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MODELING THE IMPACTS OF CLIMATIC VARIATION ON AGRICULTURAL PRODUCTION IN DRY REGIONS. AN APPLICATION OF DATA FROM STAVROPOL.

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PREFACE

For several years researchers at IIASA have been investigating that most crucial of interactions between man and the biosphere - the interaction between climate and society.

In 1978, for example, a meeting was held on "Carbon Dioxide, Climate and Society". This meeting brought together experts from around the world to assess the state of knowledge on the prospects of climate change resulting from increasing atmospheric injections of carbon dioxide and in particular to review work on this subject in the IIASA Energy Systems Program. In the same year, IIASA hosted the International Workshop on Climate Issues organized by the Climate Research Board of the US National Academy of Sciences and a preparatory meeting for the World Climate Conference organized primarily bi the World Meteorological Organization (WMO) of the United Nations. In 1980, a Task Force Meeting on the Nature of Climate and Society Research was convened to advance our knowledge of the relationship of climate to specific aspects of physical and social systems. More recently, in 1982, an international workshop on "Resource and Environmental Applications of Scenario Analysis" was organized. Finally, in 1983, a mayor 2-year project was initiated with the support of the UN Environment Programme. This project is investigating the impacts of short-term climatic variations and the likely long-term effects of CO_2-induced climatic changes on agricultural output at the sensitive margins of food grains and livestock production in 3 types of climatic regions: high-latitude/cold regions, semi-arid regions and those at high-altitude.*

This paper illustrates some work in hand on one of four semi-arid case studies: the Stavropol region in the southern USSR (The other semi-arid case studies are in N.E.Brazil, Australia and Kenya). It reports some preliminary experiments with a crop-environment model to analyze possible yield changes under altered climatic conditions. The model itself is described in a separate Working Paper in this series.

M. L. Parry
Leader
Climate Impact Project

* For a discussion of the project methodology see: Parry and Carter (1983) Assessing impacts of climate change: the search for an appropriate methodology. IIASA Working Paper WP-83-77.

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MODELING THE IMPACTS OF CLIMATIC VARIATION ON AGRICULTURAL PRODUCTION IN DRY REGIONS. AN APPLICATION OF DATA FROM STAVROPOL.

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Introduction

This paper is intended as a first step in analyzing the impact of climatic variations on agricultural production in dry regions. Stavropol region in the USSR is chosen as an example because appropriate data are available for 8 climatological stations over the period 1971-1982. In order to estimate the effects of climate on agricultural production a dynamic model has been used for climate information averaged over ten-day time step.

Although it is clear that socio-economic factors play an important role in the determination of crop production, the present analysis is limited to production based only on those characteristics that describe the physical production environment. This simplification offers us more insight into the functioning of the crop production model under varying climatic conditions.

After a brief discussion of methods in assessing the effects of climate on agricultural production and an explanation of the procedure followed in applying the model, some details of the crop production model are described. Of particular importance in validating the model is the processing of input data to be compatible with outputs and at the same level of aggregation.

Finally the results of some runs are presented along with conclusions about subsequent work to be undertaken.

Climate impact and agricultural production.

When considering climate impact on agricultural production we must examine both short-term annual and interannual variability, and also long-term changes in the climate.

One can recognize two different ways in which short-term variations of the weather will affect the yields.

First there are those sporadic events that occur at critical stages of plant growth, like for example the occurrence of nocturnal frost, or the occurrence of a cold period at blooming, which may cause plant sterility.

Secondly there are those weather variations that determine the level of the production but which are not disastrous since critical levels are not reached. For example cloudiness may lead to less radiation thus leading to lower yields provided other yield determining processes do not change.

Besides its direct effect, the weather also has an indirect influence on plant growth, through its effect on soil properties. This becomes very obvious if we consider the climate/soil relationship implicit in many of the various soil classification systems. Often the effect of a change in the climate shows with a considerable lag, e.g a sudden increase in the air temperature is accompanied by a change in organic matter content of the soil that takes a considerable time to attain a new equilibrium value.

Procedure in estimating the impact of climatic variations on crop production

A first step in determining the impact of climatic variations on crop yield is to model the effect of annual variability of the climate. This is particularly important if we wish to estimate the impact of more long-term climate changes. It is desirable to construct a model using relationships that can be shown to hold for a variety of physical environments. We may then expect the model to have some predictive capacity.

However, even if we are convinced that we have a good model for prediction of the crop production under different physical environments, we can not yet predict what is going to happen to the climate, i.e. to the parameters that describe its variability, the occurrence of extreme events and the weather pattern. We have therefore to create scenarios that are realistic enough to have a reasonable probability of occurrence in the future.

Characteristics of the model

General description

The structure of the model is broadly similar to the model developed at the Center for World Food Studies (CWFS, 1980). A rather detailed description can be found in Konijn (1984).

There is a certain hierarchy of processes that are considered to be yield determining, each setting a new constraint on the maximum output level. After the determination of the dry matter production by the radiative and temperature regime, it is the availability of water for plant production that may limit the crop production. Estimation of these is carried out per 10 days.

Next the decay of organic matter is estimated. During this decay nutrients may be mineralized, depending on the quality of the soil environment. The nutrients mineralized from organic materials in the soil and the nutrients from inorganic sources in the soil together contribute to the plant nutrition. Both sources can be "naturally" available or applied. The decay of organic matter is also determined on a third of a month time period.

The nutrient availability is modeled on an annual basis, therefore the model becomes at that stage more static. The reason for this is that there is no sufficient information upon which to base a dynamic model of the relationship between crop production and inorganic nutrients availability.

Structure of the model

In determining the dry matter production we follow the method developed by De Wit (1965). The actual radiative regime helps us to determine potential photosynthetic dry matter production from the values estimated by De Wit for standard circumstances.

The water balance for a certain type of land we are interested in may be expressed as:

$$dSM = P + I + CR - R - D - ET$$

where

dSM = the change in soil moisture content

P = precipitation

I = irrigation water applied

CR = capillary rise from ground water

R = overland flow (runoff)

D = excessive water percolated (drainage)

ET = evapo-transpiration

The dry matter production is converted to plant material by considering the characteristics of the particular crop being investigated. Each crop is assumed to have a certain composition, and therefore have a specific maintenance respiration and conversion coefficient. The maintenance respiration covers the losses in dry matter production, because of the necessity to maintain various metabolistic plant processes. The conversion coefficient changes the dry matter as expressed as carbon dioxide (CO_2) into the final plant material produced. Photorespiration is already included in the initial estimation of photosynthetic dry matter production.

We will not describe here the nutrient/crop production model, since, as we mentioned before, the nutrients in the soil are assumed to be non-limiting. However, if we wish to quantify the indirect effect of the climate on crop production (i.e. due to changes in soil properties) we cannot omit the effect of soil nutrients.

Input requirements for the model

According to their nature and origin the input characteristics can be grouped as follows:

- climate characteristics
- site characteristics
- soil characteristics
- crop characteristics
- fertilizer characteristics
- management characteristics

The first three characteristics depend exclusively upon local conditions. The others are partly or wholly exogenous.

We assume that a mapping unit or a grid unit can be described by a particular set of characteristics. We shall call this unit the land class. Each unit is considered to be homogeneous. Such an assumption clearly requires some aggregation, because soil and climate information is not usually available at the spatial resolution appropriate to the investigation.

In this study we have assumed the whole region to be covered by one type of land class. The aspect of aggregation becomes important only when we turn to future work described in the last section of this paper.

The validation of the model

We will try to rely as much as possible on what can be called the internal validation of the model, that is in the model we use relationships for the various composite yield-determining processes which have been proved to be sound. The possibilities for validation of the model depend upon our ability both to aggregate where necessary the required input characteristics and to collect adequate crop production observations.

Two steps can be recognized in the validation. First we validate the model as a whole or in parts, depending on the available input data. A complete set of input data allows us to run the whole model. For incomplete sets we can only validate parts of the model. In this first step we will work with an original set of data, that is data which have not been aggregated. The observed results on agricultural production used for validation, should be at the same level of aggregation and there should be no doubt about the origin of the data. It is important to validate under different physical environments.

The second step in validation aims at assessing the quality of the method of aggregation. This assumes that the model itself is validated and has proved to work satisfactorily. Comparing the estimated values with the measured values we are able to evaluate the various aggregation procedures.

Application to data from Stavropol

The area, assumptions and presentation of results

The Stavropol region is located near the Caucasus at a latitude of around 41 degrees north. It has an area of approximately 80.000 km^2, i.e. about the size of Austria. The spatial pattern of mean annual rainfall is highly variable, being near and in the Caucasus more the 1000 mm, and in the driest parts not more than 300 mm.

In the following examples of model runs for the Stavropol region we have considered plant nutrients to be non-limiting. The yields are determined by the radiative, temperature and soil water regimes.

Although there are a number of different kinds of soil in the Stavropol region we will only consider one soil type. This makes it more convenient to present the results. The soil we have chosen has a sandy loam texture with an organic matter content of 3 percent containing plenty of nutrients.

Climatological observations of air temperature, relative humidity, global radiation, precipitation and wind speed were available at 8 sites for the period 1971-1982.

Oats was taken as the crop. The characteristics that describe this crop are prescribed in the model, e.g. length of the various development stages, rooting depth, sensitivity to water stress etc.

First we show examples of the variability of the yields over the period 1971-1982 for some locations and next we show the effect of increased precipitation on yields of oats. As scenarios we have chosen the increase of the annual precipitation by respectively 10 and 20 percent.

FIGURE 1 •

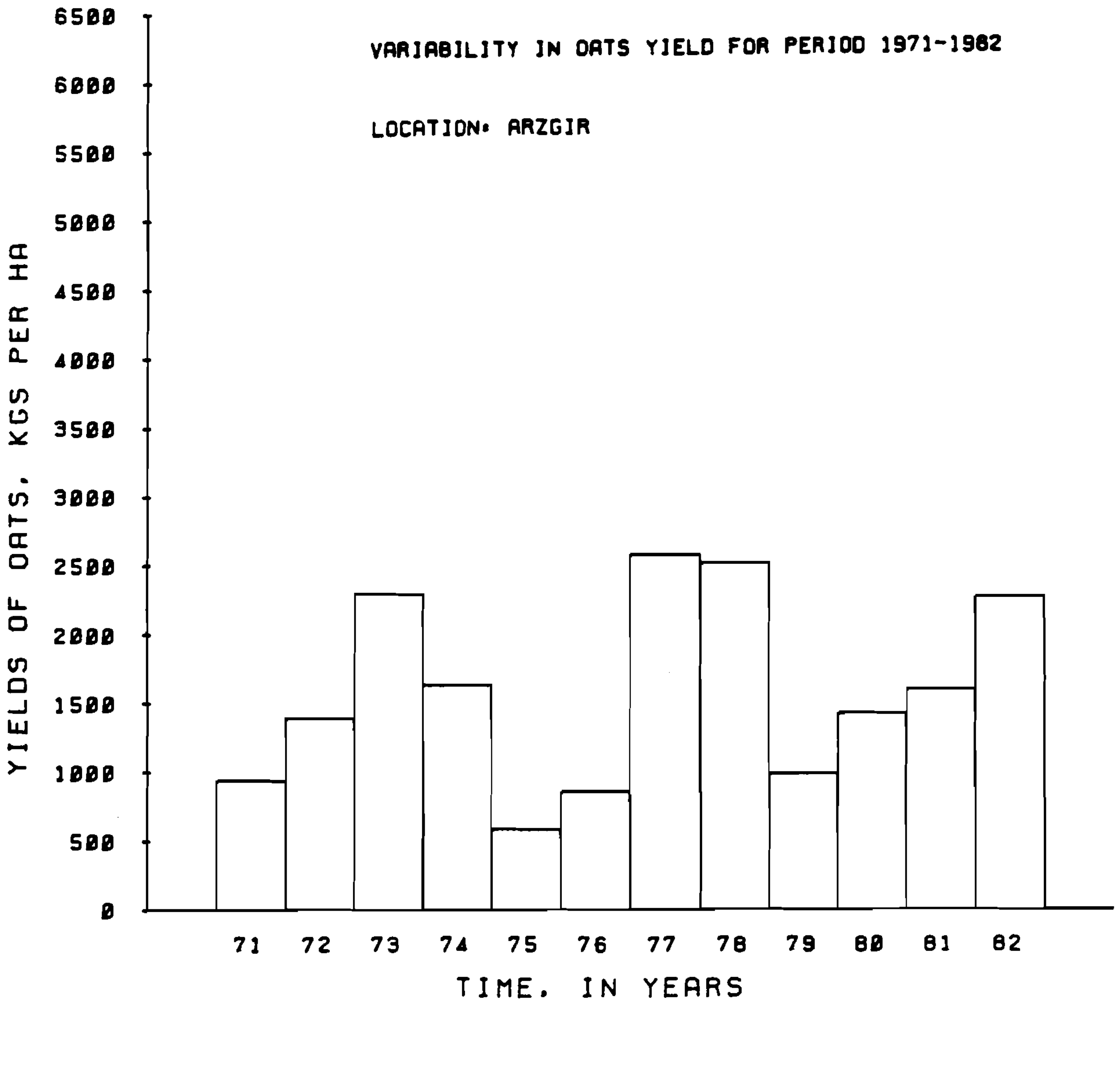

VARIABILITY IN OATS YIELD FOR PERIOD 1971-1982
LOCATION: ARZGIR
YIELDS OF OATS, KGS PER HA
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
71
72
73
74
75
76
77
78
79
80
81
82
TIME, IN YEARS

FIGURE 2 .

VARIABILITY IN OATS YIELD FOR PERIOD 1971-1982

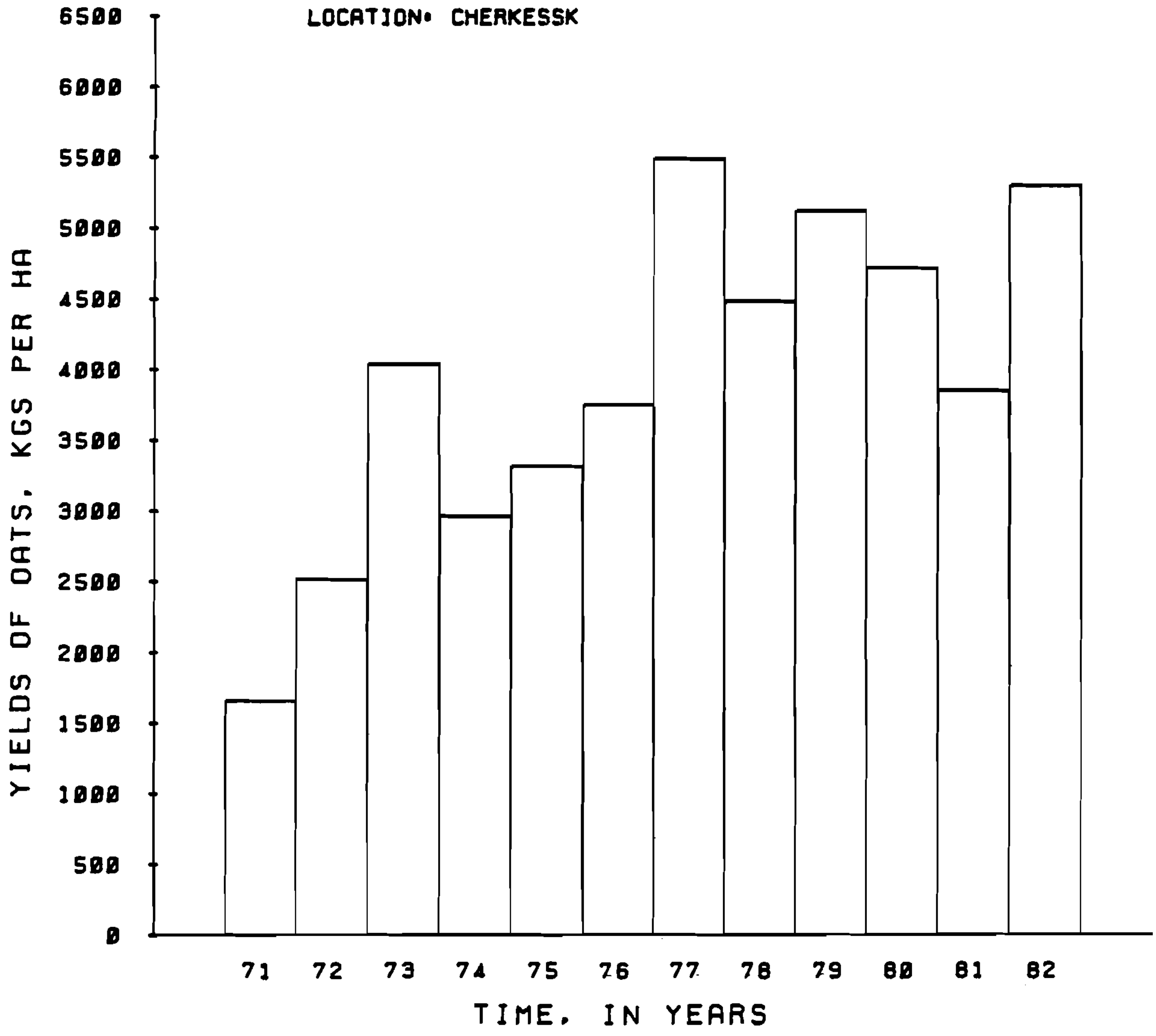


FIGURE 3 .

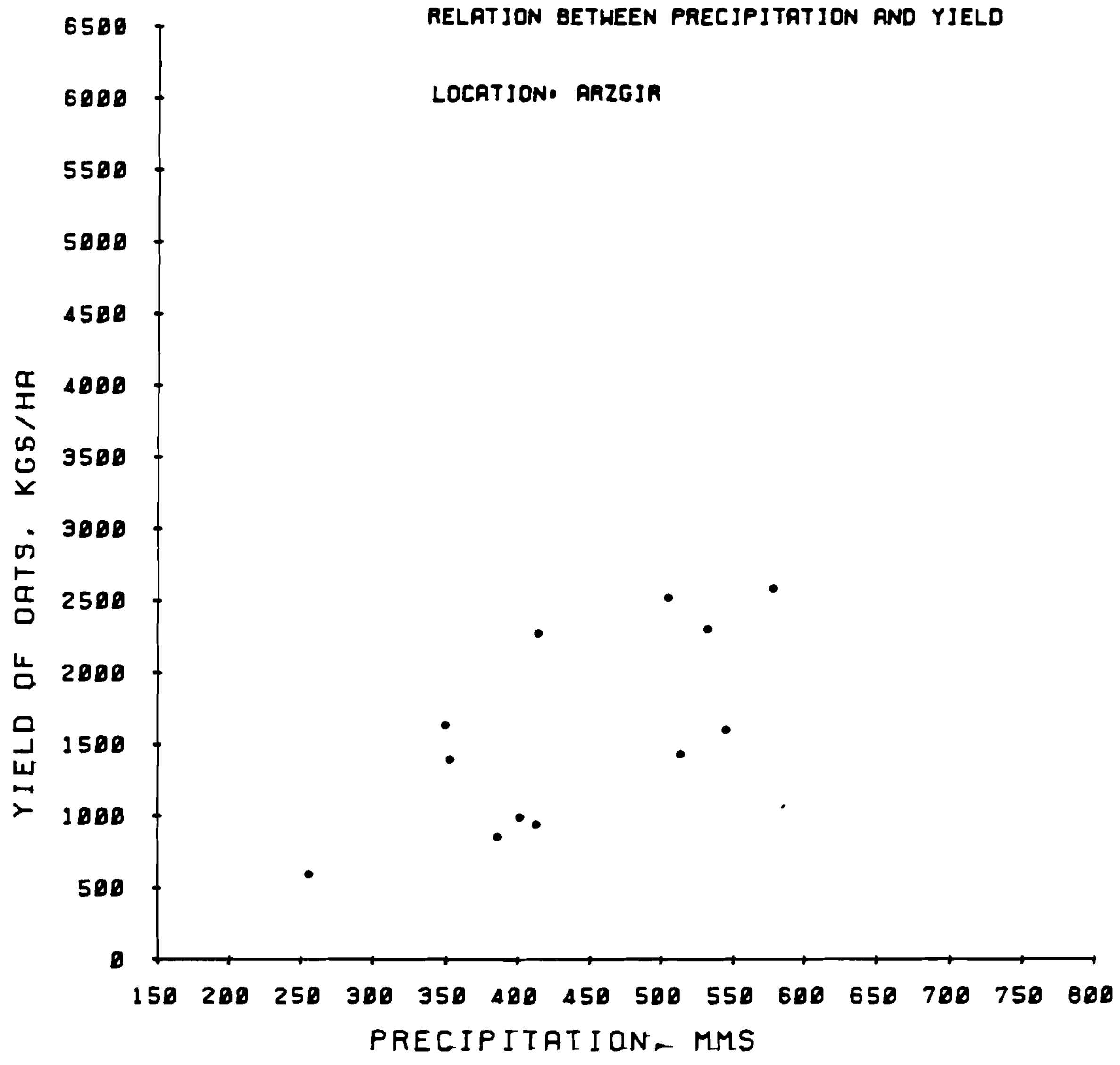

RELATION BETWEEN PRECIPITATION AND YIELD
LOCATION: ARZGIR
YIELD OF OATS, KGS/HA
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
150 200 250 300 350 400 450 500 550 600 650 700 750 800
PRECIPITATION, MMS

FIGURE 4 .

RELATION BETWEEN PRECIPITATION AND YIELD

LOCATION: CHERKESSK

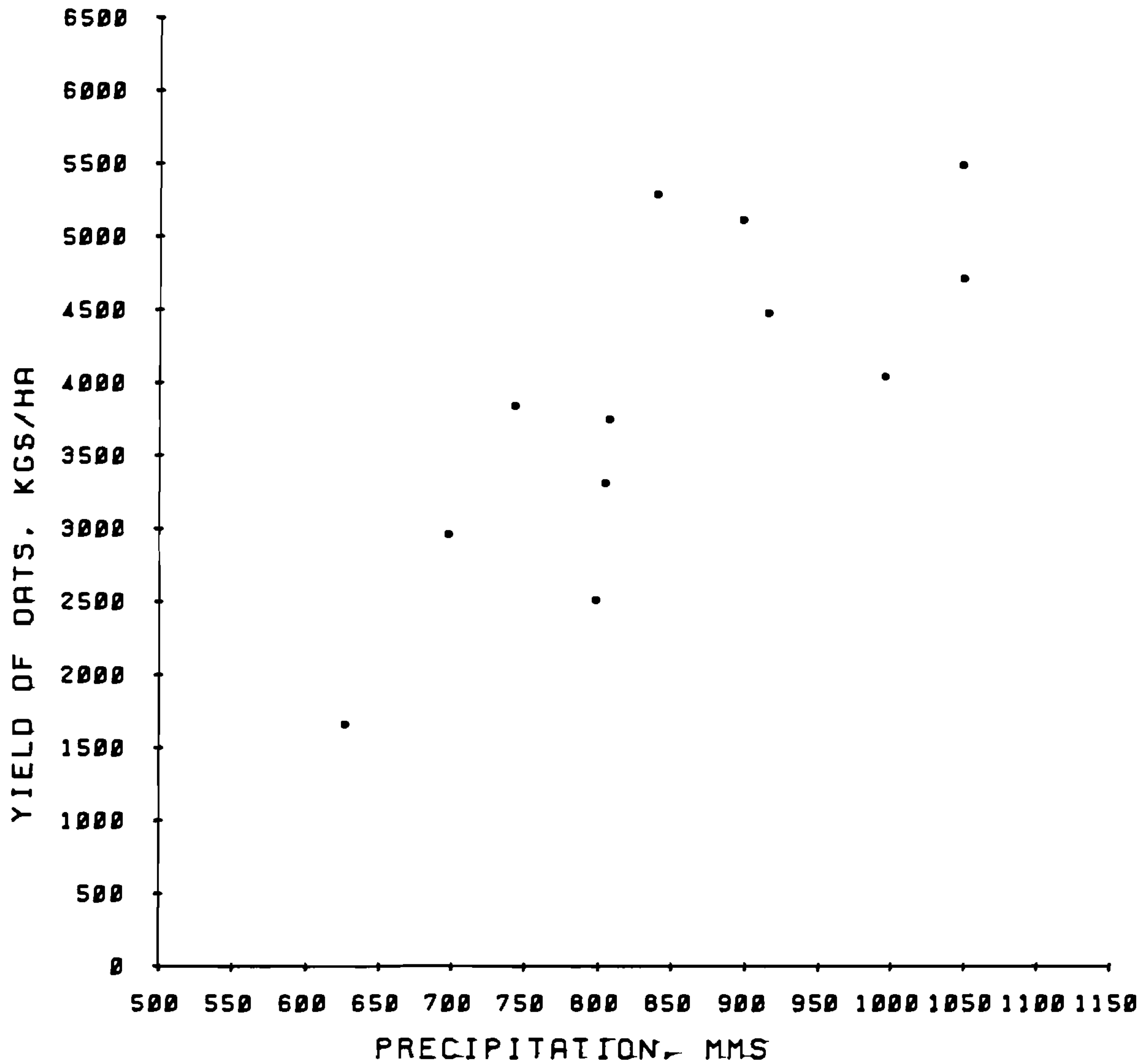


FIGURE 5 •

PRECIPITATION INCREASE AND CHANGE IN YIELD

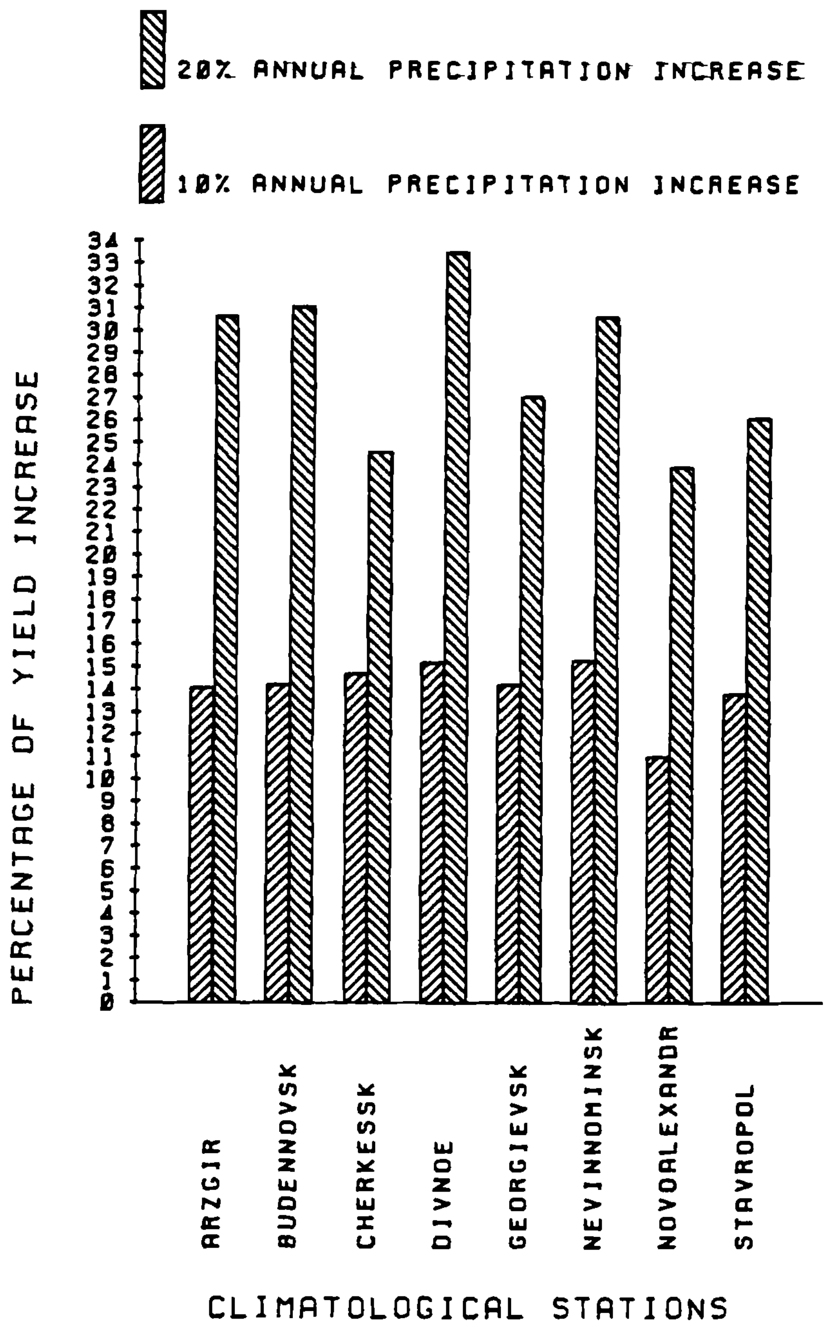


FIGURE 6 •

ACCUM. WATER DEFICIT DURING THE GROWING CYCLE

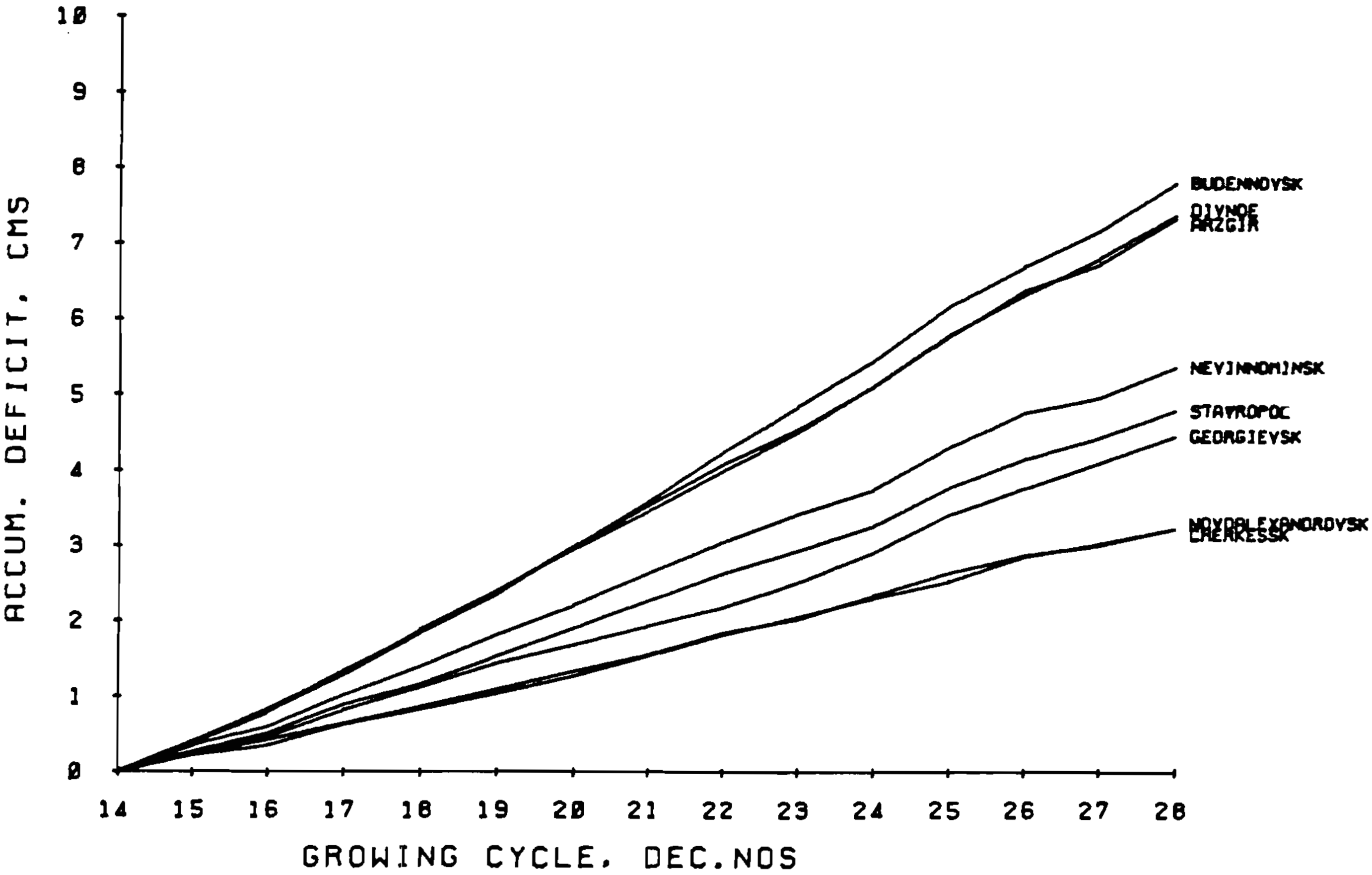


FIGURE 7 :

ISOLINES FOR OATS PRODUCTION AT 3 PRECIPITATION LEVELS

STAVROPOL REGION

SCALE 1:2500000.

ISOLINES FOR 3000 KGS OATS/HA
—— 100% ANNUAL PRECIPITATION
········ 110% ANNUAL PRECIPITATION
- - - - 120% ANNUAL PRECIPITATION

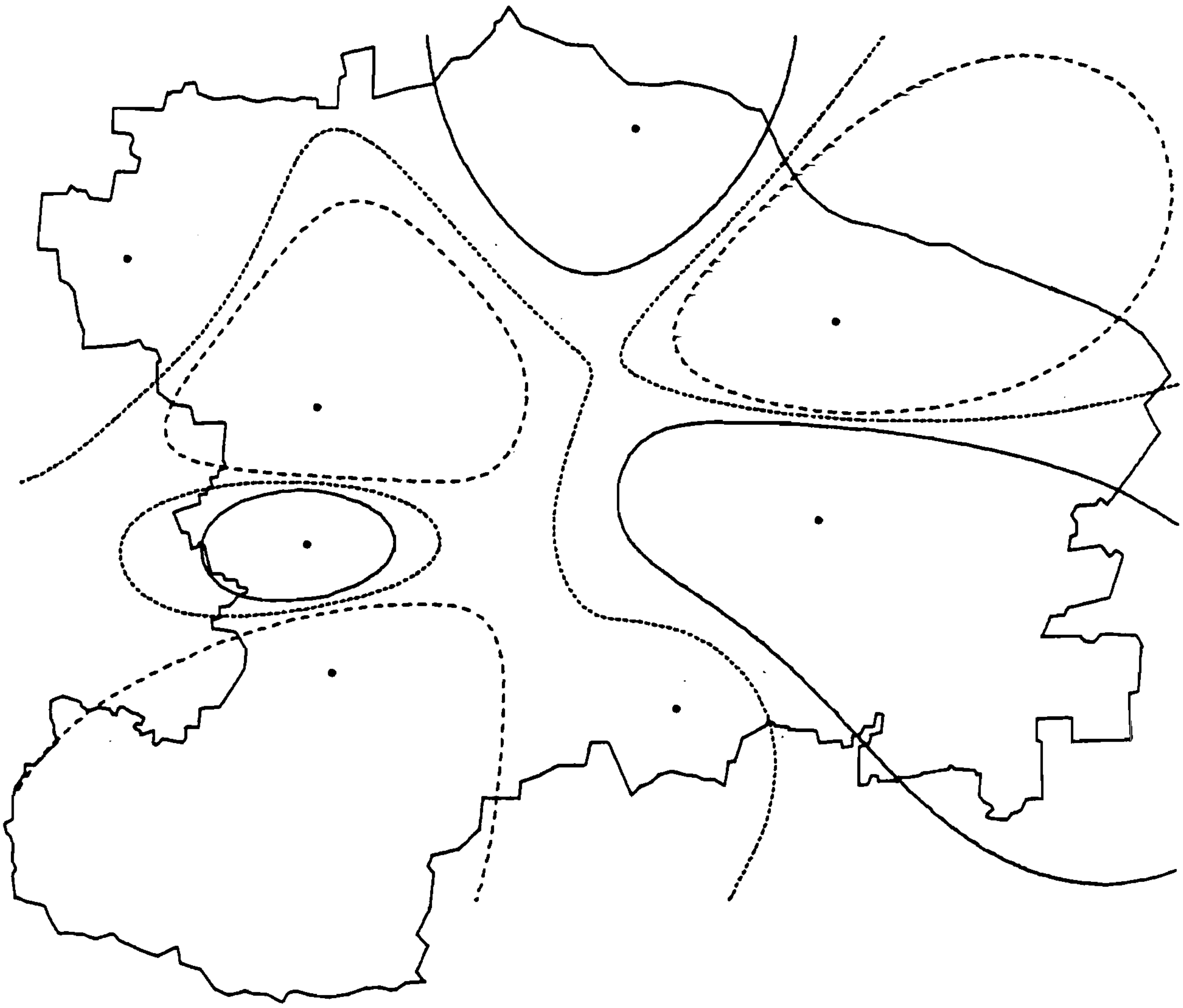
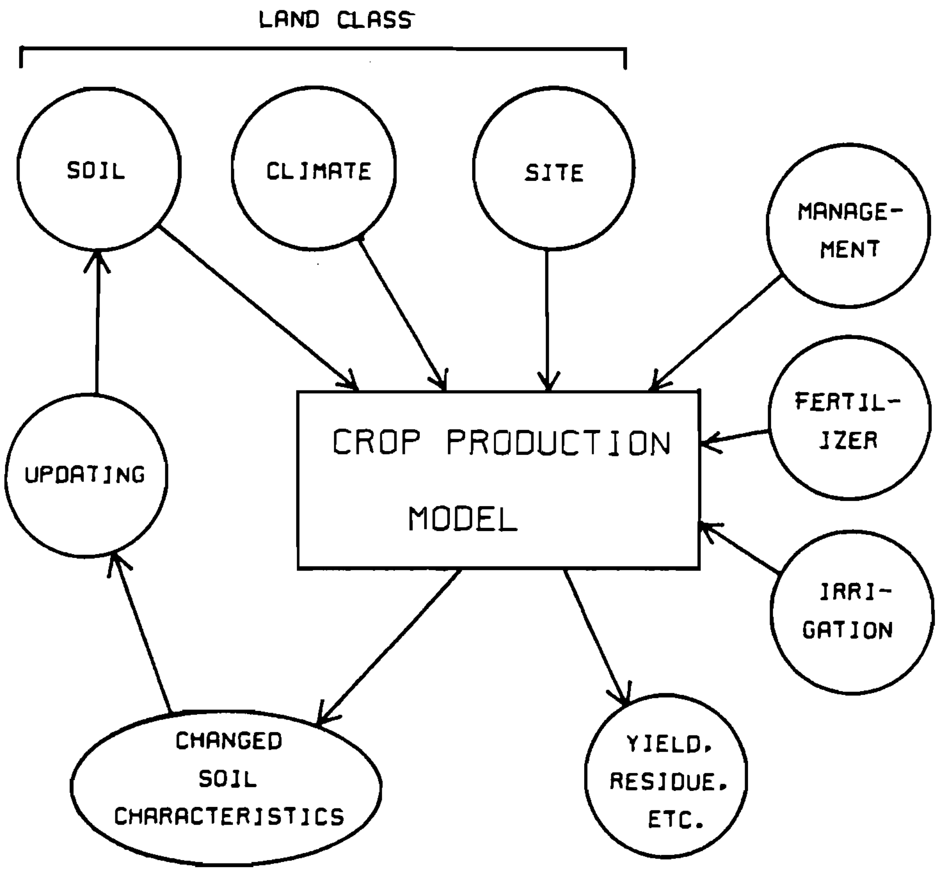


FIGURE 8 • THE CROP PRODUCTION MODEL AND FEEDBACK



Description of the results

The Figures 1 and 2 show the variability of the yields for two locations, Arzgir and Cherkessk, over the period 1971-1982. To give an idea of the significant effect rainfall has on yields, we have plotted the yields against the related annual precipitation (Figures 3 and 4). No perfect fit could be expected, because the distribution of the rainfall over time is different from year to year, moreover the radiative and temperature regimes affect the relationship.

Figure 5 shows how yields increase as a result of increases in annual precipitation. All climatological stations are presented and the climate data used were period-averages for the years 1971-1982. Here again as could be expected, the difference in rainfall distribution together with the different amounts of precipitation lead to varying responses to precipitation increase. Figure 6 presents the potential accumulated water deficit by 10 day increments throughout the growing season, for the 8 climatological stations. The drier areas show in general the larger response to precipitation increase.

Finally a map of the Stavropol region is presented (figure 7), indicating the shift in yields isolines predicted by the model for a changing climate. The area yielding less than 3000 kilograms of oats per hectare is reduced by approximately 12,000. km^2 for a 10% precipitation increase and 26,500. km^2 for a 20% increase in precipitation. This pattern however would be somewhat different if soil differences and varying management practices are considered.

Conclusion and future work

The runs with the crop production model have been made based on one soil type, supporting a single crop, and assuming no limits in nutrient availability. The results would be considerably more realistic if we include the soil pattern and such management practices as fertilizer use. Estimating crop yields for different soils and plotting the results as in figure 7, would create a less continuous pattern of isolines; this in spite of the climate-soil relationship.

Having included the effect of soils and fertilizers on crop yields the next, logical step will be to keep track of changes that are brought about by various farming practices. Residual effects of organic and inorganic fertilizers are often important and should be accounted for. Climate variability and climate changes are also accompanied by residual effects. Soil properties like organic matter content can be expected to respond to variations in the climate. Since our yield estimations are based on such soil properties as organic matter content, by regularly updating the soil properties we are able to show the effect of residual effects on crop yields. Figure 8 illustrates in a simple manner the role of the updating procedure for soil properties within the model framework.

Finally, as a cautionary note, it should be stressed that the value of this whole exercise relies largely on the validity of the model. Therefore model validation will have to receive considerable attention in the future.

REFERENCES

Center for World Food Studies. (1980). The Model of Physical Crop Production. Research Report SOW-80-5 Wageningen.

Wit, de C.T. (1965). Photosynthesis of leaf canopies. Agricultural Research Report 663. 57 pp.

Konijn,N.T. (1984). A crop production and environment model for long-term consequences of agricultural production. WP-84-51.