Crop Growth Simulation Models for Research, Farm Management and Agrometeorology

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ABSTRACT

In the last years crop growth simulation models have become an essential tool to support field research and to improve agricultural productivity of developed and developing countries. Simulation model results, in contrast with the usual field observations, can be extrapolated to different conditions, other cultivars or other cropping schemes. Some actual and potential applications are here reported concerning the use of simulation models for research, yield prediction and agricultural planning, farm management and agrometeorology. Two case study climatological investigations are then illustrated in detail: a) the evaluation of the effect of CO_2-induced climatic change on the cultivated area of olive trees, b) the study of the effect of climatic change on wheat development.

INDRODUCTION

There are many interpretations of the concept of simulation model in the literature. Models may range from the empirical model which use makes of daily average temperatures to predict crop yields, to very sophisticated models which try to describe the effect of growth substances on plant development. The level of detail of a simulation model depends on its objectives and on data availability.

In this paper different approaches to modelling will be briefly discussed and principal application reviewed. Subsequently two case studies of model applications for predicting potential effects of climate change on the area of cultivation of olive trees and on the development rates of wheat will be illustrated.

1. INTEGRATIVE CONTROL IN PLANTS

The growth and development of the various parts of a multicellular organism is quantitatively and qualitatively coordinated and controlled at all levels of biological organisation, from the genetic material to the higher levels. The genome supplies the machinery and the rules about growth and development. Metabolic systems operate in the environment and depend on carbon and nutrient supplies, water status and on the extension of roots and leaves. For example, control and regulation at higher levels are evident in most aspects of plant growth, as the pattern of exponential growth observed in young plants where the rate of carbon supply and growth are highly linked to the increase in leaf area.

On the basis of these considerations, it is possible to state that:

- growth and development can be explained by the basic physiological, physical and chemical processes and by the effect of environmental factors on them,
- simulation models that integrate processes over several levels of biological organisation appear as the principal tools for the study of plant growth.

2. CROP GROWTH MODELS

A crop model is a simple representation of a crop. In general, it is used to study crop growth and to calculate growth responses to the environment. Crop models can be distinguished as descriptive and explanatory.

2.1 Descriptive models

A descriptive model simulates the behaviour of a system in a simple way. A system is defined as any well delimited

part of the real world and for an agronomist, this may be a crop with its elements, plant organs (such as leaf, stem and root) and processes (such as growth, transpiration, etc.). In descriptive models experimental data are used to find one or more mathematical equations which are able to describe the behaviour of a system.

An example of this aproach is shown in fig. 1, where the regression equation is derived from successively measured weights of a maize crop (Penning de Vries et al., 1989). However, since the behaviour of the crop will not be the same when soil, crop practices and weather are differents, large deviations can result from differences in weather pattern between years (fig. 2). In theory it is possible to derive the required constants and equations with a good accuracy from many experiments; but then in practice, many variables influence growth pattern of a crop, and thus it is impossible to quantify in a correct way all variables through extensive field experiments. Descriptive models are therefore of interest only when a quick tool is required to describe the behaviour of a crop under field condition and where conditions remain relatively stable.

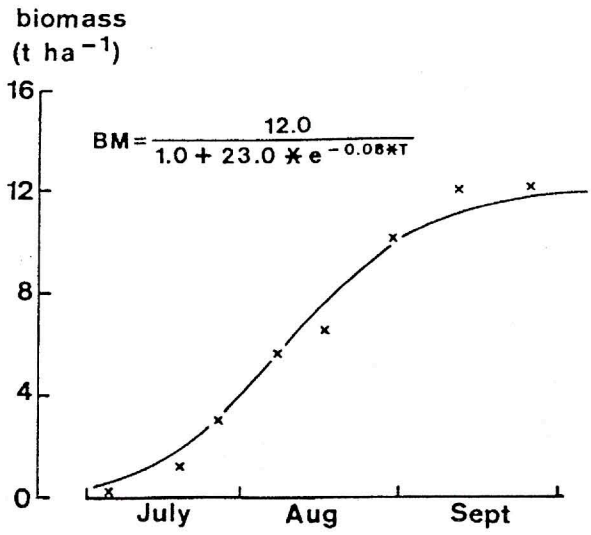


Fig. 1 - The coarse of the the dry weight of a maize crop in the Netherlands in 1972. Crosses represent observations, the line the regression equation. BM = biomass in t ha^{-1}, T = time in days since emergence (Source: Penning de Vries et al., 1989).

2.2 Explanatory models

On the other hand explanatory models consist of a quantitative description of the mechanisms and processes that guide the behaviour of a system. In order to create explanatory model, the system is analysed and its processes and mechanisms are separately quantified. The model is then built by integrating these for the whole system. An explanatory crop growth model calculates rate variables (photosynthesis rate, leaf area expansion rate, etc.) and state variables (crop biomass, yield, etc.). Processes are quantified as a function of environmental factors, such as radiation, temperature, etc., and in relation with the state of the crop, including leaf area, development stage and nutrients availability. In this way growth rates can be computed at each plant stage during the growing season, on the basis of the status of the crop, soil and weather. In general the number of the processes of prime importance for simulating crop growth is limited and detailed calculations such as the efficiency of synthesis of each biochemical compound in a biomass or the dynamic aspects of cell physiology are not necessary. However, the number of processes that have to be included in a crop growth model depend on:

- the detail required in the results of the model,
- the growth-limiting factors considered in the model (such as water and/or nutrients shortage).

The relational diagram in fig. 3, indicates the processes and the environmental factors that are considered in a growth model of a crop without water and nutrients short-

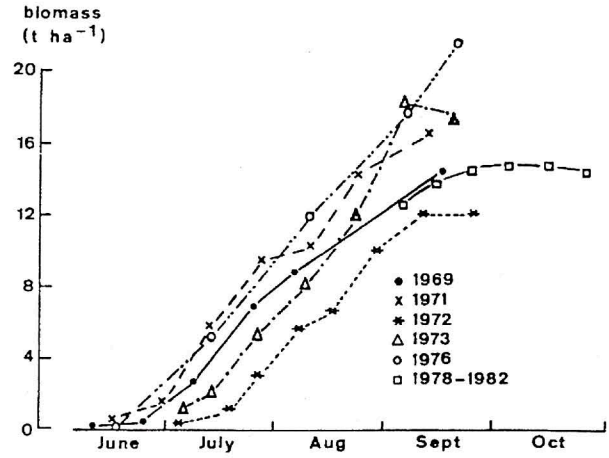


Fig. 2 - The dry weight of maize crops under optimal conditions in different years in the Netherlands (Source: Sibma, 1987).

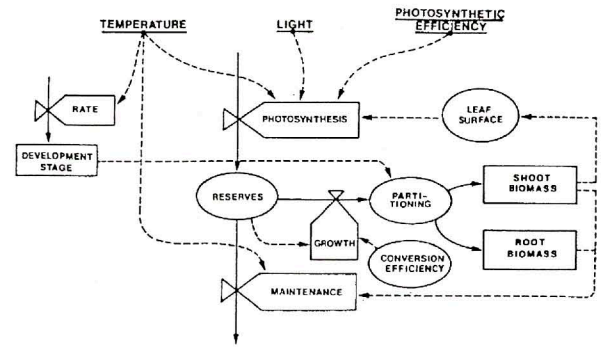


Fig. 3 - A relation diagram of a growth simulation model for a crop without water and nutrients shortage. (Source: Penning de Vries et al., 1989).

age. Light and temperature are the driving variables of the system and assimilation, development, respiration, conversion and partitioning of assimilates between organs are the principal processes considered in the model (Penning de Vries et al., 1989).

3. USE OF CROP GROWTH MODELS

Crop growth models can be used in research and application (yield predictions, agricultural planning, farm management, climatology and agrometeorology).

In the last 15 years, simulation models have been principally used to determine the potential growth and establish the biological limits of agricultural production. A valid example of how modelling helped research can be given by the activity conducted at Wageningen. In the sixties, de Wit carried out the first attempt to model the photosynthetic rate of crop canopies (de Wit, 1965). Results obtained from this static model were used, among others, to estimate potential food production for some areas of the world and to provide indications for crop husbandry and breeding (de Wit, 1967, Linneman et al., 1979).

Next, an ELementary CROp growth Simulator (ELCROS) has been constructed (de Wit et al.,1970). This included the static photosynthesis model and crop respiration was taken as a fixed fraction per day of the biomass, plus an amount proportional to growth rate. Moreover, a functional equilibrium between root and shoot growth was added (Penning de Vries et al, 1974).

The introduction of micrometeorology in the models (Goudriaan, 1977) and the quantification of canopy resistance to gas exchanges allowed to improve the simulation of transpiration and evolve into the BAsic CROp growth Simulator (BACROS) (de Wit & Goudriaan, 1978).

Today, Wageningen scientists use BACROS as a reference model for developing other models and as a basis for developing summary models such as SUCROS (Simple and Universal CROp growth Simulator) (van Keulen et al., 1982).

Simulation models were also applied to predict yield, to extrapolate and to interpolate crop performances over large regions and to create links with other sciences.

In general, explanatory crop models are not very well suited for yield predictions, mainly because of the large data base they require and for the hetereogeneity of large areas for which yield predictions are required. As a rule, yield prediction are made on the basis of descriptive models, sometime improved by calculating the soil moisture balance (Baier & Robertson, 1968) or crop transpiration with simplified procedures (Zaban, 1981). An example of this kind of models is represented by models that use intermediate harvest and expected weather data to update the yield prediction (Benschop, 1985). Studies of the use of remote sensing to update crop models for yield prediction indicated that updating the initialization of a simple crop model with accumulated remote sensing data can provide more accurate estimates of final yield than updating based on crop measurements (Maas, 1988).

A survey of the consequences of different timing and dosage of fertilizer applications can be carried out with a model. This kind of application is very important for improving the efficiency of fertilizers and biocides for specific cases, and for reducing the loss of excess input to the environment. Model based management, such as this, is already in use on large scale for optimizing fungicide application in crops such as wheat and grape, apple, etc (Zadoks et al., 1984, Rosa et al., 1992).

Crop models can be used to predict crop performance in regions where the crop has not been grown before or not grown under optimal conditions. This attempt was carried out by van Keulen & Wolf (1986) and it is likely to be of value for regional development and agricultural planning in developing countries.

Crop models can be used to examine the sensitivity of crop response to changes in plant characteristics so as to better define breeding strategies and goals. Accordingly breeders can survey the impact that breeding may have for specific characteristics (Landivar, 1979, de Wit et al., 1979, Ng and Loomis 1984). The combination of crop growth models with pest, disease and weed models can be used to investigate interactions between both systems (Rabbinge, et al., 1989). Strong interactions between crop growth and disease or pest development make this combination potentially interesting for crop management, for instance, a better choice of the timing of spraying fungicides and the removal of unnecessary sprayings.

Simulation models can also be used to derive simple decision rules for farmers and extension services. Simulation models, supplied with the appropriate crop, soil and weather data can help farm management as decision support systems for fertilizer and pesticides application and most of other agronomic applications.

Finally, simulation models can be used to explore the effects of the increase in temperature and CO_2 concentration on crop development, growth and yield, harvest index and water use, and can help breeders to anticipate future requirements (Goudriaan et al., 1984). In fact, the repercussions of global changes for agriculture and natural ecosystems are potentially serious and simulation models seem to be one of the more appropriate tool to explore these effects. Models used in this studies range from descriptive models that couple the information from General Circulation Models (GCMs) with the current knowledge about the environmental constraints that limits the area of cultivation of crops (Bindi et al., 1992, Parry

et al, 1991, Rochefort & Woodward, 1991), to explanatory models that predict the more detailed effects of warming and of increasing CO_2 on crop development and yield (Adams et al., 1990, Morison & Butterfield, 1990a, Porter & Miglietta, 1991).

4. CASE STUDIES

4.1 Effects of CO_2-induced climatic change on the cultivated area of olive trees

Olive is a typical species of the mediterranean basin. The 96% of the cultivated olive plants in the world are located in this area (Loussert, 1986). Most of the commercial production of the olive is confined to 2 bands around the world, between 30° and 45° latitudes (Hartmann and Whisler, 1975). The northern and southern limits of the cultivation of the olive are conditioned by the climate. The normal productivity of the olive depends on the extreme temperature and on the rainfall.

In this work the potential effects of climatic changes on the Mediterranean area of cultivation of the olive are studied.

Material and methods - To determine this effect, meteorological historical series and GCM temperature and precipitation predictions are considered. The meteorological data-bank contains information about 3329 stations located all over the world. The GCM data set used are those generated during two model experiments (so called, "equilibrium" simulations) in 1982 with the Goddard Institute for Space Studies (GISS) general circulation model (Hansen et al. ,1983).

The study of the spatial distribution of the olive in the Mediterranean area showed that the area of cultivation is limited to regions having the following characteristics (Euverte, 1967):

- mean January temperature > 4°C,
- mean July temperature > 22°C and < 30°C,
- annual precipitation > 200 mm.

These climatic characteristics are used to individuate the present and the future area of olive tree cultivation. First all the stations with an altitude lower than 600 m having the appropriate climatic conditions are identified. Then the present and future limits of olive cultivation are graphically reconstructed.

Results - The results emphasize that, with a doubling in the CO_2 climatic conditions, there is a shift of the North/North- West limit (fig. 4).

The northern limit, in fact, moves north over continental Europe reaching most of the French regions, the Po valley, the Yugoslav and Greece inlands. The southern limit remains the same, or, in some zones, slightly moves North. The different sensitivity of the northern and the southern limits of the cultivated areas depends on the different variation occurring in the limiting factors for the cultivation of the olive (low temperatures in the North, precipitation and high temperatures in the South). In the southern areas the precipitation remains the same or is sometimes reduced (fig. 5a) and the mean temperature for July increases from 4-5°C (fig. 5b). In the northern areas the mean temperature for January increases from 3 to 7°C (fig. 5c).

These results are not predictions, but they are indicative of the type of shift of olive cultivation that can be expected if the climatic changes that have been estimated by GISS-GCM actually occur. In fact, the new olive limits are zones of potential suitability, constructed on the basis of temperature and precipitation alone. Low temperature is certainly the major constraint on olive production and survival in the high latitudes, whereas the high temperature and the precipitation are the major constraint in the south, but there are environment factors that are also of importance which have not been considered here (pest and disease, type of soil, etc.)

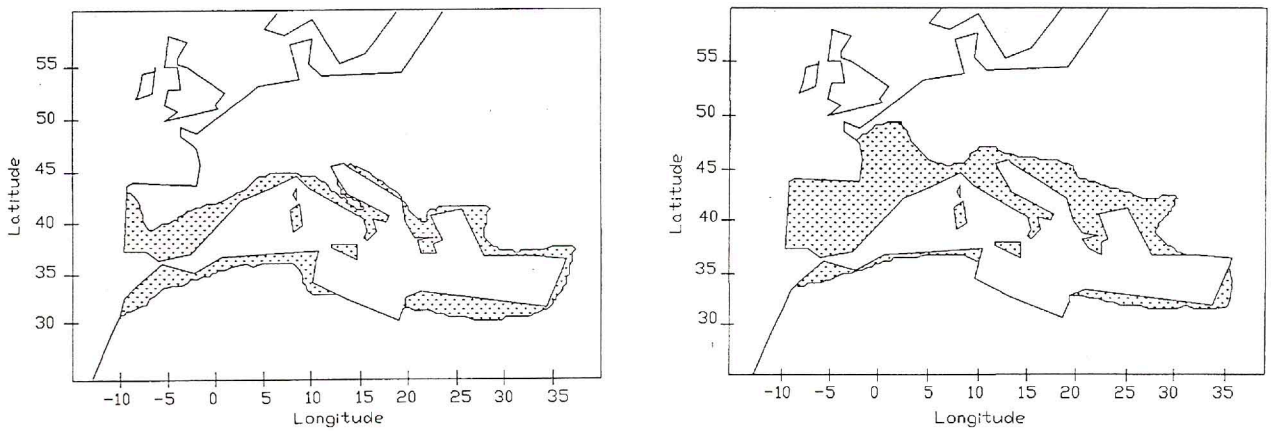


Fig. 4 - Areas of cultivation of the olive with the present CO_2 concentration (A) and with a concentration of 630 ppmv (B). (Source: Bindi et al., 1991).

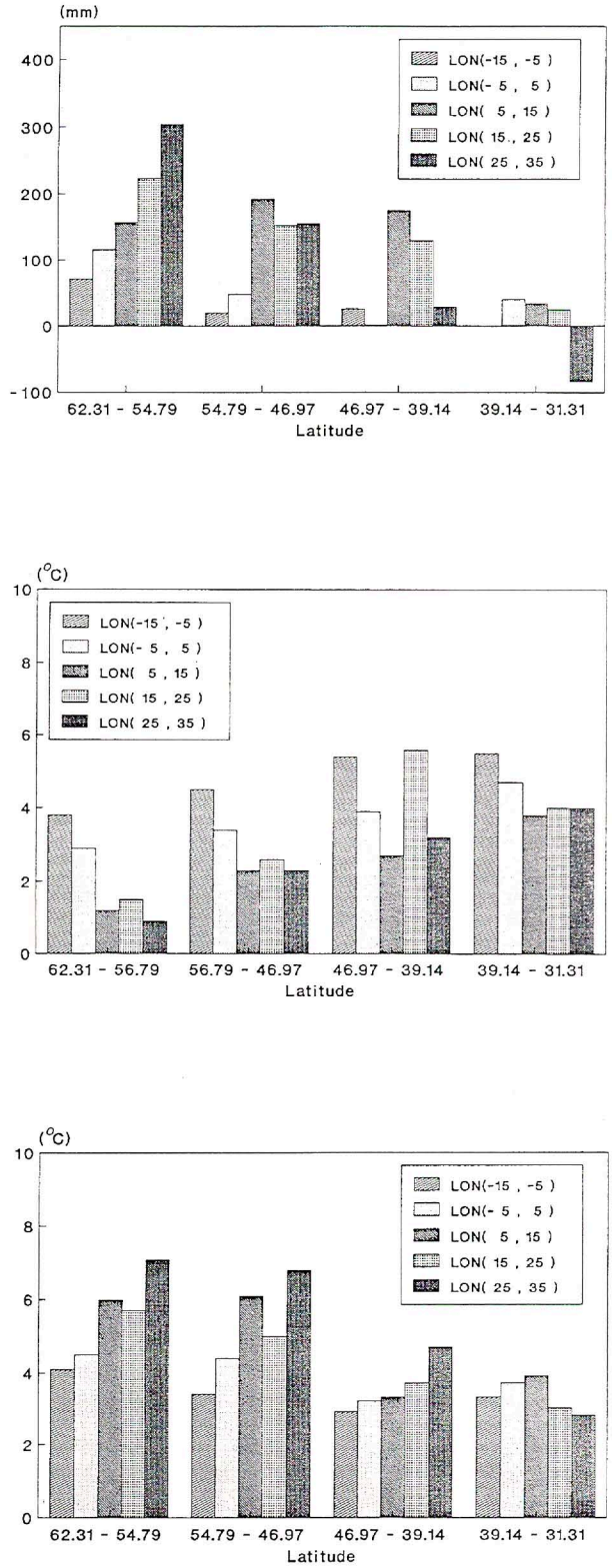


Fig. 5a - Variation in annual precipitation, b) variation in the July temperature and c) variation in the January temperature according to a doubling in the CO_2 concentration (Source: Bindi et al., 1991).

4.2 Effect of climatic change on wheat development in Italy

Prediction of the effect of an increase in temperature on wheat development is studied by means of simulation. This may be useful in understanding how wheat development responds to climatic factors and to search for appropriate management.

It has been affirmed that an increase in temperature leads to a decrease in yield of some crop because of increased development rates. For wheat, in particular, it is important to understand how an increase in temperature affects the timing of floral induction and anthesis. It is known that in these stages wheat is very sensitive to frost and drought. Spring frosts can damage the plants if they occur after floral induction or, in practice, after occurence of double ridge and this can be reflected by a dramatic reduction of final yield (Kirby, 1988, Morison & Butterfield, 1990b). Drought can also have a noticeable effect on the final yield mainly if it occurs just before or during the flowering period. In this period, in fact, a lack of soil moisture can increase floral abortion leading to a reduction in the final number of grains per spike (Saini & Aspinall, 1982).

In this work transient scenarios, corresponding to climate that might be expected to occur by about the middle of the twenty-first century, have been used as input in the IATA model in order to assess the effect of temperature increase on wheat development.

Material and methods - The transient climate scenarios used are those generated from the data of seven GCMs (Barrow & Warrick, 1992). Scenario A assumes that GHG emissions continue to rise during the period 1958 - 2062 at rates typical of the 1970s and 1980s (exponential increase of 1.5% per-annum); whereas scenario D imposes drastic reductions in GHG growth between 1990 and 2000.

The IATA model is an explanatory model which assumes that wheat development can be monitored on the basis of the leaf appearance provided that the final number of leaves formed by the crops is known (Miglietta, 1989, Miglietta, 1991a, Miglietta, 1991b, Miglietta, 1991c).

The model requires the following input:

- date of sowing,
- date of emergence (if knonw),
- latitude of the site,
- records of average daily temperature,
- variety data

Model output is as follows:

- date of appearence of subsequent main leaves from emergence to heading,
- final number of main stem leaves at heading,
- date of initiation of last leaf at apex (double ridge),
- date of emergence, heading and maturity.

Simulation runs were made for about 130 stations in Italy.

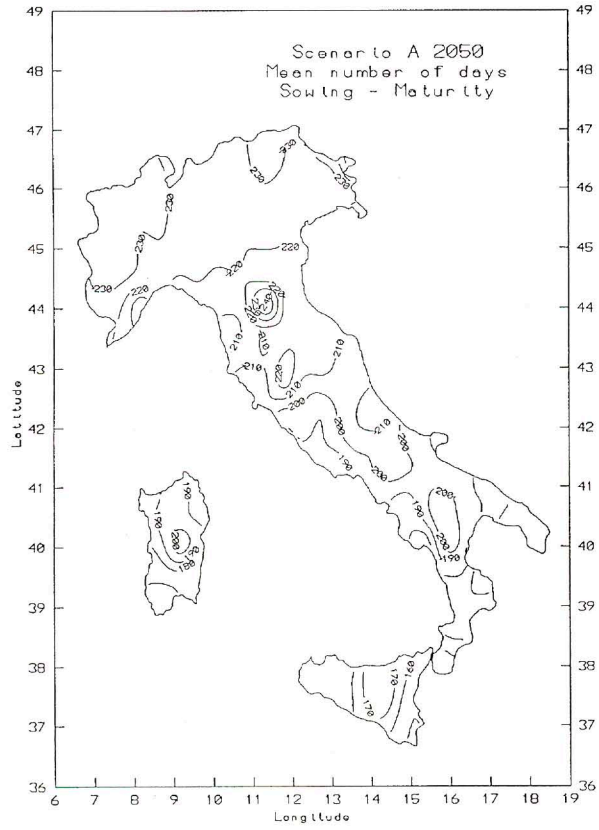
The daily weather data in the original data sets were changed according to the scenarios provided. Sowing date for each station was calculated on the basis of the field data of experimental stations of the Italian Ministry of Agriculture which are located at different latitudes in Italy.

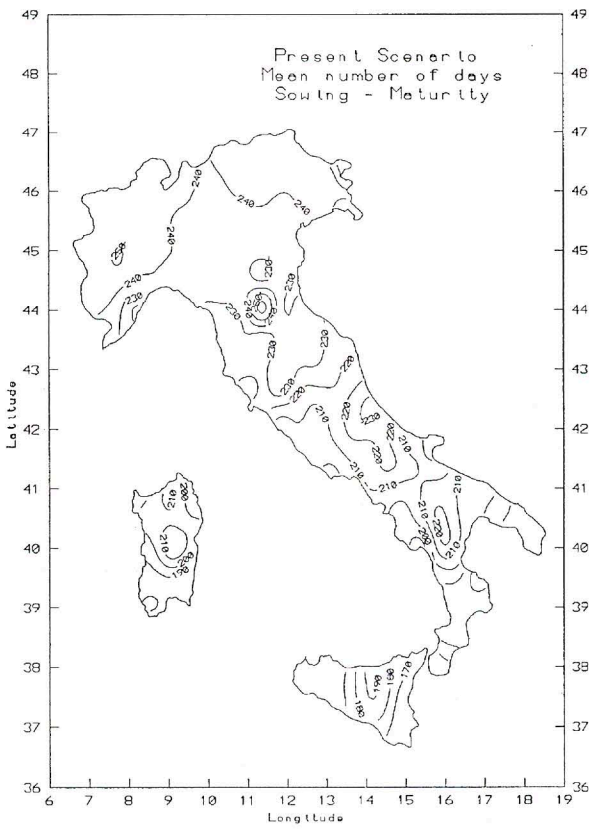
Results - Results of scenario experiments are presented in some maps, where calculated isolines are the result of an interpolation made between stations on basis of their elevation. The following information is given for each scenario:

- the mean time period from sowing to all the development stages (emergence, double ridge, heading and maturity),
- the variability around the mean (coefficient of variation) of all these time periods,
- the reduction of these time periods for an increase in temperature according to future scenarios.

Comparison of baseline maps with maps obtained according to the IPCC scenarios indicates that:

- differences in wheat development rates calculated for the different scenarios are large (fig. 6),
- the agricultural risk, expressed as the coefficient of variation, of model results is higher for years 2010, 2030 and 2050 than for present situation (fig. 7),





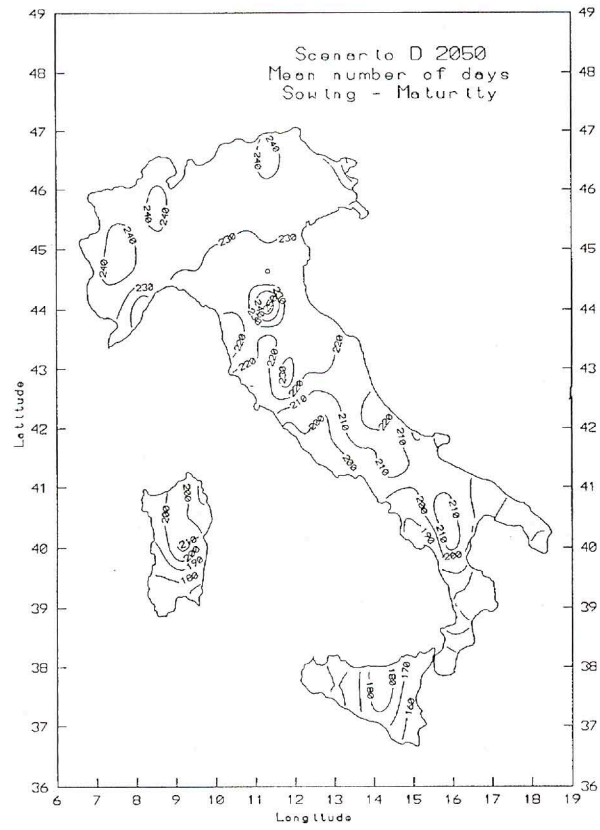


Fig. 6 - Maps of the mean time period from sowing to maturity for the present day temperature and for adjustment of the temperature according to the IPCC Scenario A and D for year 2050 (Source: Maracchi et al., 1992).

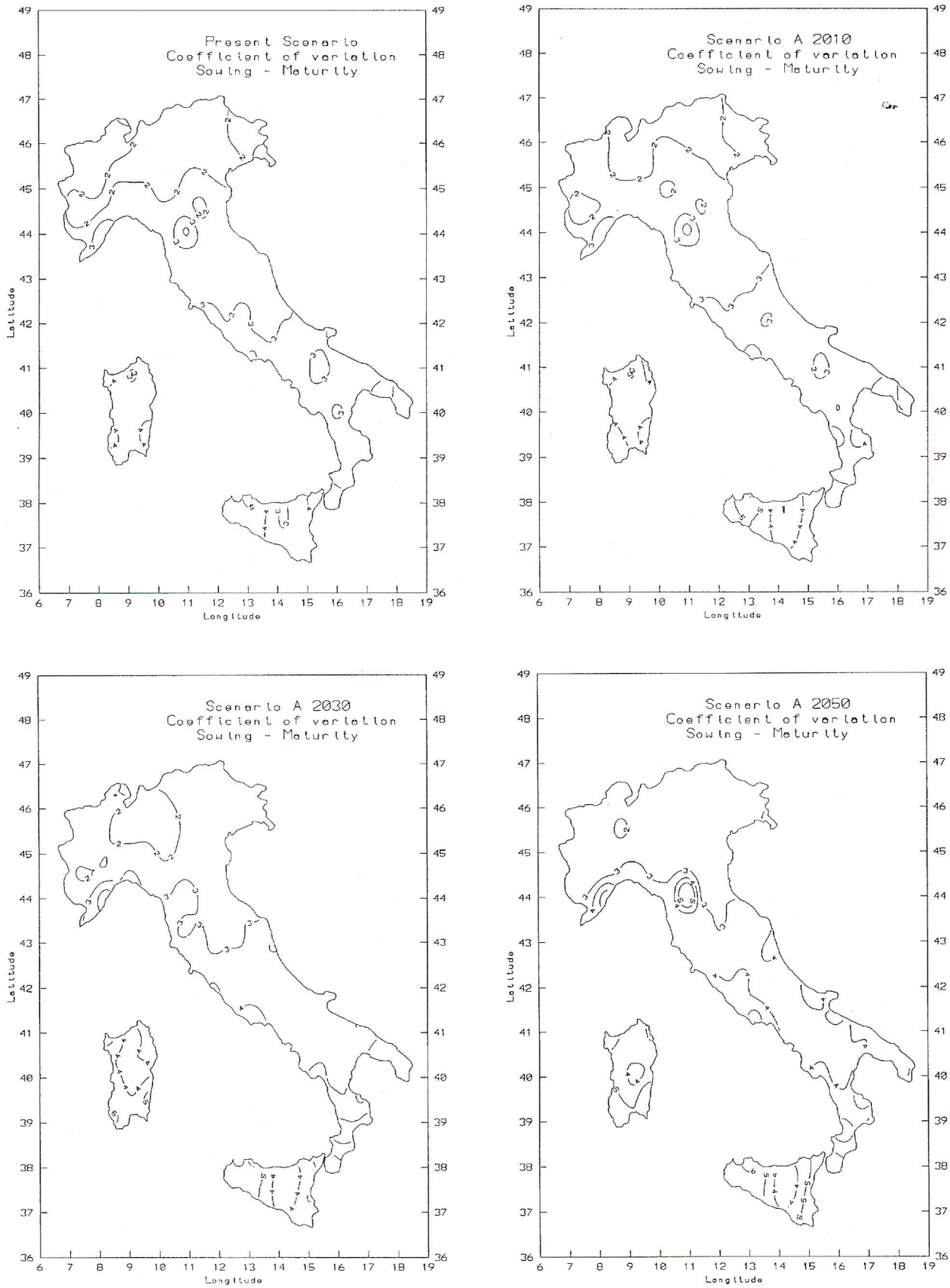


Fig. 7 - Maps of the coefficient of variation of the time period from sowing to maturity for the present day temperature and for adjustment of the temperature according to the IPCC Scenario A for years 2010, 2030 and 2050 (Source: Maracchi et al., 1992).

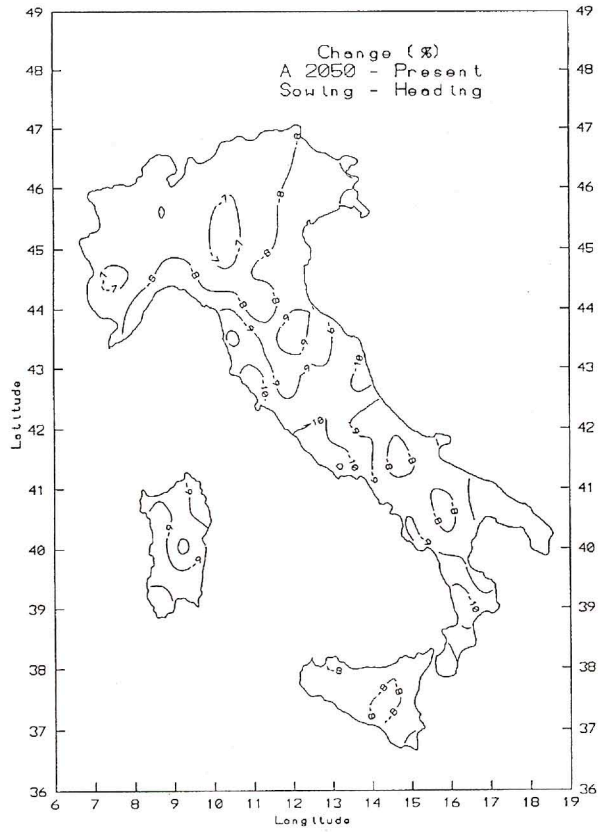
- the effect of the increase in temperature is different for different development stages and it is generally larger for the regions of southern and central Italy and smaller for the northern part of the country (fig 8).

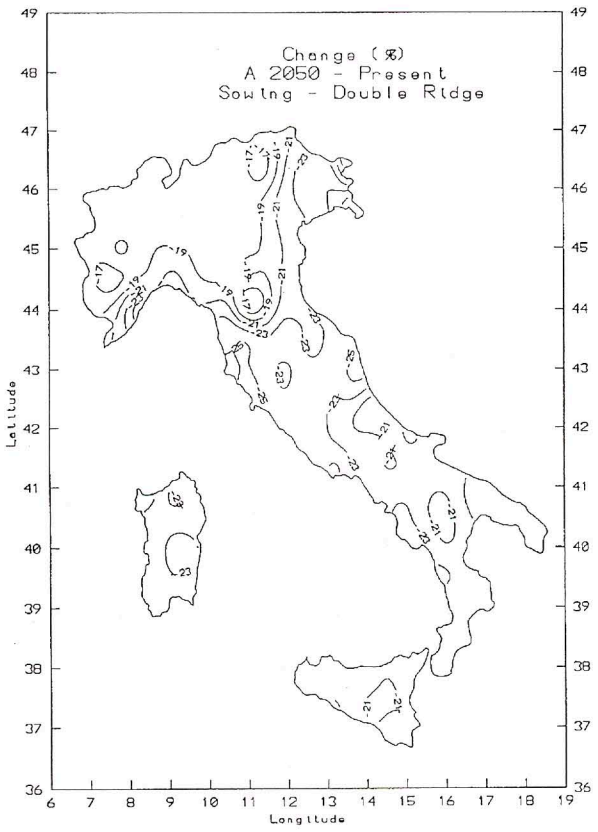
These results on current and future variability of wheat development are important. The evalutation of the phenological variability under current climate may be useful to define wheat ideotypes, for the different climatic regions of Italy. The analysis of the variability, inducted by an increase in temperature, may be useful for assessing potential changes in the duration of the different development phases and for the identification of better suited varieties and possible changes in management.

CONCLUSION

Simulation models may estimate yield levels of various crops on a regional scale, and help in exploring the effect of the increase in temperature and CO_2 concentration on agriculture and natural ecosystems. These are two of the most promising areas of simulation model application.

Crop models have to be simple, with limited input requirements, must be capable of integrating ground observations





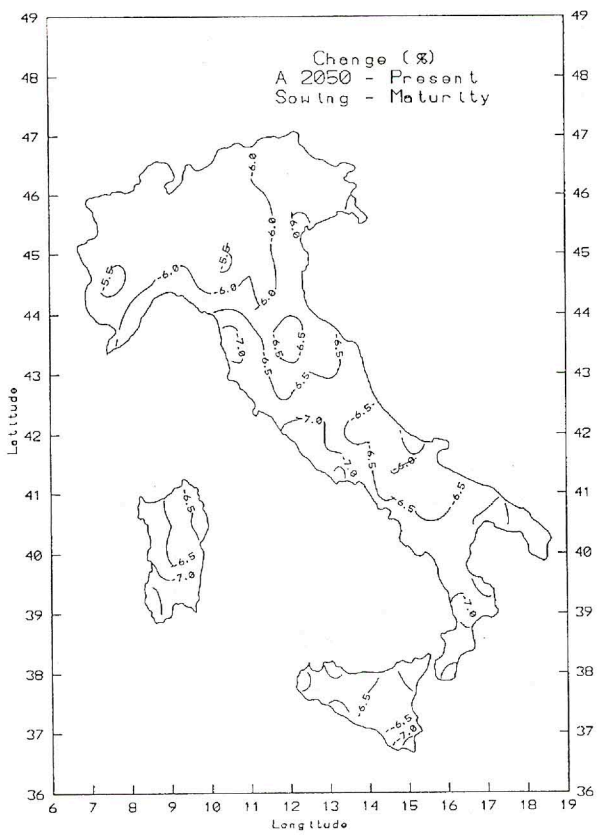


Fig. 8 - Maps of the mean change of the time periods from sowing to double ridge, heading and maturity for adjustment of the temperature according to the IPCC Scenario A for year 2050 (Source: Maracchi et al., 1992).

with remote sensing data, mostly for those countries where there is an insufficient ground observation network.
However, field experimentation still remains a priority of Agricultural Sciences, since this must provide the integration which is necessary to build every kind of simulation models.

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