Agrometeorological research and applications needed to prepare agriculture and forestry to 21st century climate change

Victorine PERARNAUD (Météo-France- Direction de la Production – 42 avenue Coriolis 31057 Toulouse Cedex (France)– Tél : 33 (0) 5 61 07 83 81- Fax : 33 (0) 5 61 07 80 79- e-mail : victorine.perarnaud@meteo.fr)
Bernard SEGUIN (Institut National de Recherche Agronomique - Unité Agroclim - Site Agroparc, domaine St-Paul - 84914 Avignon Cedex 9 (France)- Tel: 33(0)432722307, Fax: 33(0)432722362, e-mail: seguin@avignon.inra.fr
Eric MALEZIEUX (Centre de Coopération Internationale en Recherche Agronomique pour le Développement, Cirad-DS, TA 179/01, avenue Agropolis, 34398 Montpellier cedex 5 (France)- Tel 33(0)467615546, Fax : 33(0)467615512 – e-mail : malezieux@cirad.fr
Michel DEQUE (Météo-France- Centre National de Recherche de la Météorologie – 42 avenue Coriolis 31057 Toulouse Cedex (France) - Tél : 33 (0) 5 61 07 93 82 – Fax : 33 (0) 5 61 07 96 10 - e-mail : michel.deque@meteo.fr)
Denis LOUSTAU (Institut National de Recherche Agronomique - Recherches Forestières - BP 45 - 33611 Gazinet (France) - Tel 33 (0) 5 57 12 28 51 - Fax 33 (0) 5 56 68 05 46 – e-mail : Denis.Loustau@pierroton.inra.fr)

SUMMARY

The adaptation of agriculture and forestry to the climate of the twenty-first century supposes that research projects will be conducted in cooperative actions between meteorologists, agronomists, pedologists, hydrologists, and modellers,…. To prepare for it, it is appropriate first of all to study the variations in the climate of the past using extensive, homogenised series of data (meteorological, phenological, etc.). General circulation models constitute the basic tool for forecasting the future climate. They may still be improved, and the regionalisation techniques used for downscaling climate predictions could also be made more efficient. The crop simulation models using input data from the general circulation models applied at the regional level ought to be the favoured tools which allow the extrapolation of the major trends on yield, consumption of water, fertiliser, pesticides, the environment and rural development. For this, they have to be validated according to the available agronomical data, particularly the available phenological series on cultivated crops. In addition, a climatic change would have a certain impact on crop diseases and parasites, as well as on weeds. Very few studies have been carried out in this field. It is also necessary to quantify the stocks and

fluxes of carbon in the large forest ecosystems, simulate their future, and assess the vulnerability of the various forest species. This is all the more important in that some choices of species must be made in the course of the next ten years in plantations which will experience the climate of the end of the twenty-first century. More broadly speaking, we shall have not only to try hard to research new agricultural and forestry practices which will reduce greenhouse gas emissions by agriculture and / or promote the storage of carbon, but it will also be indispensable to prepare the adaptation of numerous rural communities for the climatic changes (particularly those in the South countries, which are often under threat) by coming up with a series of new environmental management practices suited to the new climatic order.

INTRODUCTION

To prepare agriculture and forestry for the climatic changes forecast for the twenty-first century, particular efforts must be made in research, based on the knowledge on climate data currently available, and orienting it towards the development of the most up to date techniques. These developments must be accompanied by efforts in agronomic research which take the hypothesis related to climatic change into account in research in plant genetic improvement and development of sustainable cropping systems to attain the delivery of operational applications regarding adaptation strategies. It then becomes indispensable to single out two types of adaptation depending on the final user: those which can be implemented by the farmer himself (modification of sowing dates, varietal choice, use of seasonal forecasts, etc.) and those of decision-makers, land and natural resource managers which necessitate investment in development and construction infrastructures (particularly hydraulic constructions…). Thus, in operational terms, the results of research will have to contribute to the implementation of durable construction and management options which enable the adaptation of agrosystems and forest ecosystems to climatic change: identification of sensitive areas, choice of new crops, species replacement, calculation of future needs and water collection, geographical species area and potential impact of pests and diseases.

To the scientific and technical problems raised by adapting agriculture and forestry to climatic variability and change must also be added socio-economic considerations which will not be covered in this article but which will have to be borne in mind. Hence, any significant modification in local production will necessarily affect the global organisation of the markets, and it is clear that the major destabilisation of some economic and social balance is possible. Conversely, it is also appropriate to underline that, through the emission of greenhouse gases (GHG) or, on the contrary, the storage of CO_2, agriculture and forestry are likely to make a significant contribution to the climatic change dynamics. The combination of these elements will be analysed in the text below, supported equally by climatic research in relation to agricultural and forestry production and by issues more specifically linked to the latter. Our arguments will rely principally upon examples relating to the position in France, in a temperate region therefore, but we have tried to extend its scope by broadening our considerations to the semi-arid and tropical zones. In effect, in the countries in the South, bearing in mind the precariousness of ecological and social balance, the impact of climatic change is likely to have a major effect on the productivity and balance of cultivated ecosystems (reduction of biodiversity due to an increased drought, irreversible erosion of land linked to the aggressivity of rainfall, etc.), leading in some cases to the migration of populations if nutritional security is affected. Indeed, even though the simulations show a higher elevation of temperature in polar and temperate latitudes in relation to the tropical latitudes, tropical crops are today much closer to the thermal optimum and hence more likely to suffer from thermal excesses in the future. Insects and diseases, already very active in tropical zones, could proliferate and widen their area of influence. The combination of these factors, to which must be added the dependence of Southern societies on agriculture and its risks, the fragility of economic and social conditions make a number of tropical regions risk areas likely to suffer the implicit negative effects linked to climatic change with particular intensity (Rosenzweig and Hillel, 1978).

1- Improve understanding of the variation of the current climate and its impact on agriculture.

1-1 Collect and analyse information on ecosystems

To study the impact of climatic changes on agriculture and forestry and improve our understanding of certain mechanisms, it is important to gather regular information on the ecosystems (inventories of land use per species, phenological observations, production statistics, etc.) to study their evaluation in the course of recent decades on the territorial scale. The use of remote sensing data is now a precious tool in obtaining spatialised information on areas of the planet where ground measurements are difficult. Moreover, additional information on the land is essential in establishing their sensitivity to water excess or deficit, hydric and wind erosion, and the risks of salinisation.

1.2 Study the long chronological series of climatic and phenological data

The national meteorological services must adopt an ongoing policy of research and useable documentation of old data which thus enrich the national climatic heritage. Indeed, it is important to study the behaviour of extended series of meteorological measurements on national territories over a period which extends from the end of the nineteenth century to the present day. To detect long term trends, the raw data must be processed using statistical methods designed to constitute homogenous chronological series, enabling the isolation of the climatic signal of other effects linked to modifications of observation techniques, movements of measurement areas, or a modification of their environment (Moisselin, 2001). The analysis of these so-called "homogenised" series on a particular territory would then allow us to determine the significant variations of each parameter which may be relevant for the type of crop studied on the annual, seasonal or monthly scale and highlight spatial particularities. This kind of analysis generally allows to show that there is no single trend observed on the scale of the national territory. This study is essential when, for example, one considers the behaviour of crops in response to temperature, to its cumulative or limiting effects (frost or lethal excess). Figure 1 shows the annual number of days with frost and heat waves observed in the period 1901-2000 at the meteorological station in Marseille (France). The regular decline of the number of days of frost between the beginning and end of the twentieth century is quite spectacular. The increase of the number of days of heat wave is more marked over the last two decades, and this in a way which is consistent with the results shown by the average temperature in the report made in 2001 by the Intergovernmental Panel of experts on Climate Change (IPCC).

The processing of extended series of climatic data should also allow a validation of the regional climate simulation models.

These extended series should also to be complemented by phenological series coming either from observations of the natural vegetation or forest species, or from the species cultivated, particularly for the perennial species (fruit trees, vines, etc.). The analysis of the latter is, of course, of great importance in supporting the phenological models which constitute the basic modules for the crop simulation models (as we shall see later), but also to complete the climatological observations.

Thus, by way of an example, figure 2 shows the evolution of the flowering dates of the apple tree in south east France (Balandran) over the period 1974-2001 (Domergue, 2001) and figure 3 that of the grape harvest dates in Chateauneuf du Pape in the south of France from 1940 to

2000 (Ganichot, 2002). These two examples show an evolution in the phenological precocity of the various stages but also the large interannual variability. It is therefore appropriate to be careful in analysing these results on terms of the partitioning of causes between growing techniques and climate interannual variability. This reserve has no bearing on the flowering of the apple tree, whose is confirmed by a simulation using a phenological model.

2- How well can the climate of the future be simulated?

The climate is the result of the combination of processes of natural and anthropic origin that interact together. The climate of the future will continue to be conditioned by a global atmospheric circulation which will result from the evolution of the radiative forcing imposed by the future atmospheric contents in greenhouse and aerosol gases. The simple extrapolation of the current trend would suppose a perpetuation of the socio-economics global trends currently observed. We now know that this is not realistic and we cannot predict the direction that these developments will take in the medium and long terms. There is a large number of provisional scenarios in which the respective plausibilities and probabilities are far from being confirmed, particularly because of uncertainties on the policies of certain countries in terms of the reduction of emissions.

2.1 Improve the general circulation models

The climate models constitute the basic tool for making projections about the future. The most advanced models describe atmospheric and oceanic circulation, surface processes, the evolution of icebergs and the cryosphere, the carbon cycle and the influence of the physico-chemical composition of the atmosphere (greenhouse gases, aerosols). They take account of the interactions between the various protagonists in the climatic system, for example between oceans and atmosphere, and between the land, vegetation and atmosphere. But the general circulation models coupled with the ocean and ice floes can still be improved. Moreover, even though the predictions on global temperature are generally consensual, disparities exist in the behaviour of the hydrological cycle in the regional responses to the increase in atmospheric greenhouse gas content. Finally, questions remain on the response of our natural environment to global warming. For example, we can cite the land use changes (particularly the natural or cultivated vegetation), the storage of carbon (particularly in the ocean and in the continental biosphere) or the possible modifications in oceanic circulation.

2.2 Necessity and difficulty of regional studies

When we consider the impact of a climatic change on agriculture and forestry, in a particular country or a continent, it is clear that we must work on a suitable spatial scale which is generally more detailed than the current horizontal resolution of the general circulation models (having a grid in the order of 200 km). Research on the regionalisation of climatic changes (Wilby et al, 2000) ought to be carried out, which focus on improving the techniques themselves but also on the evaluation of their impact on agriculture and the environment. Two techniques, based on the modelling, are now used to study the regionalisation of climatic impact. The first consists of using complementary models. We take an atmospheric model, the scope of which covers only the region being studied (Europe, for example): this model is called the regional model. Hour by hour, we impose on its boundaries the meteorological conditions calculated by a global model with a coarser resolution. This method has already been used by numerous countries, the USA, Great Britain and Germany. The methodological disadvantage comes from what happens at the boundaries of the area. The global model takes absolutely no account of the parameters (winds, temperatures, etc.) calculated by the regional model. We may therefore be led to link a depression calculated by the regional model to an anticyclone calculated by the global model. To correct this error, we can extend the boundaries far outside the area under consideration.

The second method consists of using a model with a variable grid, which allows us to zoom in on the area of interest or, on the contrary, to use a restricted area to curb the complementary model. The implementation of such models is now possible thanks to the power of supercalculators. This latter method seems the most promising and is used by Météo-France with the Arpège-Climate model in its stretched grid version aimed at the region under consideration (Déqué et al, 1995). This numerical model, which arises from the operational meteorological forecasting model, covers the planet with a more detailed horizontal resolution (60 km) in France than in the South Pacific (450 km) as shown in figure 4. Figure 5 shows the average temperature anomalies in °C and precipitation in mm/days simulated for the end of the twenty-first century with the IPCC B2 scenario by the Arpège-Climate model in which the focal point is placed in the Mediterranean (between Italy and Sardinia). The regional impact of climatic change is illustrated for winter (December, January, February).

2.3 Improve the significance of the predicted variables

In relation to the forecasts currently available, progress is expected by users on the following points:

- the enlargement of the range of variables considered.

Even though temperature is obviously given priority treatment, and rainfall is already the subject of studies (which should, however, be deepened), it would appear necessary also to consider global solar radiation, as well as air humidity and wind speed, variables which affect agricultural and forestry production.

- for the various meteorological variables, it would be necessary to obtain information not only on the average values, but also on the extreme values (for example, for rainfall or wind speed) and exceeded threshold values (the case of frost or shrivelling).

- the duration of the period simulated using a climatic model subject to a defined scenario. If we consider the average zonal atmospheric response to the doubling of the concentration of CO_2, a simulation over a single year is sufficient. If we wish to consider the interannual variability of a parameter in the course of a season in a given region, a simulation over ten years is necessary. If we wish to study the variability of the precipitation regime, at least 30 years are necessary. To provide a concrete illustration of this thesis, we may consider that an average diminution in precipitation of 10% in the course of a single summer will not be too damaging to vegetation if it is regularly reproduced each year. But, if this average value of 10% corresponds to a diminution of 50% which may occur once every five years, the damage to the biosphere could be higher, or even irreversible. In studying the impact of climatic change on agriculture and forestry, it is therefore essential to have an extended series of simulated meteorological data. Thus, for example, Météo-France has put together a simulation of 140 years on the ARPEGE-Climate model using the IPCC B2 scenario. The data are available on a daily basis (or four times a day) for a large number of meteorological parameters. They are made available to agronomical research scientists who are going to study the impact of climatic changes on agriculture and above all on forests.

3- The production forecast

Climatic change may engender several kinds of impact on agriculture (Delecolle, 2000):

- on production, in terms of quantity, and also of quality, by taking account of the direct effect of the climate on crop productivity and also the indirect effect on diseases, insects, and weeds,

- on the various lines upstream via any modifications of the consumption of irrigation water, fertilisers, herbicides, and pesticides, and downstream if the quality of the products available and/or sold is modified,
- on the environment, particularly if the frequency and intensity of rainfall, combined with an increased use of nitrogen, mineral elements and pesticides leads to a leaching or a run-off of these substances.
- on the rural environment, according to which the climatic change forces the abandonment of certain species or the introduction of new ones, the modification of the land-use and the development of hydraulic constructions,

The integration of these various components represents the main challenge to the research to be done and coordinated in the near future.

3.1 The agronomical models

Various projects have already been carried out to evaluate the impact of the expected modifications. They generally incorporate the effect of the increase in CO_2 on photosynthetic production, in addition to the direct effect of modification of climatic factors (particularly temperature, radiation, rainfall). The expected effects are very variable depending on the species cultivated or the forest species, and the regions under consideration. They also depend on the climatic scenarios being used. A global increase in CO_2 generally leads to an elevation in crop productivity. This increase depends on carbon metabolism : it is more marked for C3 plants (like wheat) which are more frequent in temperate latitudes, than for C4 plants (like maize), which are more current in tropical agriculture. The increase in temperature has more variable consequences. Thus, if we forecast an increase in rice productivity in Northern countries in relation to the broadening of the period favourable to the crop, we forecast a fall in the productivity of this cereal in numerous countries in South-East Asia, particularly linked with the negative effect of high temperature induced spikelet sterility (Matthews et al., 1997). The current assessment of this work has been carried out in the context of the work of the IPCC but it remains partial.

In this text, we want emphasize the fact that there predictions must increasingly rely on crop simulation models that are likely to effectively combine the differentiated effects of CO_2 and the various variables of the climate on the physiological processes, whilst the empirical models based on statistics available in agrometeorology have been established in the context of implicit combinations between climatic variables which will again be called into question should a climatic change occur. To address this issue, the most sophisticated are the dynamic models which simulate and integrate specific mechanisms:

- the ecophysiology of the aerial parts of plants (development, aerial growth, elaboration of yield),
- the soil functions in interaction with the underground parts of plants (root growth, water uptake, nitrogen uptake, transfers),
- the management of the interactions between the cultural techniques and the soil-crop system, whether they concern the contribution of water, fertiliser or climate.

Integrating the accumulated knowledge in terms of the influence of climate, the soil, and cultural practices on production, these models can be provided with climatic data from the general circulation models. They should thus provide a production forecast per type of crop, but also of the quantities of water or fertilisers consumed, and allow us to test strategies for adapting to modifications in the environment. The results which can be deduced from this will have to be validated using increasingly numerous experimental results. Taking into account the indirect effects linked to disease or insects, as well as weeds, however, still remains to be achieved in numerous cases.

Numerous models exist around the world (Hoogenboom, 2000). Without wishing to be exhaustive, we can cite the families of CERES models (for maize, wheat, millet, sorghum, rice, etc.) and the CROPGRO models (for soya, peanuts, etc.). The CERES model has been used to quantify the consequences of climatic change in France on the production of wheat and maize (Delecolle et al, 1995).

STICS software (Brisson N. et al, 1998 – Brisson N. et al, 2002), perfected in France by a multidisciplinary team at the INRA (National Institute for Agronomic Research) with the collaboration of other research organisations and the agricultural profession is a multi-crop model. Coupling it with parameters from the soil database and the spatialised meteorological parameters (Pérarnaud, 1997, Ruget *et al*., 2001) thus enables the estimation of grass production in France.

The international community should be able to take advantage of the results of the research carried out in the context of crop modelling. However, the use of these models must be approached with caution, ensuring that certain input parameters (types of soil, meteorological data, etc.) are adapted to the local or regional conditions of use. Therefore, the retrospective evaluation of the models with series of observed data, together with their sensitivity and uncertainty analyses are essential steps to build up confidence in model predictions.

3.2 Spatial applications of crop models

Originally the crop simulation models were designed to operate on a homogenous plot of land. The use of these models to evaluate the impact of a climatic change on a regional scale (of production, water consumption, nutrient use etc) necessitates the use of specific techniques for spatial representation. It is essential to apply the model to a spatial unit defined according to use (simulation unit) and then aggregate the results (yield, quantity of water consumed by the crop, etc.) on the desired regional scale. This type of application necessitates a considerable volume of input data to understand the spatial and temporal variability of the studied parameter. The databases and geographical information systems (GIS) are essential tools in implementing such applications. However, it is appropriate to analyse the desired level of precision and therefore the possible level of simplification in terms of each layer of GIS information (soil, management practices, meteorological parameters, etc.). One of the greatest difficulties lies in taking account of the spatial heterogeneity of the soil, which is not always available in digital form and, might suffer from a lack of precision in terms of georeferencing. Moreover, the calculation of the different parameters of the soil water balance (like the available water), although estimated from the rules of pedotransfer, need improvement. In the Sudano-Sahelian region, agricultural productivity is closely linked to the variations of the climate and, more precisely, to the intensity and duration of periods of drought. Thus, to forecast the yield of millet in the Sahelian area, the precision applied to water stress is essential and is subject to particular attention both regarding the forecast of the volume and the spatial and temporal rainfall distribution, and regarding the plant's use of water. However, the other determinants of the crop production such as e.g the cultivar, sowing date, and plant density make forecasting more complex. The development of models which take account of these factors enables the evaluation of risks and technological scenarios in real time or for the future (Samba *et al*., 2001). We can then visualise, for example, delayed sowing in certain areas or identify areas which may suffer a production deficit. Figure 6a presents the divergence between the beginning of the 1998 season and the average for the years 1961 to 1990 in countries in the Sahelian area, which thus allows us to visualise early or late sowings in certain areas in relation to a reference year. The model may be used to forecast the yields of the current year by adjusting the historical date and the provisional climatic data in real time. To counter the lack of pluviometrical measurements on the ground, rainfall estimation methods using satellite imaging (Meteosat) are used. Figure 6b illustrates the differences in yield thus estimated (at the end of the growing season) between the current year and the average of the last thirty years. This device, illustrated here for short term forecasting, will also allow us to evaluate the adaptation of Sahelian agriculture to climatic change.

In studying the impact of a climatic change, it is necessary, on a daily basis, to use meteorological series (temperature, rainfall, potential evapotranspiration, global radiation) as input for the crop simulation models which come from a climatic simulation model at a regular point of reference with the finest spatial grid possible.

The use of crop simulation models (Hansen et al, 2000), which are not perfect, fed with spatialised information from diverse origins with varying degrees of uncertainty, leads to the propagation of errors which may distort the final results. It is therefore appropriate to carry out theoretical research to quantify these errors and try to minimise them.

4. The development of parasites, pests and weeds

In natural ecosystems, and also in cultivated or forest ecosystems, climatic change is capable of disturbing the balance between the species, whether they are plant and/or animal, both in terms of the individual and the population. These changes will also modify the development of weeds, diseases and parasites among the crops, as well as their area of distribution. The effect of climatic changes on the development of pests and diseases could manifest itself according to two main processes:

- a direct effect on the biological cycle of the parasites. In the event of climatic warming, certain thermophilic parasites would find even more favourable conditions in their current area of distribution and could extend this to as yet little affected areas where their hosts are present.
- an effect on host-parasite interaction and, more globally, on the complex interactions which exist in the trophic networks and which may modify the effectiveness of control using

biological agents. Climatic changes will modify the development of crops, and hence might affect the phenology or resistance of plants. The synchronisation between host and parasite could thus be markedly disrupted.

Several approaches are possible in trying to estimate the impact of climatic changes on plant diseases. Using climatic concordance models, similarities between the future climate in a given area and the current climate in another area can be used to forecast the sanitary risks by analogy. We can also establish predictions based on previously established empirical relations between the impact of parasites and climatic variables. But, faced with the complexity of the problem, it is much more efficient to use epidemiological models: epidemiological development is described in the form of a functional model where each biological process and its integration is linked to climatic parameters. The objective is then to couple these models to crop simulation models. However, the establishment of these models necessitates the acquisition of various observed data and knowledge acquired by experimenting on the disease. At the present time, very few of these models are available and it is absolutely essential that progress is made in this direction.

In the same vein, climatic changes will also be seen in a concomitant modification of weeds and their competition. The increase in the CO_2 content of the atmosphere, which favours the cycle of C3 plants in relation to that of C4 plants, may alter the balance between C3 and C4 plants in a mixed crop/weed population. These new competitors must also be subjected to specific research in the aim of providing additional modelling elements.

5. The roles of biodiversity

By exceeding the local species tolerance limits or altering the balance between these species, climatic changes are capable of having a major direct or indirect impact (fire, anthropic pressures) on the biodiversity of natural, and also cultivated, ecosystems. Conversely, it is possible that biodiversity constitutes a stability factor in the face of climatic change (Loreau et al., 2001). Understanding the dynamics between species therefore necessitates new functional ecophysiological and behavioural studies (for animals) but also the development of specific models which enable their simulation. On a practical level, the adoption in cultivated ecosystems of systems based on high levels of biological diversity (crop and cultivar diversity both inter- and intra-population, crop rotation and association, agroforestry, etc.) could constitute a response in the face of variability and climatic change.

6. Potential effects of climatic changes on the soil.

Future changes in the climate and the composition of the atmosphere will be shown in the evolution of thermal and rainfall regimes, the vegetation, land uses, all factors which have an effect on the soil and its dynamics. The soil is at the interface between the lithosphere, the atmosphere, the hydrosphere and living beings which it supports. In addition, because of its organic matter, it contains a major part of the biosphere's carbon. Any modification in soil agricultural practices or the vegetation ground cover may therefore have consequences for the global carbon cycle via their impact on the dynamics of the soil organic matter. Conversely, changes in the composition of the atmosphere may bring about changes in certain soil characteristics, particularly the organic reserve (C, N), nutritive elements and acidity, conditions of oxidoreduction, hydric and physical characteristics. Numerous questions remain unanswered and would benefit from research campaigns.

How will the organic reserves in the soil develop and at which rate? Will the soil behave like a sink (as is currently the case) or an additional source of CO_2 (particularly under the effect of the increase in respiration) and what, in return, will be the effect on the composition of the atmosphere? Changes in soil usage will also be important. They themselves put a question mark over ecosystems in a transitory state. Will there be synergic or antagonistic effects between changes of usage (which are determined largely by economic factors) and climatic changes, will there be any effects in return? In this respect, the example of rice is very illuminating: if, as we have seen, climatic change has effects on world rice production and its distribution (Horie et al., 2000), the production of rice on the planet may itself have a significant effect on climatic change, particularly through the emission of methane from flooded paddy fields (Reicosky et al., 2000). The hydric regimes, the properties of the soil, and the way crops are grown could significantly alter the fluxes of methane produced, according to mechanisms of which it is important to be aware.

To answer all of these questions, an understanding of the functioning of the current ecosystems is necessary. But faced with the transitory nature of the expected impact, only modelling will be able to provide information on the simultaneous consequences of changing agrosystems and ecosystems management practices.

7. The forests

The carbon balance of a forest ecosystem may be a net storage, as is the case in young forests in the growth cycle, but it may also represent a net carbon loss for certain, ageing or declining forests, or for those suffering the consequences of disruption (storms, fires, etc.) (Valentini et al , 2000). This balance is subject to major spatial and temporal variations. In addition to current forestry operations (soil preparation, drainage, fertilisation, clearings, etc.), it is sensitive to the stand age and climate (Chen et al., 1999). The respective role of these different factors, which all interact, is particularly difficult to elucidate. The short and long term impact of forestry is unfortunately often ignored, in spite of its obvious importance.

Differing approaches and methods of measurement are available to study the processes concerned and their respective role in the carbon content of an ecosystem on varying spatial scales: measurements of turbulent fluxes, measurements of stocks, calculations based on data from repeated inventories, etc.

Regarding the spatial scales under consideration, even though the recent possibilities of measuring the flows of carbon exchanged on the scale of ground cover allow us to correctly evaluate the methods of change of scale from leaf to ground cover, we have, on the other hand, a poor understanding of the link between the functioning of an ecosystem at the stand scale and the calculation of a stock of carbon and its variations at the regional or national levels. Calculations based on woodland inventories are currently the only possible and verifiable way of detecting and measuring variations in national stocks. However, the application of this approach is limited in terms of precision and reliability.

Despite the fact that these numbers are required in international protocols, we are only able to make a crude estimation of the changes in national stocks, and to quantify the respective impacts of land use changes, forestry and agronomical activities, indirect effects of human activities and non anthropogenic causes (e.g natural disturbances).

One of the main impacts of climatic changes will be to profoundly alter the potential ecological niche of species whose distribution is wholly or partly limited by climate. Such movements have already been observed for remarkable rare species which are clearly limited by climate. An awareness of these changes is particularly important in the field of forestry, where the species planted or naturally regenerated are done so for durations in the order of a century. The forestry choices made today are therefore crucial for the longevity of the forest in a changing climatic context.

Providing a long term assessment of the future of the functioning of forest ecosystems raises various questions on their vulnerability to biotic and abiotic stresses. This prediction supposes the use of meteorological data from a climatic model with high spatial resolution, together with data associated to the ecosystems under consideration (species, fertility, etc.).

Based on the regions and forest species of a national territory, the impact of climatic change on primary functioning, hydrology and the sequestration of carbon by the forest ecosystems may in practice concern various processes.

Amongst numerous studies devoted to the impact of climatic changes, very few concern the diseases of forest trees (Coakley et al., 1999, Chakraborty et al.,1998). However, parasites are major limiting factors for forestry production, in quantity and quality, and may affect the survival of a species, or even an entire ecosystem (Weste and Marks, 1987). It is even more essential to try to predict what the impact will be of global changes on the parasitic risk to the forest when the management of woodland parasites is essentially based on a preventive approach, as the recourse to curative methods of combating the problem is unrealistic and not actually desirable. Forecasting parasitic risks is one of the elements of reasoned forest management.

In terms of research, it is therefore important to:

- quantify the stocks and fluxes of carbon in the large forest ecosystems,
- simulate the future of the sequestration of carbon in these major forest types based on a climatic scenario with high spatial resolution,
- inventory the various forestry practices which have a significant impact on the stocks and fluxes of carbon and estimate the impact of various forestry options on the sequestration of carbon in these ecosystems and their harvested products,
- assess the vulnerability of woodland species to allow alternative proposals to be made: replacement of species, fire prevention methods, etc.

8. Towards new cropping systems ?

Agriculture in the twenty-first century will have to make its contribution to the reduction of GHG emissions (principally CO_2, CH_4, N_2O) but also and above all to adapt to climatic changes to continue to satisfy the vital needs of populations in food, energy, fibres, etc. The end results and priorities will depend on the regions of the Earth concerned and it is clear that, though the development of the territory and the global reduction of agriculture contribution in the production of GHG will be a priority for the countries in the North, numerous countries in the South will still have the problem – and for some with increased intensity - of the absolute necessity of producing various food products for local and remote consumption. This general context, of course, relates back to a world economic and legal situation, but it also involves specific research efforts in the development of sustainable systems, mobilising agronomists and agrometeorologists alike. Concerning the reduction of GHG emission and the storage of carbon in the ecosystems, the necessity for research on the measurement of these emissions and storage has already been mentioned. It must be carried out for the existing ecosystems but also to evaluate the new systems proposed. For several years, reduce tillage techniques are combined with the use of mulches and ground cover plants (no tillage techniques, conservation agriculture) are undergoing a major development in various parts of the world (Brazil, United States, Canada for example) and may enable an increase in soil carbon storage and a reduction of erosion. However, the global assessment vis à vis GHG still remains to be made, as well as the sustainability capacity of these systems different contexts. In the same way, the development of agroforestry systems may contribute to an increase of the quantity of C fixed in the soils and the biomass, a reduction of the quantity of fossil fuel used for soil tillage operations, a reduction in the use of pesticides and also a stabilisation of the ecosystem thus cultivated in the face of climatic variability. It is, however, often difficult to persuade farmers to adopt these often promising solutions for various economic or social reasons. It is therefore important to use integrated approaches, which take into account the farmers' decision-making process, to design operational systems (Boiffin et al., 2001). Moreover, the development of innovative systems in response to these many criteria necessarily combines experimentation on the ground and complex models with varied but coupled processes: for example, the construction of models capable of simulating the response of flooded rice-production systems to climatic change would involve not only taking into account the modification of CO_2 content and temperature (and their interactions) on all physiological processes (photosynthesis, transpiration, phenology, ripening, etc.) but also the effect of changes in practices (sowing date, density, varietal choice, fertilisation, management of groundwater), on the elaboration of yield and the emission of GHG (here CH_4).

9. Conclusions and recommendations

The adaptation of agriculture and forestry to the climate of the twenty-first century supposes that major research efforts will be made. The complexity of the problem necessitates cooperation between research scientists in various disciplines: meteorologists, agronomists, pedologists, hydrologists, modellers, etc. This cooperation, which has to be international, must produce immediately useable results to respond to the questions of the developing countries. Indeed, though all regions of the world are different because of their climates, their soils, their water resources, the methods of using and managing the land, they are also different because of their vulnerability to climatic change. In this respect, an increased sensitivity appears in the countries of the South. It is therefore becoming important that we rapidly identify the gaps in our knowledge and initiate research aimed at increasing the adaptability of agriculture in the face of climatic change. This research will aim both to increase our forecasting capacity and to anticipate the design of new cropping and forestry systems. It is also essential to deepen our expertise to orient and evaluate international negotiations in a critical manner, both in terms of quantifying stocks and forecasting impact. We must come up with calculations of sequestration potential of the various sources of carbon (soil, biomass, etc.), the forest ecosystems and their behaviour in response to various management options and climatic change.

The interactions between climatic changes, on the one hand, and agriculture and forestry, on the other, are numerous. Whatever technical progress is implemented, agricultural and forestry activities remain primarily dependent on fluctuations in the climate; they contribute, for their part, to the modification of the gaseous balance of the biosphere, whether directly or indirectly, through, for example, the emission of certain greenhouse gases, through damage to the soil or deforestation, for example. Today, the international community is adding scientific and technical issues to the debate, the adoption of political and economic measures by virtue of which countries will be required to adopt new practices and new laws aimed at controlling climatic change, which will have an influence on agriculture and the forests.

But, in the first instance, it is appropriate to achieve a better understanding of the variability of the current climate and its impact on agriculture. This involves the study of extended series of homogenised meteorological data, and the analysis of ecosystems and their evolution. The most advanced models, which allow us to simulate the climate of the future, are based on general circulation models. Even though considerable progress has been made in this field in the course of the last decade, it is essential today to specify the behaviour of the hydrological cycle, taking account of the alteration of the continental land masses and the interactions of ocean and atmosphere.

Climatic change may generate several types of impact on agriculture, on production, the consumption of irrigation water, fertilisers, herbicides, and pesticides, on the environment and on rural areas generally. This impact is of varied complexity, and the systematic recourse to crop simulation models (which integrate the effects of pests and weeds) appears to be the only way possible, on condition that major efforts are devoted to validating them. These models must also evolve in order to produce environmental output, which enables the simultaneous simulating of the effect of production on the environment associated with production forecasts, taking account of both the GHG levels and the impact on surface radiative and energetic levels.

Finally, the use of spatial sensors must become systematic, both for long term monitoring and through their capacity for measuring and mapping certain variables (global radiation, photosynthetically active radiation, surface temperature, soil moisture, etc.). The contribution of satellite remote sensing information appears to be an essential complement to the development of crop models and the research underway, which allows the assimilation of remote sensing data (as this is already practised in short and medium term meteorological forecasting or hydrological forecasting), ought also to make a contribution of the first order to the progress which is necessary.

It is also essential to make progress in spatialisation and aggregation techniques to quantify the propagation of errors arising from the uncertainties linked to the coupling of information and to minimise them.

The prognosis for the development of the storage of carbon in the ecosystems in a changing climate and context also constitutes a scientific challenge which refers back to the understanding of the cycle of this element and the behaviour of the ecosystems concerned.

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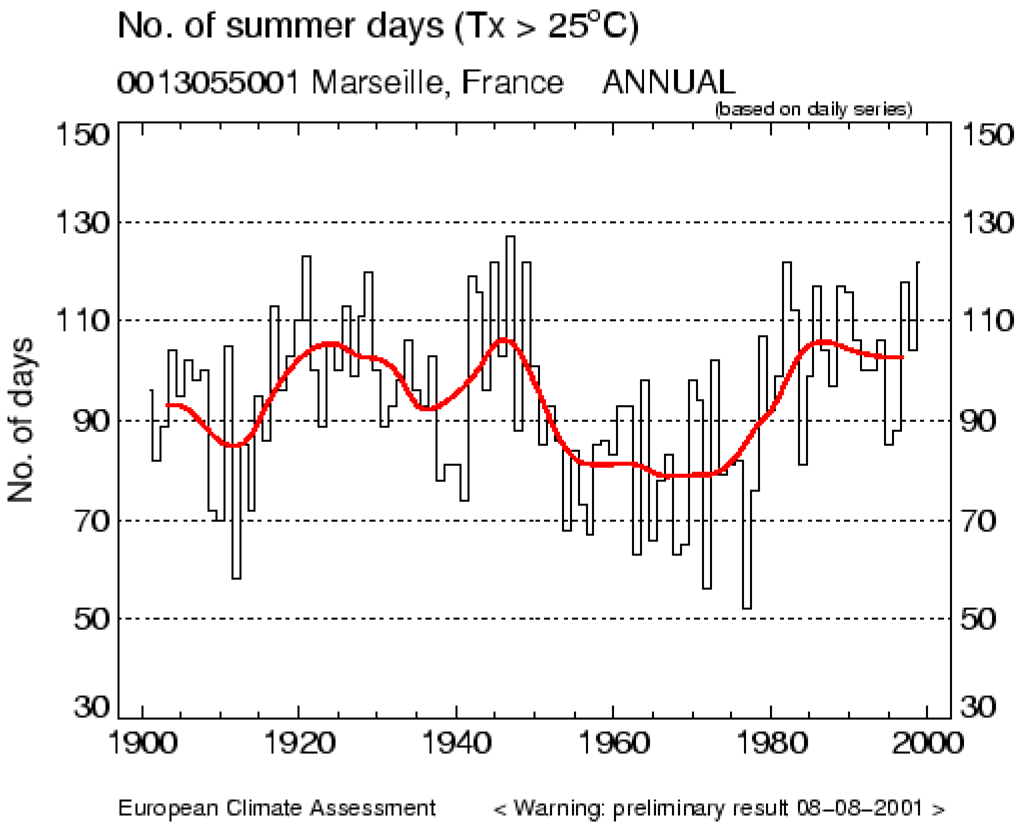
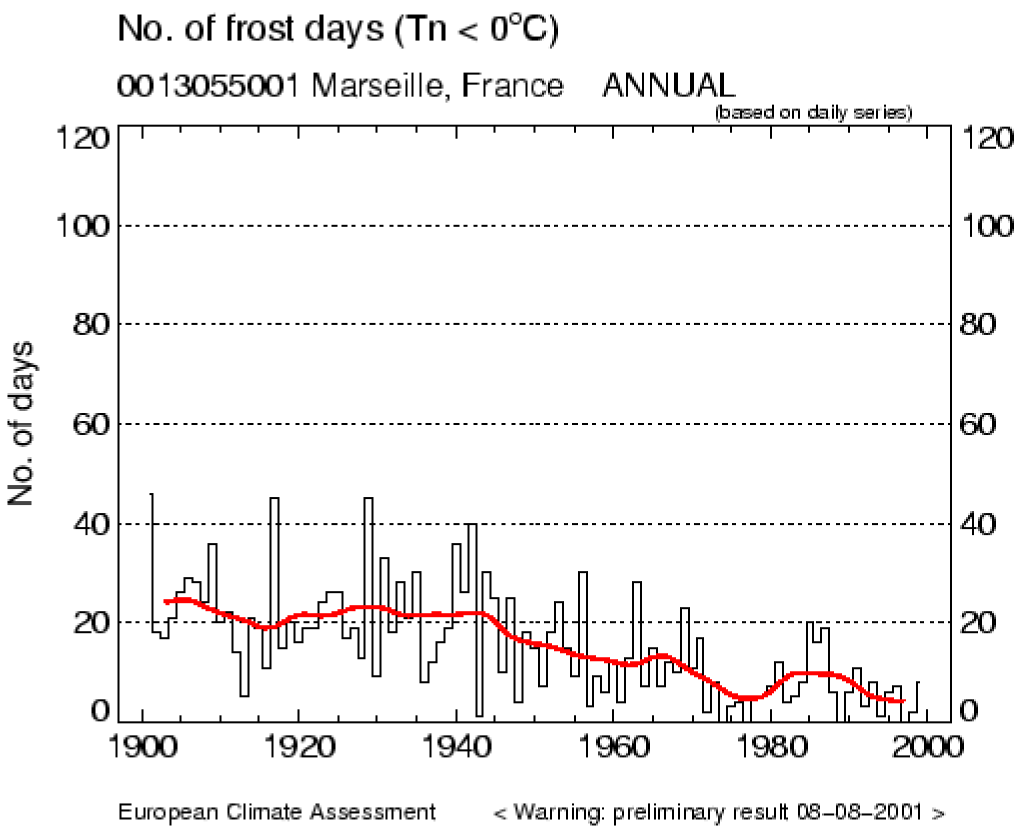
Figure 1: Annual number of days with frosts and heat waves observed over the period 1901-2000 at the weather station in Marseilles (France).





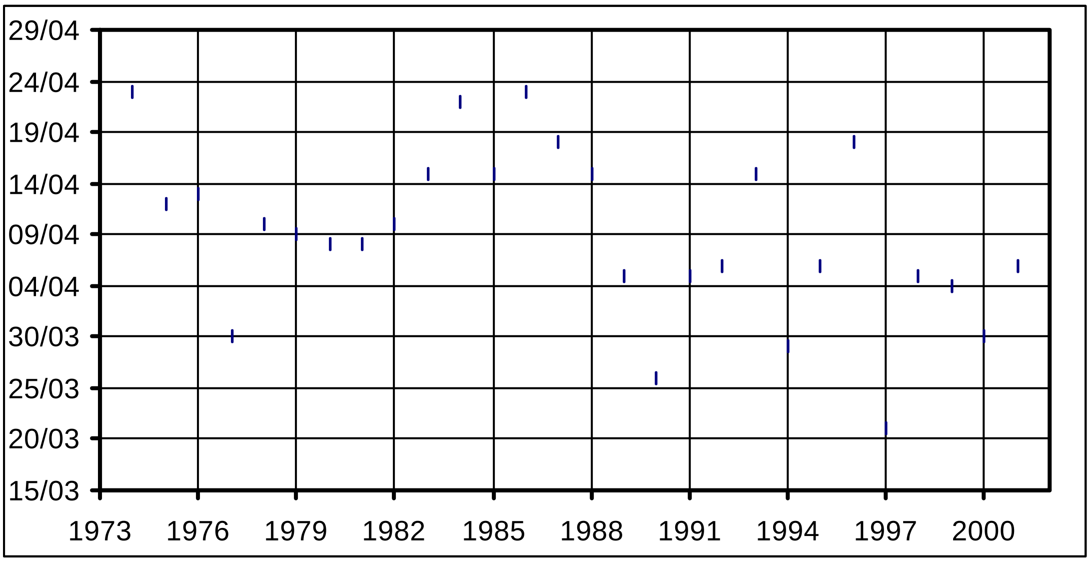


Figure 2: Flowering dates (stage F1) of the apple tree in south-west France (Balandran) over the period 1974-2001 (according to Domergue 2001)

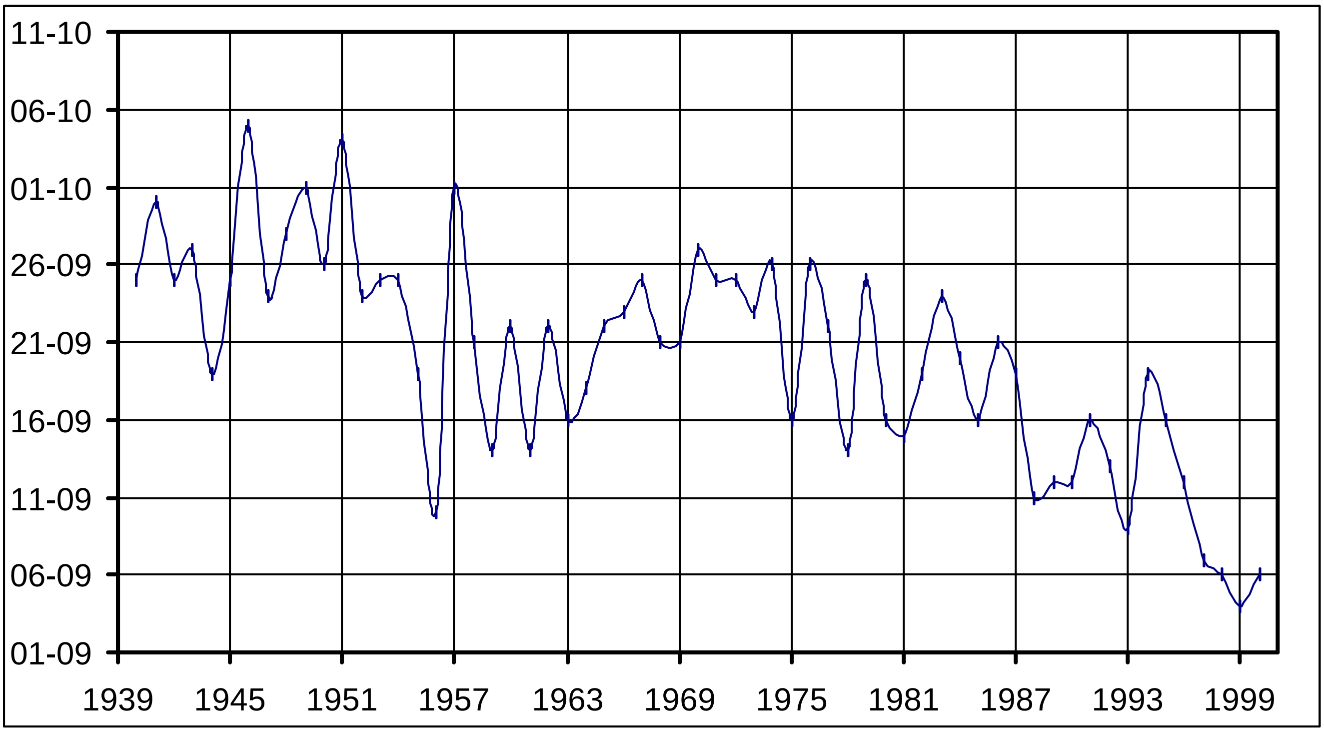


Figure 3: Dates of the beginning of the grape harvest in Chateauneuf du Pape (South of France) (according to Ganichot 2002)

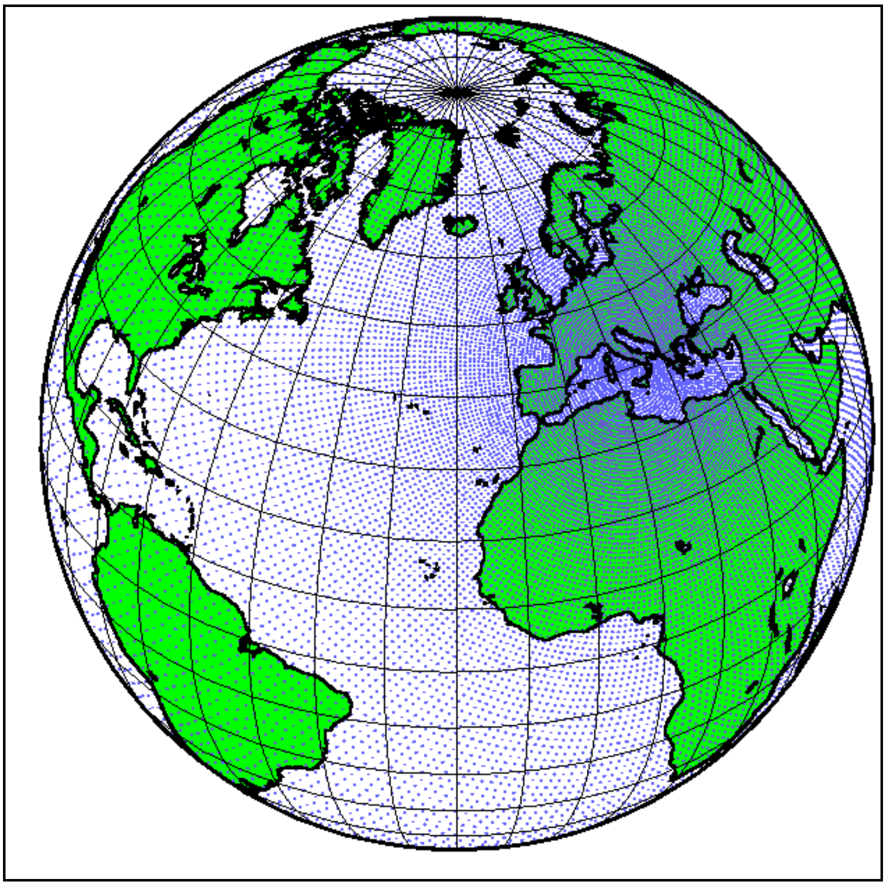
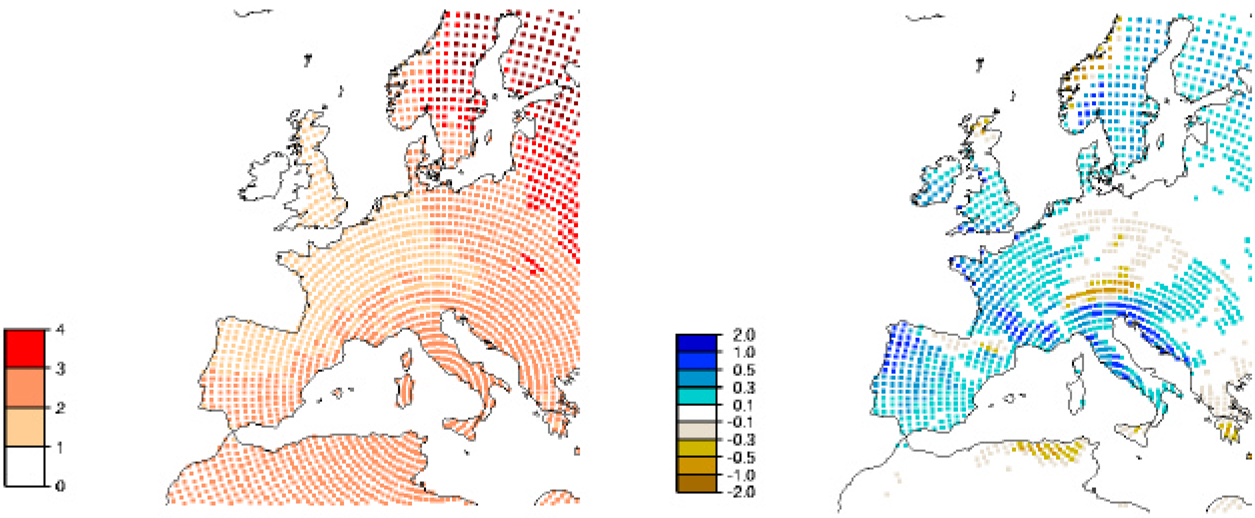


Figure 4: Horizontal grid of the Arpège-Climate model in which the focal point is placed in the Mediterranean (between Italy and Sardinia).

Figure 5: Anomalies in average temperature (on the left in °C) and precipitation (on the right in mm/days) forecasts for the end of the twenty-first century using the GIEC B2 scenario and the Arpège-Climate model in the stretched / aimed version. The focal point is placed in the Mediterranean between Italy and Sardinia. The regional impact of climatic change is illustrated for the winter (December, January, February).



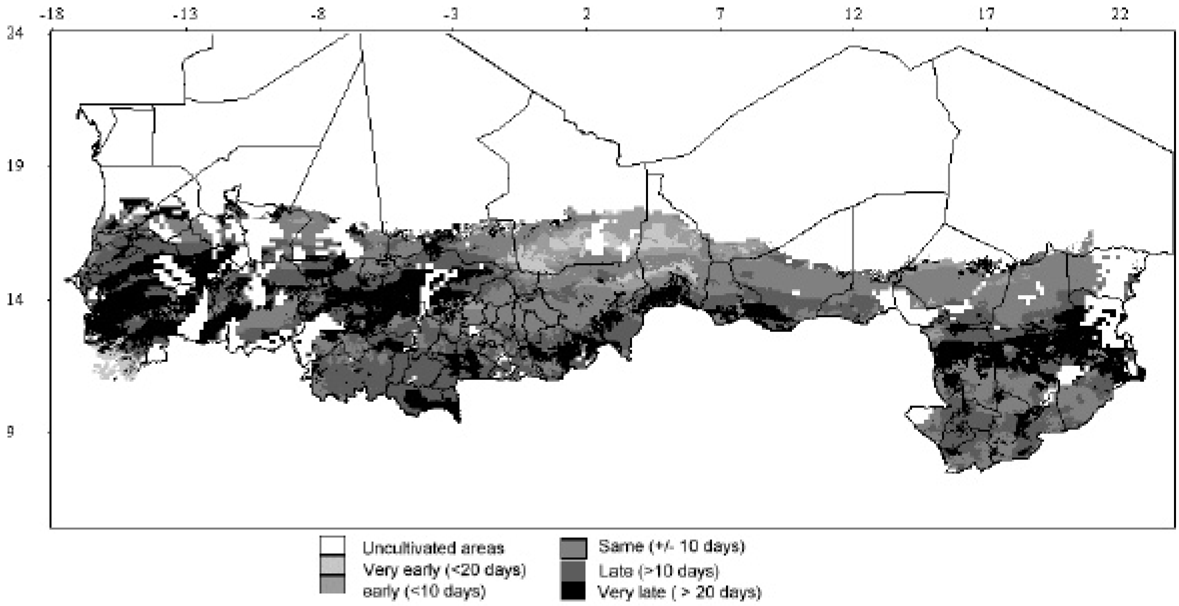


Figure 6a : A map of millet successful sowing dates differences between 1998 and an average 1961-1990 (from Samba et al., 2001)

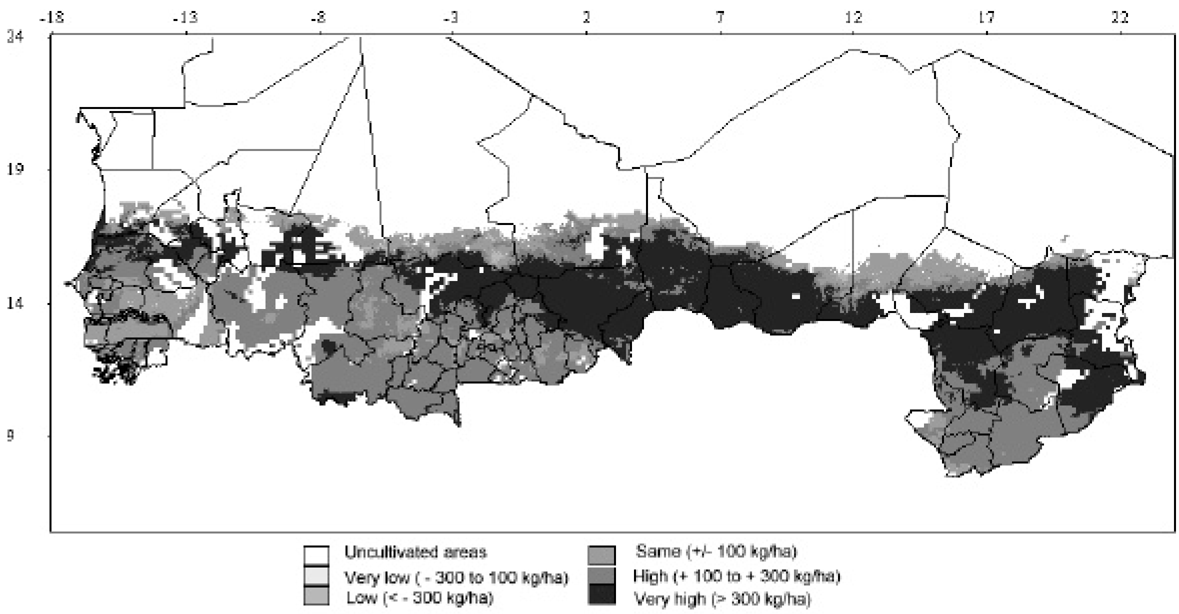


Figure 6b : A map of millet yields differences between 1998 and an average 1961-1990 (from Samba et al., 2001)