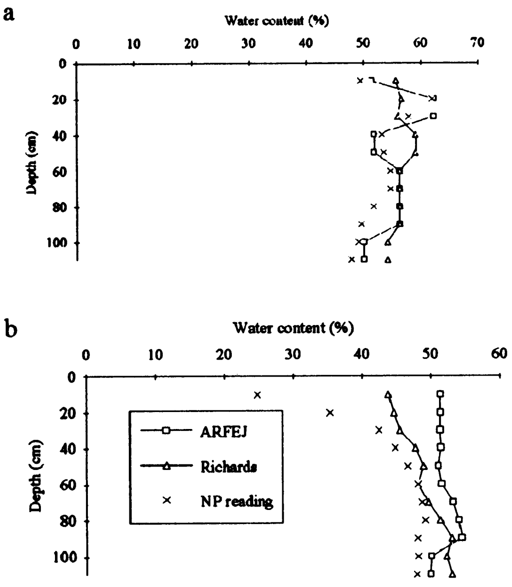

Fig. 3. Observed and predicted soil moisture profile, Brimstone Farm, on 17 Dec 1987 (a) and 21 June 1988 (b).

neither model predicts the drying out of the soil sufficiently well. In particular, the soil moisture content predictions using the ARFEJ model were less realistic, as this model does did not allow for any drainage of the subsoil above root depth, because ARFEJ has no model for the movement of water below saturation.

It is considered that the underlying reason for the failure of both models to reproduce all the characteristics of the site is the failure to reproduce macropore flow in either the Richards' equation or in ARFEJ. Armstrong *et al.* [2] have shown that models that explicitly consider macroporosity are required to reproduce the hydrology of this soil.

Despite the fact that the two models (ARFEJ and the Richards' equation) do not give identical estimates of the distribution of water within the profile, there is clear agreement on the overall water balance, and no systematic divergence between the two models. The estimates of drainage volumes through the artificial drainage system are very close, and show no systematic variation between years. It is considered that the differences between the two models for water balance calculations are small. There is thus no reason, in water balance terms, for choice between the two models, and the choice thus need to be made by reference to the importance of the location of the water within the profile, and the trade-off between model accuracy and computer time requirements.

However, when the models are used within a theoretical context, in which mean soil properties derived from soils databases (for example, using pedo-transfer functions), then the failures of the model to reproduce the behaviour of individual sites is less critical. The failure of the model to match observations from a single point exactly is, in part, a question of parameterisation, which is not necessarily a problem when dealing with larger areas in which the relative performance of multiple sites is the focus of the investigation.

Crop growth studies

The participants of the ACCESS project furnished experimental data, from different locations in their countries, in order to calibrate and validate the ACCESS-II software. Several of these validation studies are reported in Loveland *et al.* [29]. Those reported here are those derived for the test site in the south of France [5]. Calibration of the model is difficult, because of the numerous parameters required, of which only a few are known precisely *a priori*. In addition, there are only a few output variables that could be used to control the quality of the calibration: biomass produced, yield, date of harvest, and quantity of water present in the soil at different dates.

In ACCESS II, the biomass and the yield calculations are calibrated using two kinds of experiments. First, an experiment that furnishes growth near the maximum, is used to calibrate the parameters that define the potential growth.. Then, other experiments, in which yields are lower due to limitation problems, will serve to calibrate the parameters that reduce the potential growth. The values given to the crop parameters must be realistic and acceptable from an agronomic point of view. The limits outside which the values of the parameters are unacceptable are difficult to define exactly, as they depend both on the crop variety and genetic development, and the assumptions of the quality of the cultural practices. An example of calibration results (a comparison between measured and predicted values), is given in Table 5.

Table 5. Example of calibration results for maize in Toulouse, France 1986, from Bonnet [22]

Parameter	Calculated	Measured
Crop season length (days)	130	130
Mean temperature	18.7	18.7
Degrees-days up to maturity	1275	1260
Average thermal stress	0.95	
Rainfall (cm)	8.8	8.8
Additional irrigation water	0.0	0.0
Potential evapotranspiration (cm)	53.8	
Potential evaporation (cm)	30.0	
Actual evaporation (cm)	13.2	
Potential transpiration (cm)	23.8	
Actual transpiration	18.7	
Drainage (cm)	0.5	
Water stock at the end of the season (cm)	35.4	36.0
Average water stress	0.79	
Whole biomass (t)	10.3	
Above ground biomass (t)	8.2	8.12
Yield (t)	2.8	2.62

Note: where no measured data are given, these observations were not available.

In calibrating the model, it is better to predict all of the output variables with a small error than to predict one perfectly and the others very badly. Calibration must thus be undertaken in terms of optimising the fit of all the output variables. Moreover, if calibration is impossible to achieve, the quality of the input data might be questioned. However, the calibration trials that were undertaken show that the grain yield error is seldom <0.2 tonnes for wheat or maize, and rarely <2 cm of water content at the end of the growing season. Results were obtained from a comparison for using growth experiments for maize cultivated at INRA-Toulouse in 1986 (a dry year) and 1987 (a wet year). The crop was grown in a good, deep soil without any irrigation. In the dry year under these conditions the yield is very low. For the wet year (1987) we found good correspondence between the predicted and observed profile water contents using the ARFEJ soil water model (Fig. 4), and the sequence of leaf area development (Fig. 5). As a consequence of the successful calibration and testing of the model, the results from this trial were used to demonstrate the possible impacts of climate change.

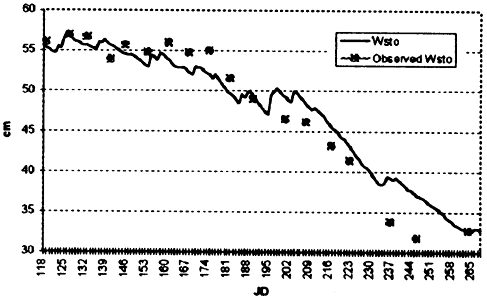

Fig. 4. Observed (points) and simulated (curve) soil water contents for maize; Toulouse experiment in 1987.

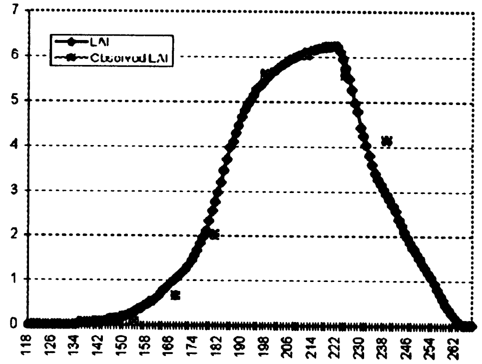

Fig. 5. Observed (points) and simulated *LAI* (curve) for maize; Toulouse experiment in 1987.

Climate change impacts on crop performance

In order to evaluate potential impacts of climate change, the calibrated model was run for the site at Toulouse [22] for two years with current climate and for the same two years with the daily climatic data altered to represent the effects of a doubling of atmospheric carbon dioxide. The use of such a worst-case scenario was intended to identify the direction and magnitude of the potential effects on maize production. Daily values of the input meteorological variables were perturbed using a table of monthly mean changes (Table 6). To define the current conditions, Potential Evapotranspiration was calculated for grass and 5 % added because transpiration of maize is greater than that of the reference. All values of the output data given in Table 7 correspond to the growing period. 1987 was wet, allowing a grain yield near to 10 t/ha without irrigation. In contrast, 1986 was very dry and the experiment, also conducted without irrigation, gave poor biomass and yield.

Some of the simulation results are obvious for the year 1987. Firstly, the temperature increase reduces the length of the growing period because this is mainly controlled by the sum of degrees-days. The result is that the solar energy accumulated is smaller and that the biomass potentially formed from this energy is smaller also. Secondly, as rainfall decreases, transpiration is reduced and water stress becomes

Table 6. Climate change transformations used for maize in Toulouse

Month	T_{max}	T_{min}	Rainfall	PET	Solar Rad.
	(°C)			(%)	
January	+0.82	-0.25	-11.62	+10	+4.33
February	+1.34	+1.91	+30.77	+10	+13.65
March	+4.91	+2.84	+10.70	+10	+17.12
April	+0.63	+0.46	-9.39	+10	+6.36
May	+1.47	+1.49	+3.48	+10	+9.14
June	+4.17	+2.68	-18.99	+10	+9.56
July	+8.31	+3.60	-56.20	+10	+2.93
August	+7.00	+4.67	-0.44	+10	-7.50
September	+5.96	+4.77	-38.90	+10	+21.78
October	+3.19	+2.40	15.61	+10	-5.18
November	+2.51	+2.96	+3.11	+10	-4.02
December	+2.54	+3.37	+5.45	+10	+2.09

Table 7. Climate change simulation for maize, starting from the actual field experiment at Toulouse in 1986 and 1987 (From Henric, [22])

Parameter	Actual climate	Modified climate	Actual climate	Modified climate
	1986		1987	
Growing period (days)	130	100	151	110
Mean temperature (°C)	18.7	25.2	18.6	23.3
Rainfall (cm)	8.8	7.0	23.5	14.0
Irrigation (cm)	0.0	0.0	0.0	0.0
Drainage (cm)	0.0	0.0	0.0	0.0
Residual water stock	31.7	35.3	32.8	36.9
PET (cm)	56.4	46.6	59.7	46.4
Actual ET (cm)	35.2	29.7	46.5	33.3
Pot. evaporation (cm)	28.8	22.6	26	23.7
Actual evaporation	12.4	8.6	14.3	12.4
Potent. transpiration	27.7	24.0	33.6	22.7
Actual transpiration	22.7	21.1	32.4	20.9
Water stress	0.73	0.77	0.91	0.86
Thermal stress	0.96	0.97	0.96	0.98
Total biomass (t)	10.2	11.5	23.0	13.2
Above ground biomass (t)	8.2	9.2	18.3	10.6
Yield (t)	2.6	3.6	9.2	4.9
Degree-days for period	1521	1783	1764	1754
D° days for maturity	1500	1750	1750	1750
N° of maturity days	252	222	266	226

more severe. For both these reasons, biomass and yield under the change-scenario are smaller than those yield obtained under current conditions. The yield is roughly halved if no irrigation water is added, but conversely, if the increase of the water demand is compensated by irrigation, the yield will not change markedly.

However, if we consider 1986, the situation is completely different. The shortening of the growing period, linked with the temperature increase, brings the crop growth period forward, so that more growth occurs before the dry period of summer. The result is an increase in yield even if this yield remains small. However, the interpretation of this result is tentative, because the model has not been calibrated for such high temperatures. However, it was noted that both in 1976 and 1990, the temperature was as high as those used in this simulation, and water was equally scarce, with the consequence that maize was severely damaged, and unirrigated yields were generally less than 1t/ha everywhere in the region. However, if irrigation satisfies the water demand, the yield will be identical to 1987 and not far from the maximum actual crop potential.

Thus several conclusions can be made, following these simulations:

i) a major climate change scenario, characterised by CO_2 doubling, gives a yield decrease no greater than the decrease we know today when we pass from a normal wet year to a dry one. This allows us to make rather good predictions, because it is possible to calibrate our models on situations that are not very different from those predicted as common or normal for the future, except for the quantity of CO_2 in the atmosphere and for long periods of higher temperatures;

ii) for maize, the consequences of the change will be linked with annual climatic variability. In the driest years the situation will not be worse than today and, in some cases, it could be better. In the wetter future years (that relatively will still always be more or less dry by comparison), the growth of maize without irrigation will not be profitable, even if the soils are good and deep;

iii) even if water is supplied, the cropping season will be modified by the temperature increase. Selection of new varieties might then seek to increase this length of the growing season, to utilise the benefit from the extra solar radiation.

ACKNOWLEDGEMENTS

The development of ACCESS was funded by the European Commission, (contract number EV5VCT920129) under the Framework 3 Programme. We are grateful to our many colleagues who have greatly contributed to the development of this model: D. Bellivier, A. Bonnet, J.F. Henric, and D. Leenhardt of INRA Montpellier, France; M. Cabelguenne, of INRA Toulouse; A.M. Matthews, and A.M. Portwood of ADAS Land Research Centre, Anstey Hall; and all our collaborators on the ACCESS project.

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