Int. Agrophysics, 1996, 10, 145-153

THE ACCESS PROJECT: AGRO-CLIMATIC CHANGE AND EUROPEAN SOIL SUITABILITY - A SPATIALLY DISTRIBUTED SOIL, AGRO-CLIMATIC AND SOIL HYDROLOGICAL MODEL

P. J. Loveland

Soil Survey and Land Research Centre, Cranfield University, Silsoe Campus, Silsoe, Bedford, MK45 4DT, UK

Accepted May 21, 1996

A b s t r a c t. Most attempts to predict the effects of climate change on soils, and hence land use, have been made at coarse scales and have made little use of the detailed soil, land use and climatic information available. Much of this information is available in digital form and lends itself readily to manipulation by computer procedures, often within geographic information systems. The ACCESS project was designed to take advantage of this situation. The target was a spatially distributed soil, agro-climatic and soil hydrological model to predict the effects of climate change on land use within the European Community. In the event, the project was extended successfully to Hungary, Poland and Romania, which gave a much wider range of soil, soil hydrological and climatic regimes than originally envisaged. The model structure drew on earlier work, which related simple soil properties, such as might be obtained during soil surveys, to crop suitability. More powerful approaches to the estimation of the soil hydrological state and crop water demands were incorporated into the new model, as are new approaches to land type classification. Much effort also went into deriving robust pedo-transfer functions, which allow the derivation of soil hydrological properties from simple soil survey data. The new model (ACCESS) was purposely designed to run at two levels; a more general approach to utilise the results of the site specific approach to allow extrapolation of the modelling to large areas of land, and a detailed approach to use site specific data for calibration and validation. The most significant difference between the two routes through the model, is that the site specific model operates at a daily meteorological time-step, whilst the broad scale model runs at a monthly time-step.

K e y w o r d s: model, soil hydrology, agro-climate, land use

INTRODUCTION

Global warming is expected to result, for Europe as a whole, in a mean rise in temperature of about 3°C over the next 50 to 100 years [25], whilst precipitation is expected to increase by about 10 per cent over the same period. Seasonal and spatial distribution are expected to change in ways that are currently little known, and extremely difficult to predict [10]. Winters will probably become wetter, and summers drier, although the severity of summer convection rainfall (thunderstorms etc.) might increase [11]. These factors will clearly affect land use potential, especially in the ability to grow strategic crops on a range of soils which may suffer considerable change in their hydrology as a result of climate change.

Recent attempts to predict the effects of climate change on major kinds of land use within the European Community have suffered from some important limitations:

i) they are driven almost entirely by climate, and regard the soil as essentially uniform;

ii) they operate at very coarse scales, typically of the order of tens of kilometres [7,18].

iii) they are essentially statistical in their approach and do not give enough attention to processes and mechanisms, particularly with respect to soil/climate interactions.

These approaches have tended to be 'broad-brush', and have not utilised fully the very large amounts of high resolution soil, land use and climate information available within the Community [e.g., 3,9,12,17]. A second drawback is that few of these approaches have been aimed at the planner who wishes to operate at a local or regional scale using locally available data, i.e., someone who wishes to know, in some spatial detail, what might happen in his or her area. Thus the ACCESS project set out to build an overall model that takes climatic variables as part of the evaluation of land for crop suitability, and thus has the flexibility to deal with any proposed climate change scenario. An important part of the modelling was, however, validation against current climatic situations, although we were not concerned with predicting climate change itself.

The principal objective was to be able to predict the effects of a given climate change scenario on the cropping potential of areas of land based on knowledge of their known soil pattern, the properties of these soils and the growth requirements of strategic crops. This is the kind of information which would be available through, for example, development or other plans which make use of soil surveys. Because of the complexity of the possible combinations of crop-soil-climate interactions, we adopted the approach that the most sensible way to predict any potential changes is to take data derived from national experimental soil-crop programmes, and use these as the scientific basis for modelling and simulation. This novel aspect of the project was to support regional modelling, which we refer to as Level I modelling, through use detailed site modelling (Level II modelling).

We took the framework of an existing crop-agroclimate model, which relates crop requirements to soil-climate factors, and developed this into a tool usable over a wider spectrum. Development concentrated on improvements to the water balance-crop growth module, the erosion module, a vulnerability module, and an expert system to assess salinisation risk.

THE BASIC MODEL

This was derived from Thomasson and Jones [23]. Each compartment of the this framework is a sub-model and, overall, the flow of the model gives a suitability rating for a particular soil and crop combination, taking into account the following limitations (Fig. 1):

a) site factors: slope, aspect;
b) soil factors: depth, stoniness;
c) tillage properties: machinery work days, compaction risk;
d) agro-climatic factors: altitude, accumulated temperature;
e) crop available water: precipitation minus evapotranspiration.

The information needed by the model comes from:

a) site factors - topographic maps and/or landform analysis;
b) soil factors - soil mapping (survey) and associated databases;
c) tillage properties - calculated from the number of days at which the soil is likely to be too wet for mechanical cultivation;
d) agroclimatic factors - from meteorological data;
e) crop available water - calculated from precipitation data (long-term or short-term)) and a simple model of soil hydrological properties.

In its original form, the model was used to predict soil status and crop suitability in 6 years out of 10, i.e., to give an average response of the soil, based on climate patterns derived from long-term meteorological datasets. The ultimate output of the model was the classification of a particular soil in relation to a particular crop, so that a soil map could be classified in terms of crop suitability. The model could be run at a range of scales depending on the detail of the input data, and a new map of crop suitability could be drawn

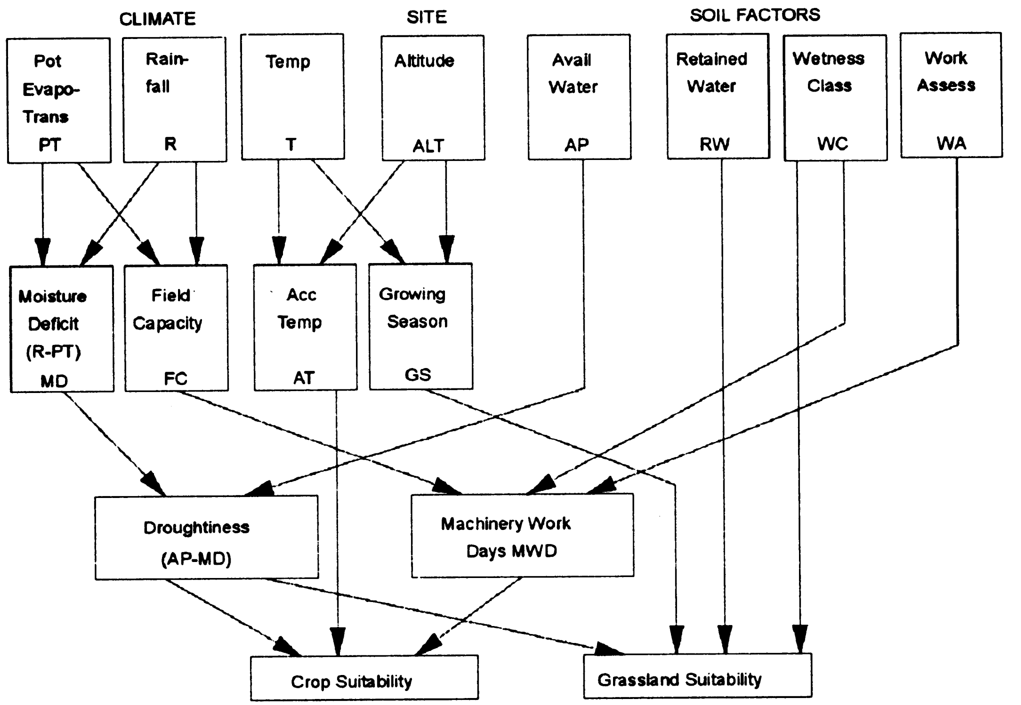

Fig. 1. The framework of the original land use suitability model [23].

automatically using a digitised soil map (see, for example [20]). The model permits any land use limitation to be specified.

REVISION OF THE BASIC MODEL STRUCTURE

The framework

The basic framework was developed for use in the agricultural landscapes of the UK, and assumed:

a) the crop growth-water balance model was designed for the UK where winter rainfall exceeds transpiration, and *vice versa* in summer;
b) there is an average level of management, and that mechanised farming is the norm;
c) there are no nutritional limitations (major or minor elements), and that soil pH is adequate;
d) there is no erosion risk;
e) the range of crops is restricted to grass, winter cereals, potatoes and sugar beet;
f) there is no irrigation requirement.

Several factors were taken into account, in developing a revised model structure (Fig. 2). The most important was the decision to construct a model which would run at different levels. At the first level, called ACCESS-I, the model runs at a monthly time-step with respect to meteorological data, and is applicable to large areas of land, i.e., it is able to make use of large soil spatial datasets, without enormous penalties in computing requirements. At the second level, ACCESS-II, the soil-water balance operates at a daily time-step. This part of the model is intended to run largely for experimental sites within the larger areas covered by ACCESS-I. Thus, detailed site-specific modelling can be used to support the larger spatial modelling by giving, if required, an output from the same point, but calculated from different time-steps in the hydrological sense.

The revised model is targeted at a wider range of crops than the original model. For practical reasons, these are limited as follows:

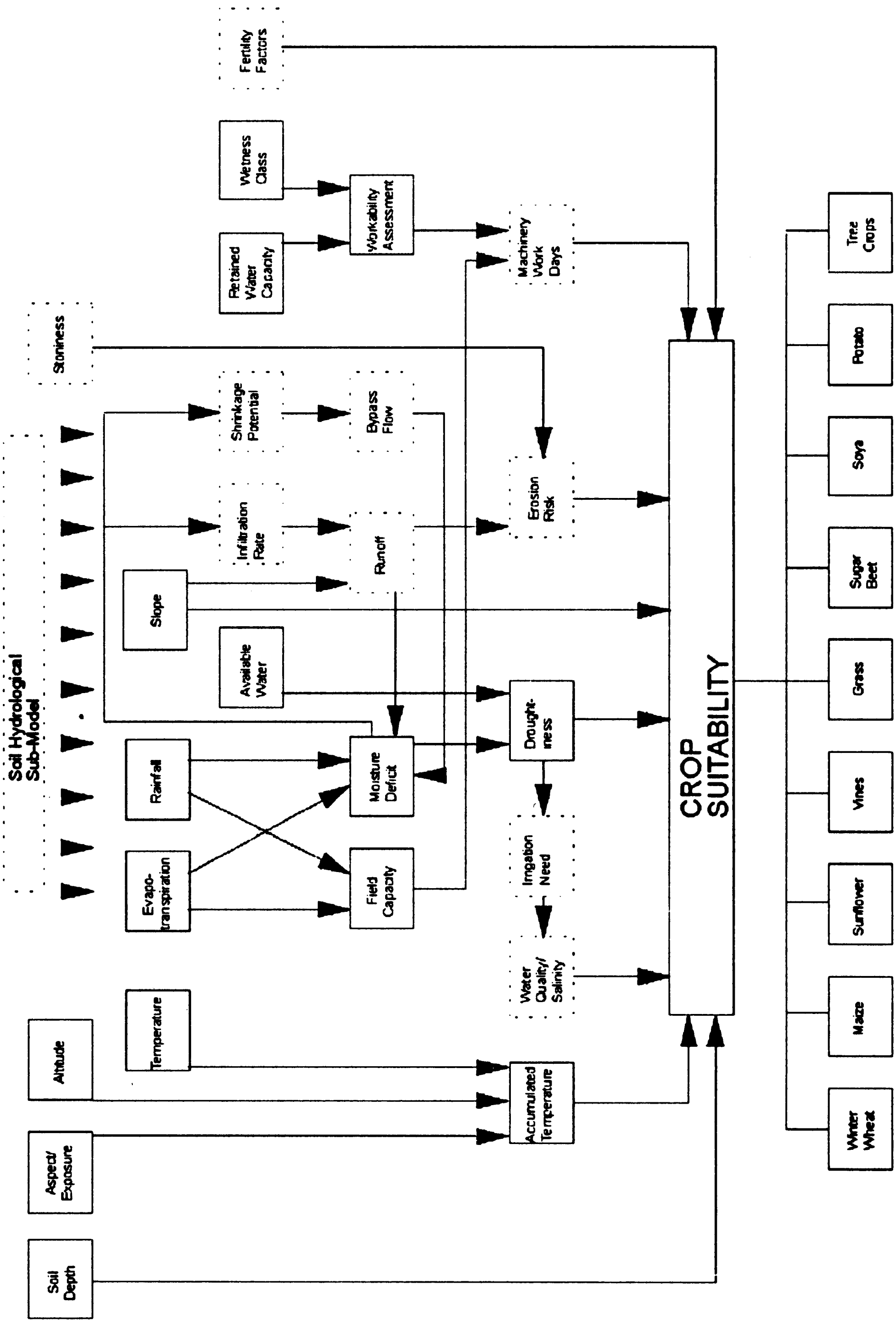

Fig. 2. The framework of the revised model used in the current project.

ACCESS-I: maize, winter wheat, sunflower, potatoes, grass;

ACCESS-II: winter wheat, maize, sunflower.

It was clear that a major task of the whole project was to improve on the hydrological aspects of the original model, and these were, in fact, almost completely re-developed. Changes in these components, and the ways in which they might interact, also required revision of the system of land evaluation.

A further important aspect, inherent in this approach, is what we chose to call spatialisation of data into areas where actual measured values might be few or non-existent for particular soil/land units. This is particularly true of soil hydrological properties, e.g., the soil moisture retention curve, where measured data would be very limited. For this reason considerable effort went into the development of pedo-transfer functions, based on datasets from seve- ral parts of the European land mass. In order to cover the climatic and agricultural diversity of Europe in its widest sense, we chose the following test regions. We knew these to have good soil, crop and climate data, much of it in digital form, and a network of experimental sites/farms where extensive site-specific data are available:

a) central England - cool, per-humid climate;
b) Languedoc-Roussillon, France - Mediterranean climate;
c) Andalucia, Spain - very hot, dry summers, limited winter rainfall;
d) Lublin Upland, eastern Poland - warm Continental with winter snow cover;
e) Middle Tisza Region (Nagykunság), eastern Hungary - dry Continental, cold winters, little snow, very variable rainfall.

Finally, in order to make the improved model widely available, it has been developed so that it will:

a) run on an IBM-compatible PC platform;
b) use standard data input formats;
c) provide output as standard file formats acceptable to a range of geographic information systems.

All programming is compatible with Microsoft™ FORTRAN (Version 5.1).

The improved water-balance and crop-growth model

The principal soil water-balance approach within ACCESS-II [1], is derived from the French model MOBIDIC [13]. The crop growth model used for calculating potential yields is derived from the EPIC model [26], but is revised for European conditions. The root development model assumes a linear development of roots against maximum depth attained in relation to the number of days between emergence and flowering. The root density function is similar to that in the CORNGRO model [2]. In parallel with this part of the programme, a large database of crop phenological data, from different regions, has been established for use as inputs into the appropriate parts of the models. Preliminary work indicates that over model run periods of 15 days or more, the differences between the evapotranspiration components of MOBIDIC tend to become small, seemingly due to mutual error cancelling. One aspect of soil water movement that is dealt with poorly within MOBIDIC, is that of upward flux (capillary rise), and there are also uncertainties about how well the movement of water between soil compartments (either horizons or layers of specified thickness) is modelled. The latter, in particular, was tested independently through parameterisation of the Richards' equation. Infiltration, especially during intense storms and/or into cracked soils, where by-pass flow could be important, was another area of development. ACCESS-I, the regional model, differs fundamentally from ACCESS-II in that it operates with meteorological data at monthly rather than daily time-steps, and relies on a minimum of soil and crop input parameters. Potential evapotranspiration is calculated according to Thornthwaite's formula, with adjustment for latitude based on day length. The potential evapotranspiration (PET) is separated into potential evaporation and potential transpiration following the Beer-Lambert law, and is based on leaf-area index (LAI). Root development is calculated from soil water pressure and soil resistance to penetration using the theory of root growth mechanics [6]. Actual transpiration is related to soil water pressure and a root sink term. The calculated monthly soil water balance is used to calculate the field capacity period by an interpolation technique. Likewise, the start and end of the growing season is calculated following the FAO approach, by which the growing period is defined as the time in the year during which rainfall exceeds 0.5 PET, extended by the time that a maximum available water content of 100 mm in the soil has been depleted. In addition, the growing period is considered to be interrupted during the time that the mean air temperature is below 6.5°C. Accumulated temperature sums are estimated using TRIM (Temperature Remainder Index Model [19]), whereas day-length and effective photoperiod are derived from Julian day number and latitude. Biomass accumulation is based on water use efficiency and cumulated transpiration deficit [24]. The partitioning of the newly synthesised biomass to plant roots is based on phenologically dependent coefficients. Final crop yield is obtained from final total biomass using a crop dependent harvesting index.

The land use - sustainability module

This module is applicable to both ACCESS-I and ACCESS-II. The central concept is that of 'attainable productivity' for selected strategic crops, expressed as a yield value or yield class. This is the maximum possible productivity of a land unit within the constraints of the land unit, e.g., drought stress, workability, length of growing season. These factors are clearly linked to the parameters considered by the crop-growth/water-balance model, and the latter can be used to guide the estimation of this parameter. However, in reality, the 'attainable productivity' is an ideal, and 'actual productivity' is the norm. The latter depends on management, which often affects the constraints imposed through the properties of the land unit. Thus the actual productivity can be regarded as an 'efficiency indicator' of the potential of a land unit. If the actual productivity is less than the attainable productivity estimated by ACCESS, then clearly the farming system has reserves of productivity which could compensate for climate change. A novel development has been to extend the productivity concept to the definition of Land Use Types (LUT) (see Fig. 3). Traditionally (e.g., [8]) the assessment of land use types i.e., agricultural systems that have developed in response to local circumstances, is made in subjective terms before a suitability assessment is made. We use 'allowable' productivity, i.e., the acceptable quantity of crop produced which allows a farmer to cultivate a particular land unit in a specified region, to define the LUT. Thus, there can be several LUTs for the same crop, distributed through the European Community in terms of allowable yield.

The soil erosion risk module

This is confined, at present, to the risk of water erosion on agricultural land, and represents an 'attainable erosion risk' class. This is the maximum possible erosion risk in terms of relief, soil erodibility and rainfall erosivity (known as 'land qualities' - LQ). Relief is self-explanatory, erodibility is a measure of the detachibility of soil particles without regard to the influence of topography, and rainfall erosivity is a measure of the power of raindrop impact. Much of the initial approach was derived from work done under the CORINE programme [4]. Relief is divided into four slope classes which reflect low, moderate, strong and very strong risk of severity of erosion; erodibility is complex in that there is interaction between effective rooting depth, particle size distribution class, surface stoniness, surface horizon bulk density, and surface horizon permeability, to give four classes of severity (very low, low, moderate and severe). This system was first developed for Mediterranean situations, but the methodology is transferable to situations where erodibility might be modified to take account of higher contents of organic

Current Conditions for the LUT: Sunflower/Rainfed
*BENCHMARK AREA: CAMPINA (SE-03), ANDALUCIA, SPAIN

*CROP (*Helianthus annuus*)
Main varieties: Florasol; Ariflor; Hysum-33
Growing season length: 159 days (mean); range 126-184
Maximum rooting depth (cm): 80-100
Phenological calendar: Emergence: end Feb/mid Apr; Ripening: mid July-end Aug.

*MANAGEMENT PRACTICES
Primary tillage: 1 - mouldboard plough, September; 3 - disking, December-January
Secondary tillage: 1, inter-row rotavator - end March - early May
Sowing: 4-8 kg seed/ha, 70 cm row spacing, mid February - end March
Fertiliser: Urea 46% N, 100-150 kg/ha; December-January
Herbicides: 1.5 L/ha, trifluralin, mid February - end March
Pesticides: 50 kg/ha, Lindane 2%, mid February - end March
Harvesting: combined, end July - early September
Residues: straw ploughed in, October
Irrigation: nil
Artificial drainage: nil

*PERFORMANCE IN THE BENCHMARK AREA
Indicative yield/quality: 1.9 - 2.2 t/ha seed; 46 - 50% oil
Environmental impact: high erosion risk; low pollution potential

Fig. 3. An example of a Land Use Type (LUT) for Andalucia, Spain.

matter. Finally, erosivity is defined in terms of the 'derived Fournier/aridity index', as discussed by Morgan [16], and again divides into four classes: low, moderate , high, very high. The first application of this system is *via* a matrix which gives the 'attainable erosion risk class' [5].

The natural fertility module

Fertility is not normally regarded as a landuse limitation in Europe, as it is seen as a management option. However, given that climate change could well delineate areas of land that would be suitable for agriculture apart from a constraint due to lack of natural fertility, we believed that a mechanism was required to indicate that this is so. Natural fertility is defined in chemical terms for the upper 20 cm of the soil (the topsoil) and the layer between 20 cm and 50 cm. The system is based on ten criteria, namely: pH, weatherable minerals, CEC, base saturation, exchangeable sodium percentage, electrical conductivity/salinization, C/N ratio, gley properties, K-supplying power, P-fixation power, of which up to three can be identified as limiting. Each category has two classes (high and low), and the 'low' categorisation is regarded as non-limiting. The purpose of the system is not to give a quantitative measure of the degree of remediation which might be required. It is to indicate where there are problems, which will almost certainly require further investigation in order to give a reliable estimate of the degree of infertility and the practicability of remedial action. ACCESS yields 18 fertility classes from combinations of the various categories.

Spatialisation

Application of crop-suitability modelling, within a framework of the crop-water cycle, requires the estimation of soil hydrological properties. These are rarely measured at sufficient points in the landscape, so must be derived from pedo-transfer functions. Routines have been developed to estimate the soil water-release curve from particle size distribution, bulk density and organic carbon, over the range 0.05 to 15 bar suction, unsaturated hydraulic conductivity, and soil resistance to root penetration. The algorithms give estimated values within about 5 per cent of measured data [21]. Thus, we have methods for deriving these properties for soil map units from soil survey data. Further developments allow estimation of crop yield from similar data in conjunction with monthly weather data [14]. A more difficult problem has been the interpolation of site-specific weather data to large areas of land (soil polygons). Because the polygons are 'better defined' spaces than climate zones, we decided to conserve the boundaries of the soil polygons, dividing the larger ones as necessary only where clear climate boundaries can be identified. Further, for development purposes we worked with a practical lower polygon size of about 100 ha, although many are, of course, much larger. In temporal terms, it proved difficult to extend daily meteorological data to large numbers of polygons, because of the demands on computing time. So for the present ACCESS-II (where most of the development was concentrated) runs at 10-day time-steps. Further investigation is in progress to deal with the problems arising from the irregular, in the spatial sense, distribution of meteorological stations in relation to the distribution of soil polygons, but this is not reported here. It is hoped that a technique involving 'spatial deformation' will lead to improvements in the estimation of climatological properties at interpolation points, but the method has yet to be tested outside Languedoc-Roussillon, although first results appear promising [15].

CONCLUSIONS

A model has been developed to estimate the suitability of soils within the European Community for a range of strategic crops. The structure of the model is such that it uses site-specific data to validate a simpler, regional model. The project has been developed within test regions from central England, southern France and southern Spain. Within the model there is a robust crop-growth/soil water-balance component, and extra routines have been developed to allow assessment of soil erosion, soil fertility and new approaches to land use. The model is structured to accept standard data entry and output in formats acceptable to a range of geographic information systems. Routines have been developed to calculate pedo-transfer functions from simple soil data. The ACCESS model thus provides a powerful tool to evaluate crop suitability and land use within the European Community in relation to changes in climate.

REFERENCES

1. **Armstrong A.C., Legros J-P., Voltz M.:** ACCESS-II: a detailed model for crop growth and water conditions. Int. Agrophysics, 10, 171-184, 1996.
2. **Childs S.W., Gilley J.R., Splinter W.E.:** A simplified model of corn growth under moisture stress. Trans. ASAE, 20, 858-865, 1977.
3. Commission of the European Communities. Soil and Groundwater Research Report 1: Soil Survey - a Basis for European Soil Protection (Ed. J.M. Hodgson). EUR 13340. Luxembourg: Office for Official Publications of the European Communities, 1991.
4. CORINE. CORINE database manual version 2.1. Commission of the European Communities (DG XII), Brussels, 1989.
5. **De la Rosa D., Crompvoets J., Mayol F., Moreno J.A.:** Land vulnerability evaluation and climate change impact in Andalucia, Spain. Int. Agrophysics, 10, 225-238, 1996.
6. **Dexter A.R.:** Mechanics of root growth. Plant and Soil, 93, 303-312, 1987
7. DoE.: The Potential Effects of Climate Change in the United Kingdom: First Report of the United Kingdom Climate Change Impacts Review Group. HMSO: London, 1991.
8. FAO.: A Framework for Land Evaluation: Soils Bulletin No. 32. United Nations Food and Agriculture Organisation, Rome, 1976.
9. **Hough M.N.:** Agrometeorological aspects of crops in the United Kingdom and Ireland: A review for sugar beet, oilseed rape, peas, wheat, barley, oats, potatoes, apples and pears. EUR 13039 EN. 310 pp. Office for Official Publications of the European Communities, Luxembourg, 1990.

10. IGCC. Preliminary Guidelines for Assessing Impacts of Climate Change (Eds T.R. Carter, M.L. Parry, S. Nishioka, H. Harasawa). Report prepared by Working Group II of the Intergovernmental Panel on Climate Change, Environmental Change Unit, Oxford, 1992.
11. IPCC. Climate Change: The IPCC Scientific Assessment (Eds J.T. Houghton, G.J. Jenkins and J.J. Ephraums). Report prepared by Working Group 1 of the Intergovernmental Panel on Climate Change. Cambridge University Press, UK, 1990.
12. **King D., Daroussin J., Tavernier R.**: Development of a soil geographic database from the soil map of the European Communities. Catena 21, 37-56, 1994.
13. **Leenhardt D.**: Spatialisation du Bilan Hydrique. Thèse: Doctorat; Spécialité - Sciences Agronomiques. Ecole Nationale Supérieure Agronomique Montpellier, France, 1991.
14. **Mayr T.M., Rounsevell M.D.A., Loveland P.J., Simota C.**: Agroclimatic change and European soil suitability: regional modelling using monthly time-step data. Int. Agrophysics, 10, 155-170, 1996.
15. **Monastiez P, Sampson P.D., Guttorp.**: Modelling of heterogeneous spatial correlation structure by spatial deformation. Journées de Géostatistiques (Fontainebleau), (in press).
16. **Morgan R.C.P.**: Soil Erosion. Topics in Applied Geography. Longmans, Harlow, 1979.
17. **Narcisco G., Ragni P., Venturi A.**: Agrometeorological aspects of crops in Italy, Spain and Greece: A summary review for common and durum wheat, barley, maize, rice, sugar beet, sunflower, soya bean, rape, potato, tobacco, cotton, olive and grape crops. EUR 14124 EN. 440pp. Office for Official Publications of the European Communities, Luxembourg, 1992.
18. **Parry M.**: Climate Change and World Agriculture. Earthscan Publications Limited, London, U.K., 1990.
19. **Robertson G.W.**: Weather-based mathematical models for estimating development and ripening of crops. Technical Note No. 10. World Meteorological Organisation, Geneva, 1983.
20. **Rounsevell M.D.A.**: A review of soil workability models and their limitations in temperate agriculture. Soil Use and Management, 9, 15-20, 1983.
21. **Simota C., Mayr T.M**:. Predicting the soil water retention curve from readily available data obtained during soil surveys. Int. Agrophysics, 10, 185-188, 1996.
22. **Thomasson A.J.**: Soil and Climate Aspects of Workability and Trafficability. In: Proceedings of the 9th Conf. Int. Soil Tillage Research Organisation (ISTRO), Osijek, Yugoslavia, 551-557, 1982.
23. **Thomasson A.J., Jones R.J.A.**: Computer Mapping of Soil Trafficability in the UK. In: R.J.A. Jones and B. Biagi (eds). Proc. EC Symposium: Agriculture - Computerisation of Land-Use Data. Pisa, Italy, 74-108. Commission of the European Communities EUR 11151 EN, Luxembourg, 1989.
24. **van Keulen H.**: Crop production under semi-arid conditions as determined by moisture availability. In: Simulation of Plant Growth and Crop Production. (Eds. H.H. van Laar, F.W.T Penning de Vries). Pudoc, Wageningen, 1982.
25. **Viner D., Hulme M.**: Climate Change Scenarios for Impact Studies in the UK: General circulation models, scenario construction, methods and applications for impact assessment. Report prepared for the Department of the Environment, Climate Research Unit, University of East Anglia, Norwich, UK, 1993.
26. **Williams J.R., Renard K.G., Dyke P.T.**: A new method for assessing the effect of erosion on productivity. J. Soil Water Conserv., 38, 381-393, 1983.