



## Climate change in the Centre-North zone: a survey of the agricultural impacts

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# D

## *The regions*



# The regions

# D

**T**his part describes, for seven geographical zones, the main results obtained on the most symbolic crops in these zones, thus offering a territorial approach to the agricultural and forestry impacts of climate change.

- **D1 - Geoclimate**

- **D2 - Centre-North**

Centre/Champagne-Ardenne/Île-de-France /  
Nord-Pas-de-Calais/Haute-Normandie/Picardie

- **D3 - West**

Bretagne/Basse-Normandie/Pays de la Loire

- **D4 - North-East**

Alsace/Bourgogne/Franche-Comté/Lorraine

- **D5 - Centre-East**

Auvergne/Limousin/Rhône-Alpes

- **D6 - South-West**

Aquitaine/Midi-Pyrénées/Poitou-Charentes

- **D7 - South-East**

Languedoc-Roussillon/Provence-Alpes-Côte-d'Azur

- **D8 - West Indies**

Guadeloupe/Martinique

The geographical zones were created by trying to group together administrative regions into agriculturally and climatically uniform regions.

The results come from one to three sites in each geographical zone, so that they are illustrative rather than strictly representative spatially.





# Potential for geographical displacement of crops and forest species

Éric Lebon, Vincent Badeau

## A Introduction

Geographical displacement of crops constitutes the “ultimate” adaptation\* strategy for agricultural and forestry production systems to climate change\*. It could provide the answer to major changes in regional climates. Its socio-economic and environmental impact\* will be important, but one can expect large regional differences according to the level of specialisation and the characteristics of the dominant production industries.

The objective of this section is to present the expected scale of these displacements through the study of the impact of climate change on a choice of industries representative of the diversity of plant production, and to draw attention to some features of each main type of production.

This section continues, in some respects, the ADVANTAGES and VULNERABILITIES section (but without considering the notion of yield\* in its economic sense, and without going into physiological details), as well as part of the information in the CROPS sections.

## B Concepts, mechanisms and variables used

Our approach is based on an analysis of the factors limiting production (feasibility\*, crop yield and/or product quality) for low-lying areas, i.e. not taking account of the relief, which may be decisive for certain crops (vines for example). Regarding temperature, the expected increase will affect the phenology\* of the crops, with the expected consequences of a change (i) in the length of the growing season, (ii) in the duration of the developmental\* phases, (iii) in the temperature indices which express certain physiological features. As to water, the reduction in rainfall and the increase in evaporative demand\* will be responsible for an increase in the intensity of water stresses\* (cf. WATER section). These mechanisms are analysed by way of classic agroclimatic indicators expressing the temperature requirements (cf. TIMING section), the degree of satisfaction of water requirements (cf. WATER section) and the temperatures experienced during certain critical phases of crop growth\*. Finally, the analysis may consider the direct or indirect effects of CO<sub>2</sub> concentrations (cf. FOREST section).

## C Displacements of cropping systems\*: what can we expect?

A first analysis of the results of our simulations reveals a varied picture depending on the crops and their growth patterns. For the majority of production systems, the present growing regions should be retained, thanks to the use of varieties able to reposition the growth cycle and/or the adaptation of cultural practices and the choice of soil type. On the other hand, for certain systems such as annual summer crops and perennial crops, the question of geographical displacement clearly arises.



## Systems whose spatial distribution will hardly be affected

These systems are for crops for which the elaboration of yield components takes place in spring or autumn, such as winter crops or forage crops. The harmful effects of climate change during the summer period are balanced by a lengthening of the growing period in spring and/or autumn.

In the case of wheat production, the simulations carried out suggest a maintenance or even an increase in the feasibility of growing the crop and of the yields over virtually the whole country. The scenarios (emission scenarios and downscaling\* methods) with which we worked do not seem to cast doubt on the present geographical distribution of the growing regions. We note, moreover, that the wheat crop could make use of the soils near the west coast which are subject to waterlogging.

In the case of forage crops, climate change could at best lead to a yield increase of 5-20% because of a lengthening of the growing period into spring and autumn. This increase would be larger for fescue in the east than in the west or south, where the gradual decline in rainfall will result in an increasing summer water deficit.

The sunflower crop will still be able to be grown at all the sites\* studied, with yields tending to increase and a possible return of long-term varieties in the north and east regions. There will be no problems with its cultivation in the southern regions.

## Systems whose distribution will be severely affected

This group includes systems as different as maize-growing, wine-growing and forest production, for which summer climatic conditions are decisive to yield, quality, and indeed the long-term survival of the crop (forest).

### Annual crops: the example of maize

Maize growing, in its present geographical distribution, should be greatly affected by climate change. This will cause, firstly, significant yield loss due to the shortening of the growth cycle ( $1\text{ t ha}^{-1}$  in the NF\*) and secondly, increased water requirements (about 50mm on average in the NF). To cope with this, a relocation of this crop towards the north of France, where temperatures will become increasingly favourable, and the adoption of long-term varieties should enable yields to be maintained or even increased, provided that there is enough water. This strategy could compensate for the use of short-term varieties, which need less water, in the south-west.

### Perennial crops

For woody perennial species, as for other crops, climate change will mean moving the production zones further north. These systems are nevertheless constrained:

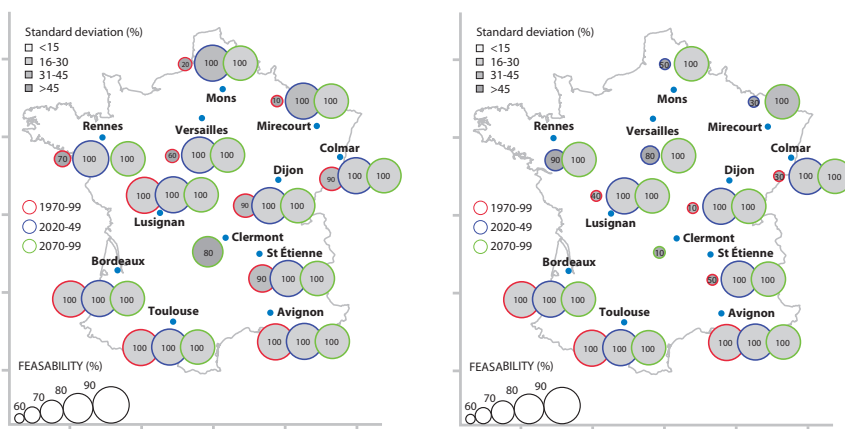
- firstly, by independent strictly production factors such as a strong regional specialisation (production facilities, know-how, cultural associations, landscapes and "terroir"\*) and the need to guarantee services which are not directly commercial (maintenance of biodiversity, regulation and purification of water, protection of soils, fire control, regional climate regulation, recreation etc.);
- secondly, by the need to plan further ahead than for annual crops (ca. 30-year rotations\* for vines, ca. 100 years for forests).



## Example of the vine

The form of the models used in the project does not take account of slopes. Consequently the results presented here should be modified for hilly wine-growing regions. Also, the level of feasibility calculated in this study for the recent past may differ markedly from that actually observed. This is particularly the case of vineyards situated at the northern limit of the growing region, for which the reference weather station used, situated outside the wine-growing area, cannot take account of localised climatic effects associated with the topography of the vineyard.

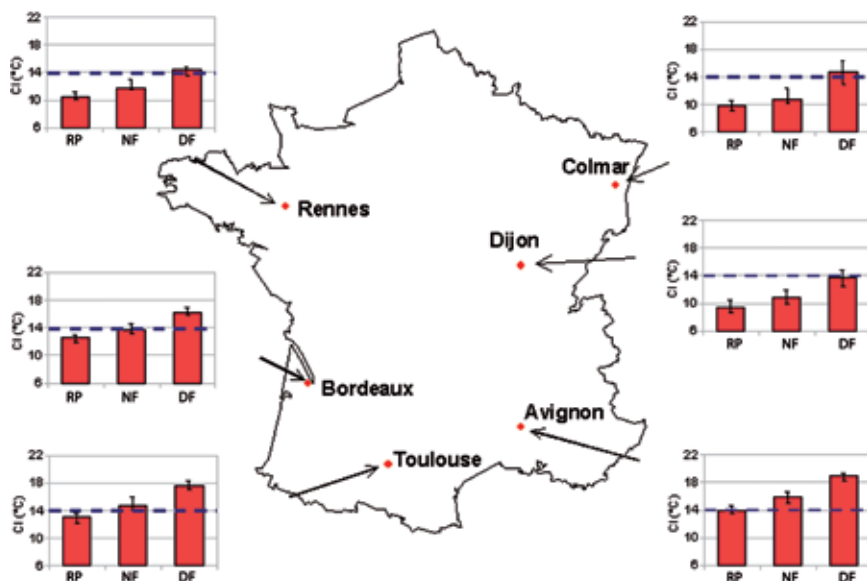
The vine is a crop which presents very strong regional peculiarities (e.g. production methods, type of product) associated with the soil and climatic characteristics (the “terroir”\*) of each zone. The most striking fact revealed by the study is a major change in the distribution of potential production zones due to the generally rising temperatures (fig. 1). This phenomenon is manifested for the NF by an increase in the feasibility indicator, which becomes > 80% in the regions traditionally situated near the northern limit of production (Dijon, Colmar) and a possible extension of viticulture towards the more northerly stations (Rennes, Versailles, Mons et Mirecourt) in the DF\*.



**Figure 1:** feasibility of growing an early grape variety (Chardonnay, left) and a later Mediterranean one (Grenache noir, right) for the periods RP (red), NF blue) and DF (green). STICS model, WT downscaling method.

This possible temperature increase will also lead to a change in the geographical distribution of the varieties traditionally associated with well-defined production zones (AOC). The simulations carried out show that growing Chardonnay, an early variety, will become possible at all the stations studied in the distant future, while a Mediterranean variety like Grenache noir will be able to be grown up to the present northern limit of vine-growing (fig. 1). Besides the new “thermal boundaries”, the zones actually cultivated will be determined by other considerations, such as the physical properties of the soils, which affect the quality and typicality of the wines.

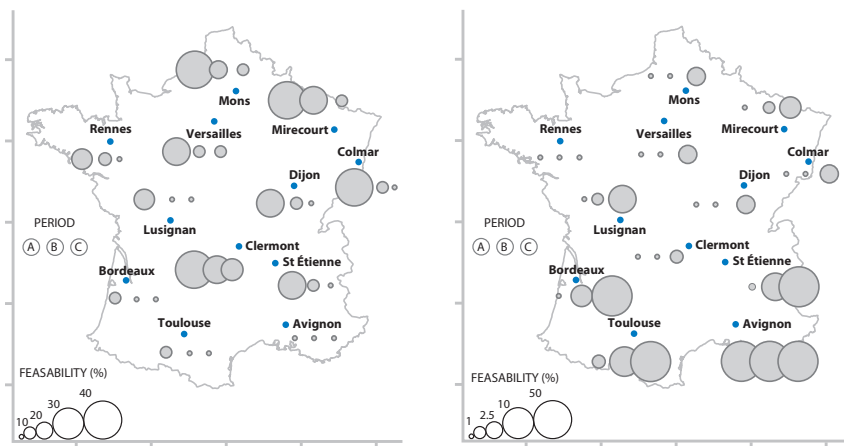
The increase in night temperatures during the maturation period in the southern regions could constitute a limitation to the maintenance of the quality potential in these regions. Mean minimum temperatures during the month of September (the night coolness index) above a threshold of about 14°C would limit the accumulation of phenolic and aromatic compounds in the grape berry (Tonietto and Carbonneau, 2004). The simulations of this index made for the wine-growing sites for the periods RP, NF and DF show that this threshold value is exceeded for the NF period at Avignon and for the DF period at Bordeaux, Toulouse and Avignon (fig. 2). This last site, representative of the Mediterranean zone, reaches values of the night coolness index above 18°C, which is close to the temperatures observed now in the hottest wine-growing areas, such as Malaga in Spain and Haifa in Israel.



**Figure 2:** change in the night coolness index (CI) (Tonietto and Carbonneau, 2004) at wine-growing sites for the three periods: recent past (RP), near future (NF) and distant future (DF). The broken horizontal line indicates the threshold of the CI, above which the accumulation of phenolic and aromatic compounds is limited. QQ downscaling method.

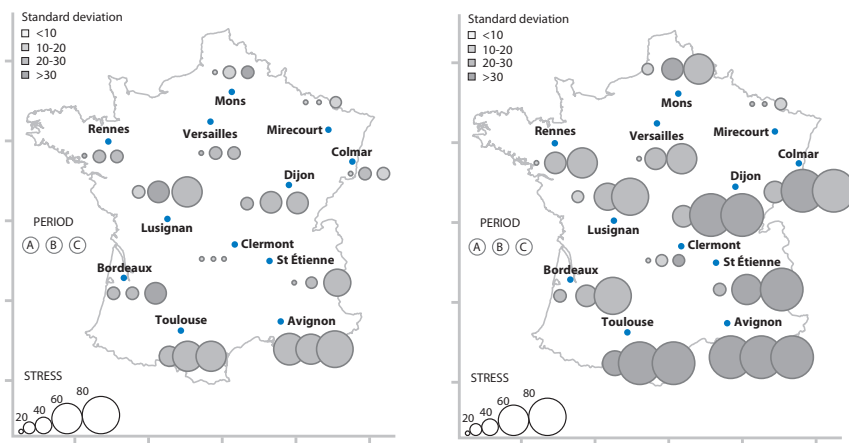
## Example of forests

The simulations carried out show, when averaged over all scenarios and downscaling methods, (i) an increase in water stress in the near future; (ii) a fall in the potential yield of the maritime pine over the 12 sites and (iii) a big change in the potential distribution of species. These results agree about the likely northward spread of Mediterranean and Aquitainian climates at the expense of oceanic, continental and mountainous influences. These trends modify the boundary of the potential areas of distribution of species. As an example, the beech tends to retreat from its southern and western limits, and then generally (fig. 3a), whereas conversely the holm oak could spread into the northern half of France in the distant future (fig. 3b).



**Figure 3:** potential presence of the beech (left) and the holm oak (right) for the periods (A) RP, (B) NF and (C) DF. WT downscaling method; the soil type is not considered.

Regardless of the available water reserve\*, canopy type or climatic projection, we see a decline in the water balance of forests: the water stress, which directly influences the yields and health of the forest, increases in duration and intensity. This change is particularly clear for coniferous forests for the NF period (cf. FOREST section).



**Figure 4:** change in water stress for a deciduous forest (left) and a coniferous forest (right) for the periods (A) RP, (B) NF and (C) DF. WT downscaling method; the same leaf area index\*. The common soil (with high AWR).





## What you need to remember

- ✓ The greater versatility of arable crops should lead to landscapes which are relatively unaltered over the whole country, except for irrigated summer crops like maize, which should probably be relocated in accordance with the available water resources.
- ✓ The distribution of long-rotation systems, such as vines and forests, on the other hand, could be profoundly altered. Changes in varieties and cultural practices should enable the gradual adaptation of most traditional vineyards, at the cost of a major change in the characteristics of the wines produced. Meanwhile new regions situated outside the present wine-growing boundary could become favourable to the production of quality wines.
- ✓ The forests will probably remain as forest because most of them are situated on land unsuitable for agriculture, the soils being very acid or chalky, stony, waterlogged etc., but it is not impossible that the continued expansion of forested areas since 1830 might cease, or be replaced by a fall. (The latest figures from the TERRUTI survey suggest this). The species composition of the forests may change, however, but in a direction which at present is quite difficult to predict. Perhaps we shall see more mixed forest, in order to buffer the possible effects of climate change and extreme events; on the other hand we may see forests with more specific aims, such as short-rotation coppices for biomass, or the development of the use of species which currently are marginal outside their present areas of distribution, such as maritime or Aleppo pine, or even cedar. These changes will undoubtedly be lengthy, gradual and cautiously executed, as they would be costly and hardly reversible, given the lifespan of tree stands.



## What needs further study ...

- ✓ One can envisage the introduction of new production systems like, for example, citrus fruit, into the most southerly regions.
- ✓ In the case of forests, the use of introduced species or from sources hitherto hardly used can be envisaged as a substitute for the forests which are most vulnerable to soil drying. The acquisition of knowledge on the identification of characters or traits which confer an adaptive advantage (phenology, drought resistance, etc.) or on epigenetic phenomena or even on the effects of intra- or inter-population variability on their vulnerability to climate change and to extreme events, could modify the distribution of forest species.
- ✓ For most crops (including vines), irrigation can be considered. This is not the case for forests. The uncertainty concerning forest canopies is thus totally dependent on the uncertainty about rainfall.
- ✓ The change in the farming landscape will be constrained by economic considerations and profitability levels. In the particular case of forests, however, the change in landscapes, species and types of management will be subject to society's demand for forest, the speed of migration of species (which will not be concomitant with the climate change), episodes of withering or even death due to extreme events\* and their recurrence (droughts, heatwaves, storms).

## To find out more ...

Badeau V., Dupouey J.-L., Cluzeau C., Drapier J., Le Bas C., 2010 - Climate change and the biogeography of French tree species: first results and perspectives. In *Forest, Carbon Cycle and Climate Change*, Denis Loustau (Ed.), QUAE, ISBN 978-2-7592-0384-0, 231-252.

Jones G., White M.A., Cooper O.R., Storchmann K., 2005 - Climate change and global wine quality. *Climatic Change*, 73: 319–343.

Poisson S., 2009. - Caractérisation des climats à venir, spatialisation sur le territoire français métropolitain et application à l'agronomie. In *Compte-rendu du colloque ACTA*. 22/10/2009 : 59-69.

Tonietto J., Carbonneau A., 2004 - A multicriteria climatic classification system for grape-growing regions worldwide. *Agricultural and Forest Meteorology*, 124: 81-97.





# Climate change in the Centre-North zone: a survey of the agricultural impacts

Frédéric Levrault, Marie-Odile Bancal,  
Nadine Brisson, Philippe Pieri

Regions concerned:

- **Centre**
- **Champagne-Ardenne**
- **Haute-Normandie**
- **Île-de-France**
- **Nord-Pas-de-Calais**
- **Picardie**



Study sites: Mons, Versailles



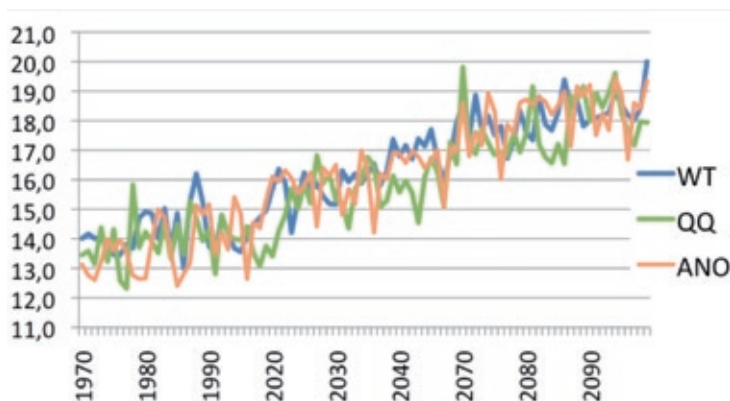
Land use	Area (ha)	% of TA	Usable agricultural area	Area (ha)	% of TA
Total area (TA)	12 152 281		Farms	7 454 287	
Woods and forests	2 509 639	0.21	Arable land	6 291 706	0.84
Total UAA	7 607 851	0.63	Permanent grassland	1 080 634	0.14
Other	2 034 791	0.17	Permanent crops	73 197	0.01

*A clear decline in rainfall, a significant increase in wheat yield in the NF and the DF, stagnation of rape yields, significant increase in maize yields accompanied by an increase in water requirements from the NF, viticulture becoming feasible from the middle of the century in the centre and north of the zone: these are the main trends revealed for the Centre-North zone.*

## A Some striking facts about climate change\* in the Centre-North zone\*

### Temperature

The mean annual temperature at the two sites\* in the Centre-North zone increases in a similar way to all the 12 sites studied: by 1.4°C at Mons and 1.5°C at Versailles between the RP\* and the NF\* and by 2.8°C at Mons and 2.9°C at Versailles between the RP and the DF\*. Hence, in the NF, the mean annual temperature at Mons (13.4°C) exceeds that of Lusignan in the RP (13.0°C). In the DF the mean annual temperature at Mons (14.8°C) exceeds that of Bordeaux in the RP (12.9°C). For the Centre-North zone, an important consequence of this warming for cultivated species is the increase in heat availability\* which will allow crops with high temperature requirements (sunflower, for example) to be grown. Very high temperatures will occur less often than in the south. We note, however, that between April and June, the mean number of heat stress days\* at Versailles increases markedly in the second half of the 21<sup>st</sup> century: from 7 days in the RP, it becomes 10 days in the NF and 19 in the DF.



**Figure 1:** change in mean annual temperature (°C), from 1970 to 2100, at Versailles. A1B scenario\*. Downscaling methods\*: ANO\*, WT\* and QQ\*.

### Precipitation and evapotranspiration

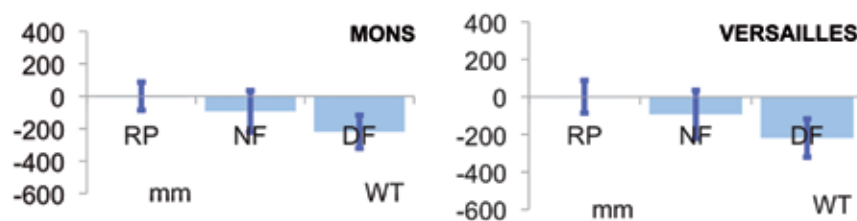
In the RP, a fairly clear contrast is observed between Versailles (620mm annual total) and Mons (876mm). In the NF each of the two sites experiences the same fall in total annual precipitation (73mm compared with the RP), which maintains the difference observed in the RP. At this date Versailles is the driest of the 12 sites studied, with 547mm as an annual total, i.e. 40mm less than Toulouse for the same period. In the DF, the drying continues, more clearly in the north of the zone, with a fall in the annual total of 109mm at Versailles and 183mm at Mons. At this second date, Versailles is the second driest of the 12 sites studied, with 511mm annual total. Compared with present conditions, the lower autumn rainfall will lead to more days available\* for autumn operations.

A noticeable increase in the potential evapotranspiration ( $ET_0$ ) is seen at Mons and Versailles, whichever downscaling method is used. The increases in the annual total (30-year means) are as follows:

- at Mons, from 60 to 75mm between the RP and the NF and from 145 to 170mm between the RP and the DF;
- at Versailles, around 60mm between RP and the NF and from 120 to 145mm between the RP and the DF.

As a mean of the WT and QQ methods, this represents a mean increase of 0.4mm/day between the RP and the DF. We have not studied the seasonal distribution of this increase, but the periods of high evaporative demand (spring and summer) will account for a large fraction of these increases.

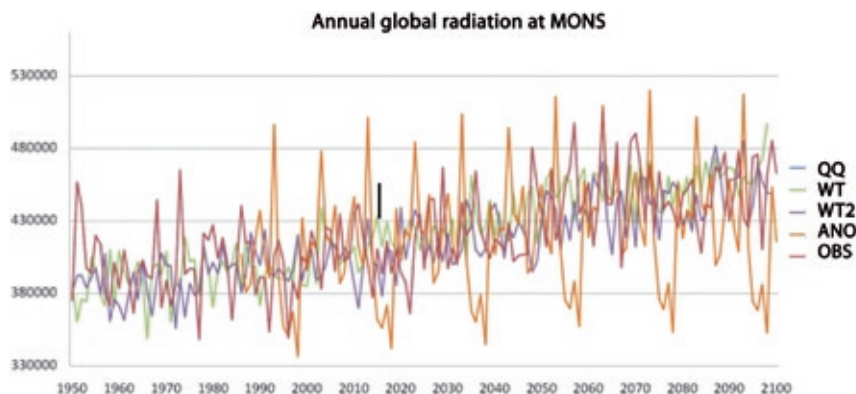
The concomitance of the decline in rainfall and the increase in evapotranspiration will lead (fig. 2) to a marked increase in the annual water deficit.



**Figure 2:** annual climatic water deficit (rainfall –  $ET_0$ ) in the RP, the NF and the DF at Mons (left) and at Versailles (right). ARPEGE AIB. WT downscaling method. The  $ET_0$  was calculated without the correction for  $CO_2$  (cf. MODELS section).

## Global radiation

At Versailles we see a gradual increase in global radiation until 2100. In the RP the mean annual global radiation was 397 000 (QQ method) to 401 000 (WT method) J/cm<sup>2</sup>/yr, which represents a mean of slightly less than 1100J/cm<sup>2</sup>/day. In the DF the mean annual global radiation is 432 000 (QQ method) to 457 000 (WT method) J/cm<sup>2</sup>/yr, or just under 1 220J/cm<sup>2</sup>/day. This radiation “supplement” of 120J/cm<sup>2</sup>/day explains the significant increase in the potential evapotranspiration (ET<sub>0</sub>). At Mons in the RP, the mean annual global radiation is 395 000 (WT method) to 399 000 (QQ method) J/cm<sup>2</sup>/yr. In the DF it is 433 000 (QQ method) to 457 000 (WT method) J/cm<sup>2</sup>/yr, which represents a mean radiation increase of more than 130J/cm<sup>2</sup>/day.



**Figure 3:** change in total annual global radiation (J/cm<sup>2</sup>/yr) from 1950 to 2100, at Versailles. ARPÈGE A1B. Standard downscaling methods: ANO, WT and QQ, to which was added the WT2 method (cf. CLIMATE section) and the data observed for the RP.

### A reminder of current agricultural production in the Centre-North zone (Source Agreste)

Crops	Area (ha)	% UAA	Yield t/h
Soft wheat	2 381 316	0.32	75
Oilseed rape	626 864	0.08	32
Grain and seed maize	285 845	0.04	90
Grass leys	273 197	0.04	87
Forage and silage maize	237 463	0.03	133
Sunflower	99 163	0.01	25
Durum wheat	70 093	0.01	62
Vines	54 423	0.01	104
Sorghum	3 281	0.00	48
.../...			
<b>Total</b>	<b>4 031 646</b>	<b>0.54</b>	

The crops studied in the CLIMATOR project cover 54% of the UAA of the Centre-North zone. This includes 65 045 professional farms and 86 579 farmers and their associates. The total number of workers represents 141 496 Annual Work Units. The value of raw and processed agricultural plant products was 13.2 billion euros in 2008.



## B Main impacts of climate change on wheat in the Centre-North zone

Soft wheat is the main crop in the Centre-North, occupying 32% of the UAA and representing about 50% of French wheat production, with the highest mean yields (about 7.5t ha<sup>-1</sup>).

For the two sites of Mons and Versailles respectively, climate change leads to significant yield increases of 8% and 10% for the NF and 9% and 12% for the DF for the early variety Soissons (tab. 1). This result is due to the beneficial effect of CO<sub>2</sub>, which compensates for the decline in water sufficiency\* of crops during grain-filling (of 4% and 14% in the NF and 13% and 21% in the DF for the Mons and Versailles sites respectively) and the increase in heat stress towards the end of the growing season (cf. TIMING section).

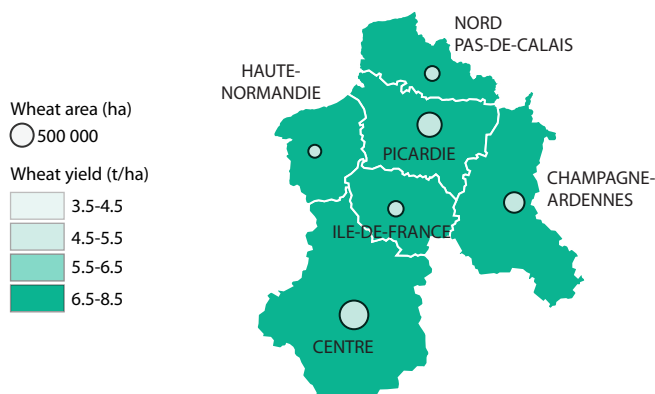


Figure 4: current areas and yields of wheat in the Centre-North zone (means 2000-2007). Source Agreste.

The same trends were observed for the late variety Arminda, with however a smaller increase in yields (4% at most), as the length of the growing season limits the escape\* phenomena, so that it is faced with a larger fall in the water sufficiency (from 12 to 24%) and a bigger increase in the heat stress towards the end of growth.

In fact the stress at the end of growth increases (cf. WHEAT section): the water deficit during grain filling increases by 37 and 28mm in the DF for the Mons and Versailles sites respectively. Similarly we expect 5-8 extra days of heat stress in the DF for the early variety. On the other hand the frosting of ears completely disappears in the NF and DF (cf. WHEAT section). Also, the yield losses caused by the two main wheat diseases fall by 15-20% in this zone (cf. HEALTH section).

Finally, although the delay in sowing allows better management of plantings at the Versailles site without loss of yield, the poor response of future wheat yields to the change in sowing date at Mons suggests that sowing dates should be decided on a site by site basis.

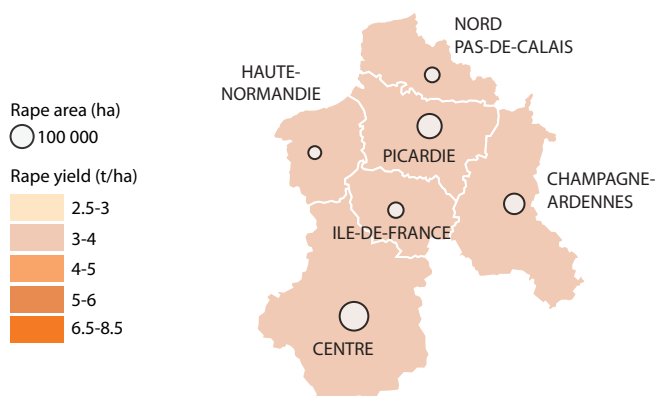
Site	NF-RP	DF-RP
Mons	1.0	1.0
Versailles	0.9	0.8

Table 1: yield gains estimated for the NF and DF for the Centre-North sites. Italics:  $P < 0.05$ ; **Bold**:  $P < 0.01$ .

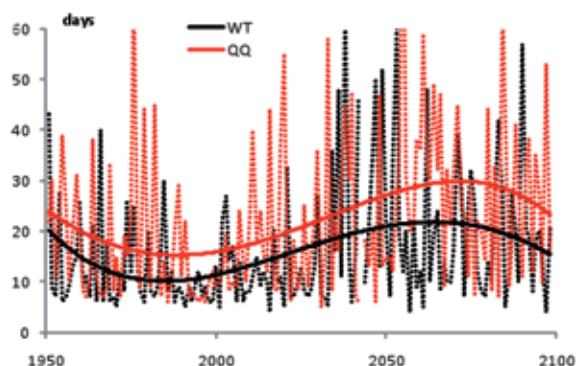
## C Main impacts of climate change on oilseed rape in the Centre-North zone

Without any change in cultural practices, at Mons, as at Versailles, rape yields stagnate, as the adverse effects of climate change prevent the crop from profiting from the atmospheric CO<sub>2</sub> increase and the reduction in frost risk. These adverse effects apply during the vegetative phase.

The first problem is poor emergence due to the dry seed-bed in summer which, by lengthening the period from sowing to emergence, leads to low populations. Figure 6 shows this trend, whichever downscaling method is used; we see a considerable increase in the occurrence of emergence periods of more than a month.



**Figure 5:** current areas and yields of rape in the Centre-North zone (means 2000-2007). Source Agreste.



**Figure 6:** change in the duration of emergence of rape at Versailles for a sowing on 20 August, for soil 1 and two climatic downscaling methods\*. A fourth-order polynomial smoothing reveals the trends.

A second adverse effect, also due to soil dryness during early crop life, applies to the nitrogen nutrition of the plants. In fact, in spite of increasing availability of soil mineral nitrogen in the future, arising from the stimulation of the mineralisation of the organic matter by warming, the plant suffers from nitrogen deficiency, because the low transpiration flux prevents the plant from absorbing it.

One or two routine “starter” irrigations (sometimes already practiced) would undoubtedly resolve these problems. In terms of varietal earliness, nothing clearly significant was found. However, it is preferable to retain a short-term variety like Olphi, which by virtue of an escape phenomenon enjoys better nitrogen absorption conditions.



## D Main impacts of climate change on maize in the Centre-North zone

The Centre-North is the only CLIMATOR zone where grain maize production will increase significantly (fig. 8), whichever climatic assumption is made. This increase takes place mainly because of stabilisation of year-to-year yields allowed by global warming, and will occur between the RP and the NF.

The maintenance of, or even increase in yields in the DF will be possible by changing varieties and by bringing forward the sowing date by about one day every four years.

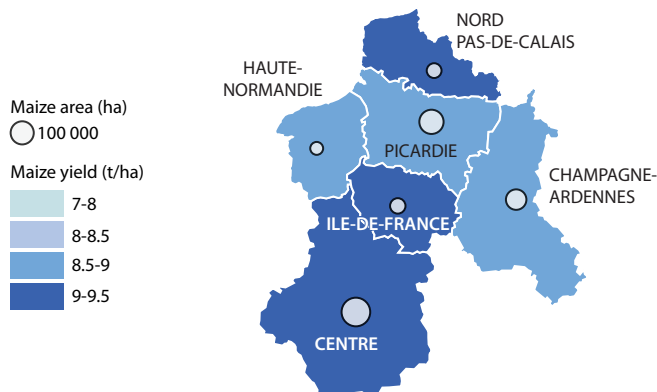


Figure 7: current areas and yields of maize in the Centre-North zone (means 2000-2007). Source Agreste.

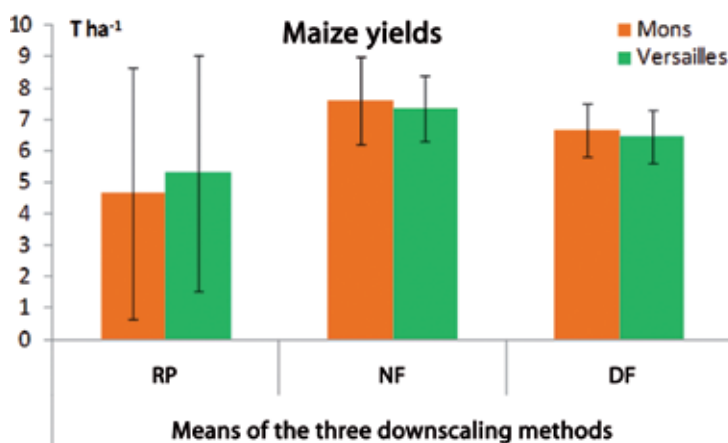


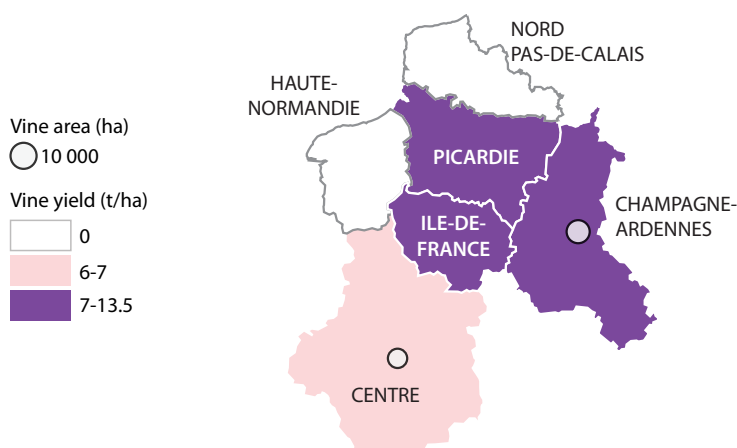
Figure 8: change in grain maize yields (variety Mérihel, soil 1) between the three periods with an indication of the variability\*, combining the year-to-year variability with that due to the climate downscaling methods.

This change is accompanied by an increase in irrigation water applications of about 60-70mm between the RP and the NF, the change of variety in the DF resulting in only a small increase in these applications (10mm on average). Thus we should go from 80-100mm in the RP to 150-180mm in the future.

Maize will in future be included in a cereal rotation\* without the need for routine artificial grain drying. Drying will remain necessary 7 years in 10 at Mons and 4 years in 10 at Versailles in the NF, but should cease in the DF.

## E Main impact of climate change on vines in the Centre-North zone

The Centre-North region is represented in the CLIMATOR project by two sites without any significant wine production at present: Versailles and Mons. It is typically a region somewhat beyond the northern boundary of current vine growing, and thus could be affected by a displacement of this boundary.



**Figure 9:** current areas and yields of vines in the Centre-North zone (means 2000-2007). Source Agreste.



The simulations (A1B scenario) confirm that growing vines is not currently possible, either for Chardonnay or for Merlot, but that it could become so here and there towards the 2030s and in most parts from about 2050 (fig. 10 a and 10b).

By the end of the century maturity dates will advance to early September for Chardonnay and mid-September for Merlot. It will begin to become feasible to grow Grenache by the end of the century, but still only sporadically (always assuming the A1B scenario). These trends are clear whichever weather pattern is simulated (here represented only by WT).

The maturation of Chardonnay and Merlot at these two sites will occur under good water sufficiency conditions on average and in temperatures favourable to quality (fig. 10 below). The increases in the temperature during the maturation phase will be moderate and will lead to levels similar to, or slightly above those of the recent past in the reference region for the variety (Chardonnay at Dijon and Merlot at Bordeaux).

The quantities of water reaching the groundwater will fall, but less markedly than in other regions. Finally, unlike other comparable sites, the new feasibility of growing the crop is accompanied by a low-moderate risk of Botrytis (cf. HEALTH section). The climate of this region will, therefore, in the medium term, become suitable for Chardonnay and Merlot in conditions favourable to quality.

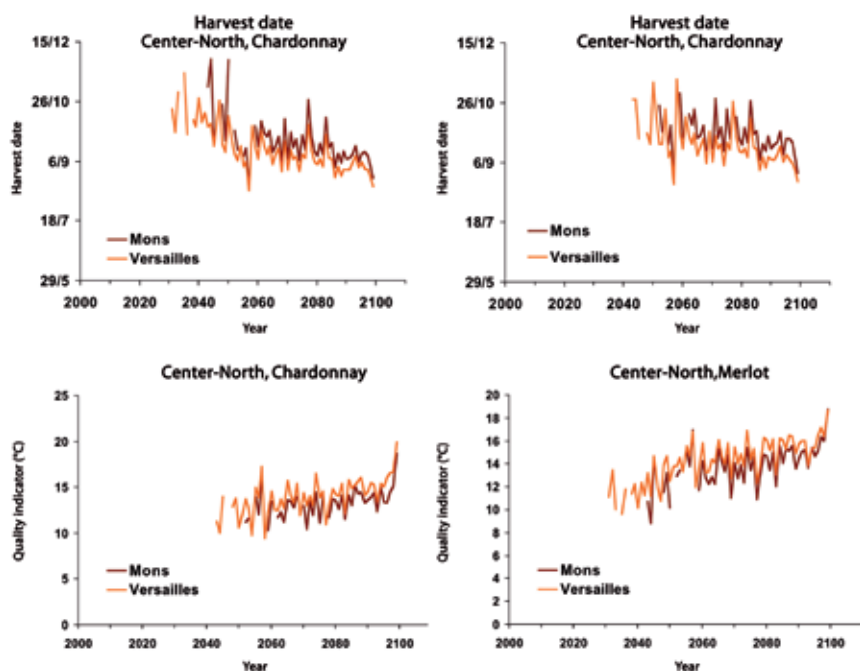


Figure 10: change in the harvest date for Chardonnay and Merlot (above, left and right) and of the quality indicator (minimum temperature during grape maturation) for Chardonnay and Merlot (below, left and right).



# Climate change in the West zone: the main agricultural and forest impacts

Frédéric Levrault, Jean-Louis Durand,  
Marie-Odile Bancal, Nadine Brisson

Regions concerned:

- **Basse-Normandie**
- **Bretagne**
- **Pays-de-la-Loire**

Study site: Rennes



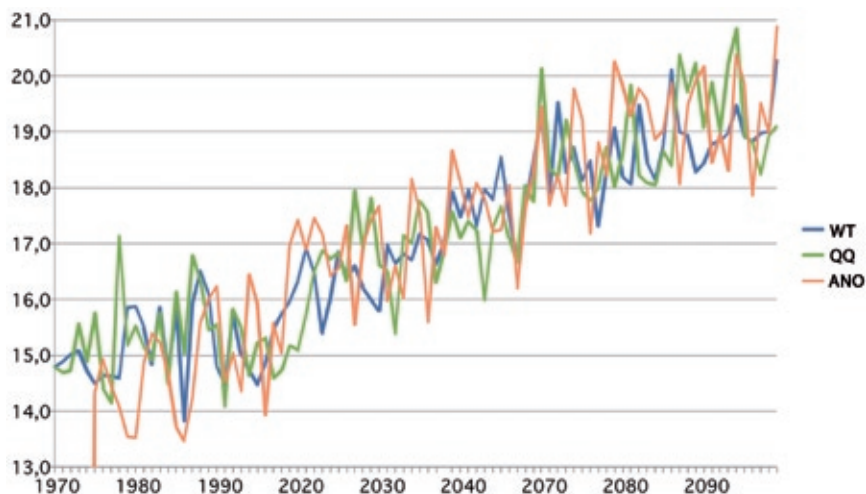
Land use	Area (ha)	% TA	Usable agricultural area	Area (ha)	% TA
Total area	7 765 014		Farms	5 088 649	
Woods and forest	854 949	0,11	Arable land	3 816 317	0,75
Total UAA	5 487 730	0,71	Permanent grassland	1 208 088	0,24
Others	1 422 335	0,18	Permanent crops	63 120	0,01

*An increase in temperatures, slightly buffered by the oceanic influence, a worsening of the annual climatic water deficit, maintenance of grassland yields in the NF and an increase in the DF, maintenance of conventional wheat yields and an increase in yields of unsprayed wheat, an increase in rape yield but non-significant as subject to high year-to-year variation, increase in sorghum yields on deep soils and possibilities of using late varieties in the DF; these are the main trends revealed for the West zone.*

## A Some striking facts about climate change\* in the West zone\*

### Temperatures

This is the zone characterised by the smallest increase in temperature (at Rennes: 1.3°C between the RP\* and the NF\*; 2.6°C between the RP and the DF\*), because of the strong oceanic influence prevailing there. For this site\* the increase in temperature predicted for the NF will lead to a mean annual temperature similar to that of Lusignan (13°C) in the RP, i.e. about 200km further south.



**Figure 1:** change in the mean annual temperature (°C) from 1970 to 2100, at Rennes. A1B scenario\*. Downscaling methods\*: ANO\*, WT\* and QQ\*.

## Precipitation and evapotranspiration

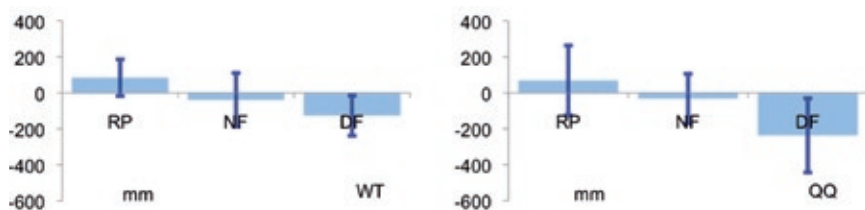
In the West zone, a marked decline in precipitation is expected, but largely in the second half of the 21<sup>st</sup> century. In the NF, Rennes is distinguished (with Colmar) from all the other sites by a moderate reduction in total annual rainfall: 37mm between the RP and the NF. In the DF, the reduction in rainfall is much larger: 110mm compared with the RP. By the end of the 21<sup>st</sup> century, with 547mm total annual rainfall, Rennes is the third driest site of the 12 studied, behind Toulouse (474mm) and Versailles (511mm).

A noticeable increase in potential evapotranspiration (ET<sub>0</sub>\*) is seen at Rennes, whatever the downscaling method. The annual total (30-year mean) thus goes:

- from 617mm/yr in the RP to 674mm/yr in the NF and to 734mm/yr in the DF with the WT downscaling method;
- from 637mm/yr in the RP to 696mm/yr in the NF and to 790mm/yr in the DF with the QQ downscaling method.

This represents (as a mean of the WT and QQ methods) a mean increase of 0.4mm/day between the RP and the DF. We have not studied the distribution between seasons of this increase, but the periods of high demand (spring and summer) will account for a large fraction of these increases.

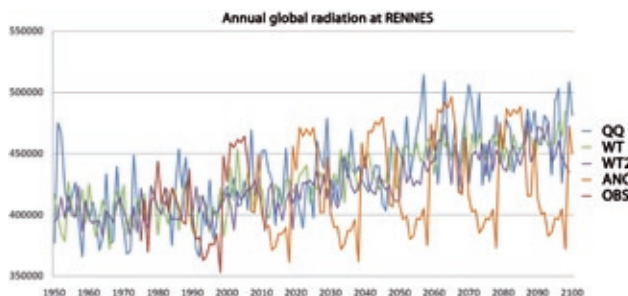
The concomitance of the reduction in rainfall and the increase in evapotranspiration will lead (fig. 2) to a worsening of the annual climatic water deficit.



**Figure 2:** annual climatic water deficit (rainfall-ET<sub>0</sub>) in the RP, the NF and the DF at Rennes. ARPÈGE, A1B. Downscaling methods: WT (left) and QQ (right). The ET<sub>0</sub> is calculated without correcting for the CO<sub>2</sub> (cf. MODELS section).

## Global radiation

At Rennes we find a continuous increase in the global radiation from the RP until the end of the 21<sup>st</sup> century. In the RP the mean annual global radiation is 405 000 (WT method) to 408 000 (QQ method) J/cm<sup>2</sup>/yr, which on average represents 1 110J/cm<sup>2</sup>/day. In the DF the mean annual global radiation is 450 000 (QQ method) to 459 000 (WT method) J/cm<sup>2</sup>/yr, or 1 245J/cm<sup>2</sup>/day on average. This radiation “supplement” of more than 130J/cm<sup>2</sup>/day, together with the rise in temperature, explains the expected increase in potential evapotranspiration (ET<sub>0</sub>).



**Figure 3:** changes in the total annual global radiation (J/cm<sup>2</sup>/yr) from 1950 to 2100 at Rennes. A1B scenario. Standard downscaling methods: ANO, WT and QQ, to which was added the WT2 method (cf. CLIMATE section) and the data observed for the RP.



### A reminder of current agricultural production in the West zone

(Source Agreste)

Crops	Area (ha)	% UAA	Yield (t/ha)
Grass leys	1 075 806	0.21	79
Soft wheat	820 094	0.16	68
Forage and silage maize	755 594	0.15	124
Grain and seed maize	280 804	0.06	81
Oilseed rape	101 954	0.02	30
Sunflower	46 860	0.01	24
Vines	38 932	0.01	74
Hard wheat	22 003	0.00	61
Sorghum	1 831	0.00	54
.../...			
<b>Total</b>	<b>3 143 876</b>	<b>0.62</b>	

The crops studied in the CLIMATOR project cover 62% of the UAA of the West zone. This includes 68 950 professional farms and 99 060 farmers and their associates. The total number of workers represents 150 901 Annual Work Units. The value of raw and processed agricultural plant products was 5.03 billion euros in 2008.

## B Main impacts of climate change on grassland in the West zone

The climate of the west will warm in winter and the number of days of frost will fall. This should almost certainly result in increased yields in winter and early spring. For tall fescue, this trend, which always appeared clearly in the simulations made with the STICS\* crop model, is less marked in those made with PASIM.

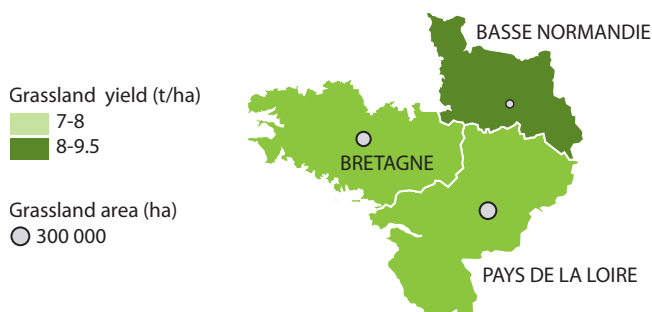


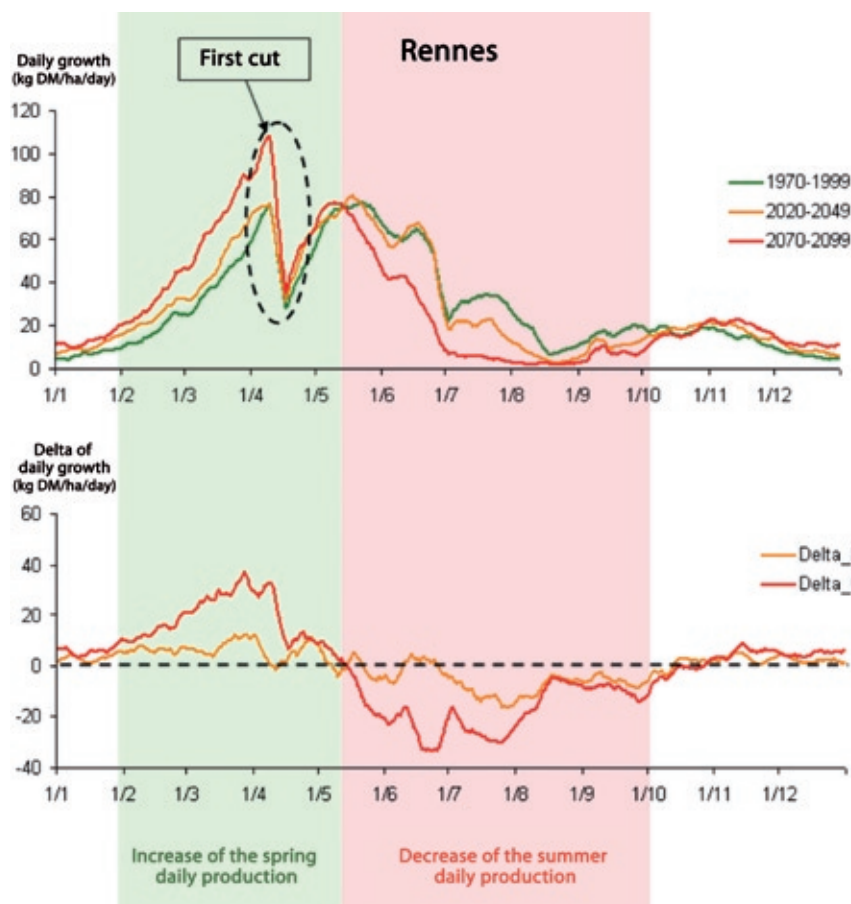
Figure 4: areas and current yields of grassland in the West zone (means 2000-2007). Source Agreste.

Although the simulations did not explore the optimisation of cutting times, one can also conclude from them the possibility of bringing forward the turnout date, provided that the soils can withstand the trampling. The quality of this grass will tend to fall somewhat for ryegrass, but not for fescue, which retains a stable nitrogen content.

The summer deficit increases markedly with both the downscaling methods used with the AR-PEGE model applied to scenario A1B (fig. 5). The annual balance reveals stability of production for the near future.







**Figure 5:** daily production (30-year means) of forage at Rennes for tall fescue for the three periods studied. A1B scenario. QQ downscaling method.

If the A1B scenario turns out to be correct, then the end of the century will see an improvement in the water balance of about 10-20%. These trends will be accentuated on a deep soil. Here also, from the same soil and climatic data, PASIM simulates much smaller variations.

Lastly, the year-to-year variability\* of forage yield will tend to increase due to the increased variability in summer rainfall.

## C Main impacts of climate change on wheat in the West zone

Occupying 17% of the UAA with mean yields of  $6.8\text{t ha}^{-1}$ , soft wheat is an important crop in the West zone.

The yields of early and late varieties are not affected by climate change in spite of a big fall in the water sufficiency\* (fig. 7) and an increase in the number of heat stress days (fig. 8). This is because of the compensating effect of the increased water use efficiency due to the increased atmospheric  $\text{CO}_2$  concentration.

On the other hand, when wheat crops are not sprayed, we see a clear increase in yields in the NF and DF, the yield losses due to rust (fig. 8) and to septoria falling by up to 25% (cf. HEALTH section).



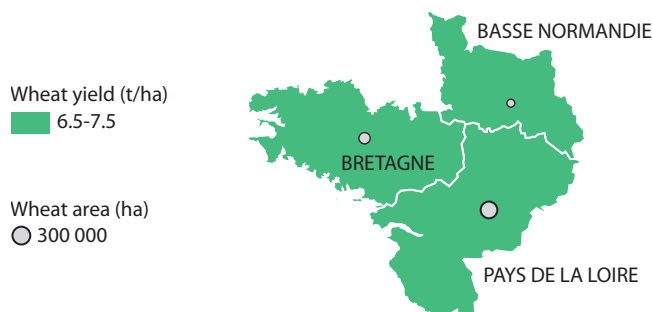


Figure 6: current areas and yields of wheat in the West zone (means 2000-2007). Source Agreste.

Finally, changing the sowing date from 20 September to 1 December results in reductions in yield which are explained by the increase in heat and water\* stresses towards the end of crop growth. The yield losses due to leaf diseases also decline when the sowing date is deferred, by a maximum of 15% and in a similar way in the RP, the NF and the DF. In this region, adjusting sowing dates seems to be a rather ineffective way of minimising the effects of climate change (cf. WHEAT section).

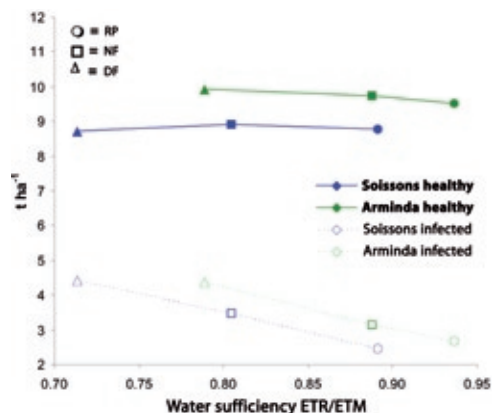


Figure 7: change in yield of healthy and brown-rust-infected crops simulated by the CERES model (soil 1, WT downscaling method, sown 10 October).

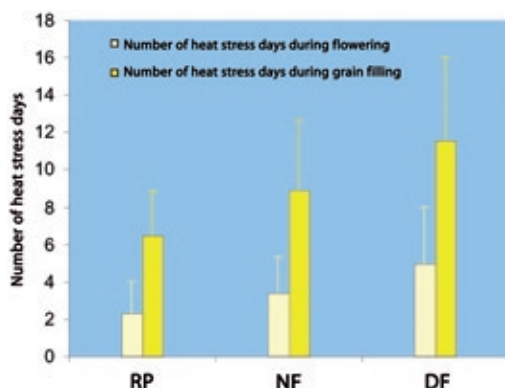


Figure 8: change in heat stress simulated by the PANORAMIX model (soil 1, WT downscaling method\*, sown 10 October).

## D Main impacts of climate change on oilseed rape in the West zone

The sites in the west are basically favourable to growing rape, as they are less subject to frosts and receive late-summer rainfall which favours crop establishment. However although we find an increase in yield at Rennes, it is not significant because of the high year-to-year variability.



Figure 9: current areas and yields of rape in the West zone (means 2000-2007). Source Agreste.

Curiously, we find that the increase in yields is greatest on soil 2 with a low AWR\* (2.8t ha<sup>-1</sup> in the RP, 3.2t ha<sup>-1</sup> in the NF and 3.5t ha<sup>-1</sup> in the DF) than on soil 3 with a high AWR (5.2t ha<sup>-1</sup> in RP, 5.3t ha<sup>-1</sup> in NF and 5.4t ha<sup>-1</sup> in DF).

These results are explained by a deterioration in nitrogen nutrition due to soil dryness in the early stages of growth, a problem already affecting soils with a low AWR\*, but which will also become serious on other soils (fig.10). In fact, in spite of increased availability of soil mineral nitrogen in the future, arising from the stimulation of the mineralisation of the organic matter by warming, the plant can become deficient in nitrogen because the decline in transpiration flux in the dry autumns which are predicted will prevent it from being absorbed.

Without a change in practices during these dry years, the crop will undergo a substantial fall in its nitrogen nutrition index (fig. 10) which will prevent it from profiting from the increased atmospheric CO<sub>2</sub>. On the other hand in wetter years (at the end of the century), nitrogen absorption, by then less limiting, will assure higher yields than in the RP.

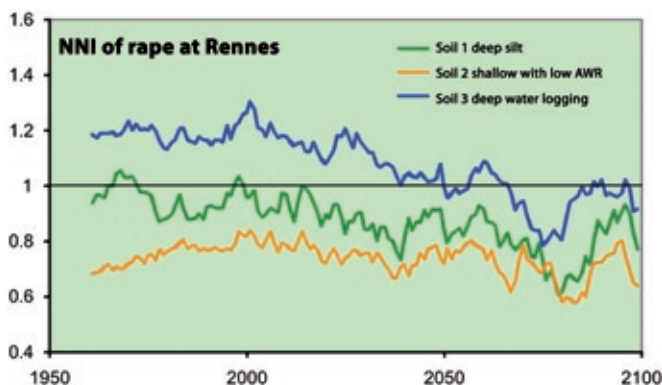


Figure 10: change in the nitrogen nutrition index during rape flowering at Rennes for 3 soil types and the WT down-scaling method. The curves represent 10-year running means.

To stabilise rape yields and increase the mean, a “starter” irrigation should be considered in dry years.

## E The main impacts of climate change on sorghum in the West zone

In spite of the decline in its water sufficiency (mean ETR/ETM of 0.84, 0.78 and 0.76 for the RP, NF and DF respectively on soil 1, a deep silt), sorghum yield at Rennes increases from the NF for the WT method and significantly for all downscaling methods in the DF (fig. 12).

Although of course the yield is low on a shallow soil with a low AWR ( $3\text{t ha}^{-1}$  on average for the rendzina as against  $4.7\text{t ha}^{-1}$  for soil 1, a deep silt) sorghum can grow on waterlogged soils which, without establishment or disease problems, allow it to reach mean yields of about  $6\text{t ha}^{-1}$  in rainfed conditions.

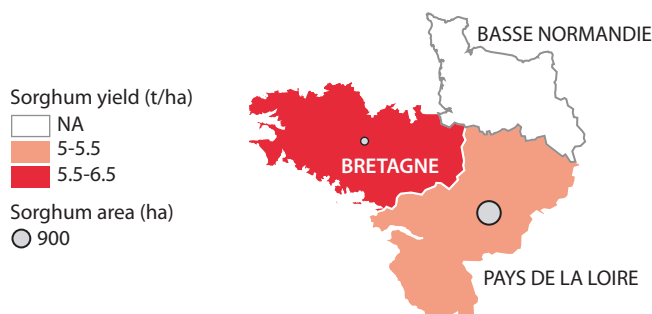


Figure 11 : current areas and yields of sorghum in the West zone (means 2000-2007). Source Agreste.

In the DF it will be possible to grow long-term varieties which will allow a substantial yield gain (fig. 12). This hardy behaviour of sorghum is a useful factor to cope with climate change, and one which favours it as compared with maize, which is more fragile.

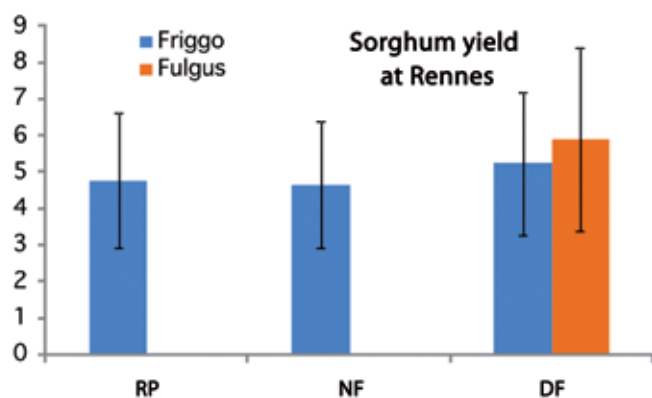


Figure 12: change in grain sorghum yield at Rennes for soil 1 (deep silt) with the varieties Friggo and Fulgus (when it can be grown). The variability shown includes the year-to-year variability and that due to the climate downscaling method.



# Climate change in the North-East zone: the main agricultural and forest impacts

Frédéric Levrault, Nadine Brisson, Alexandre Bosc

Regions concerned:

- **Alsace**
- **Bourgogne**
- **Franche-Comté**
- **Lorraine**

Study sites: Colmar, Dijon, Mirecourt



Land use	Area (ha)	% TA	Usable agricultural area	Area(ha)	% TA
Total Area	8 006 131		Farms	3 903 936	
Woods and forest	2 873 912	0.36	Arable land	2 229 635	0.57
Total UAA	2 236 699	0.28	permanent grassland	1 618 557	0.41
Others	1 032 278	0.13	Permanent crops	56 282	0.01

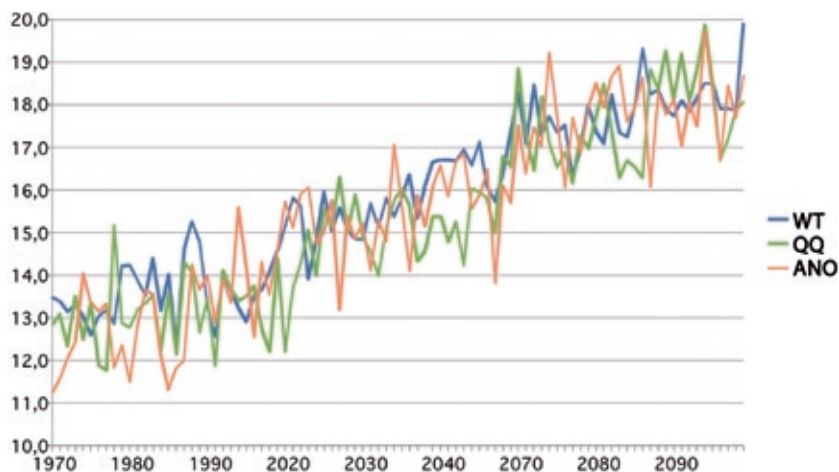


*Fewer autumn and winter frosts, worsening of the annual climatic water deficit, stabilisation of year-to-year maize yields at certain sites, more opportunities for growing rape due to the reduced autumn and winter frost risk, sunflower cultivation becoming possible in the north of the zone, slight fall in the water sufficiency of trees; these are the main trends revealed for the North-East zone.*

## A Some striking facts about climate change\* in the North-East zone\*

### Temperatures

Currently the coolest of the six zones studied, the North-East zone is characterised by slightly greater warming than the mean of the 12 sites\*: 1.4-1.6°C between the RP\* and the NF\* and 2.8-3.0°C between the RP and the DF\*. In the DF the mean annual temperature at Dijon (13.7°C) and at Colmar (14.0°C) become higher than that at Avignon (13.1°C) or Toulouse (13.3°C) in the RP, the two warmest of the 12 sites studied. Nevertheless in the NF as in the DF, the North-East zone remains the coolest in France. In this zone, two temperature-related issues emerge for cultivated species. One is that the extra warmth will allow the gradual introduction of species with high temperature requirements, such as sunflower and maize. The other is that the fall in the number of days of frost in autumn and winter will reduce the frost damage on winter crops, especially rape.



**Figure 1:** change in mean annual temperature (°C) from 1970 to 2100 at Dijon. A1B\*scenario. Downscaling methods\*: ANO\*, WT\*and QQ\*.



## Precipitation and evapotranspiration

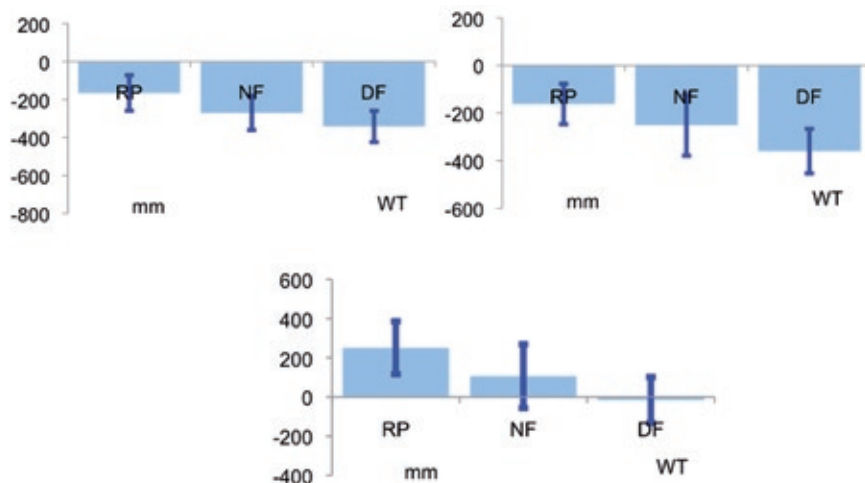
In the RP we see a strong contrast between Colmar on the one hand, with 730mm annual precipitation, and on the other Dijon (912mm) and Mirecourt (985mm), which are among the most well-watered sites in our study. In the NF, this lowest value at Colmar, due to the low-lying plain of Alsace, seems to improve a little, the reductions in rainfall being very different at Colmar (37mm), Dijon (73mm) and Mirecourt (109mm). In the DF, the reduction in precipitation compared with the RP is more marked at Mirecourt (182mm) than at Colmar and Dijon (109mm). By that time the minimum at Colmar is re-established (620mm), whilst Dijon and Mirecourt are still among the best-watered in our study, with 803mm as their annual total. In this zone, the decrease in autumn rainfall will significantly affect the number of days available\* for autumn fieldwork.

A marked increase in the potential evapotranspiration (ET<sub>0</sub>\*) is observed at Colmar, Dijon and Mirecourt, whichever downscaling method is used. The increases in the annual total (30-year means) are:

- 75-80mm between the RP and the NF and 150-160mm between the RP and the DF with the WT downscaling method;
- 55-70mm between the RP and the NF and 170-200mm between the RP and the DF with the QQ downscaling method.

Averaged over the WT and QQ methods, this represents a mean increase of 0.5mm/day between the RP and the DF. We have not studied the distribution between seasons of this increase, but the periods of high evaporative demand (spring and summer) will account for a large fraction of the increases.

The concomitance of the reduction in rainfall and the increase in evapotranspiration will lead (fig. 2) to a marked worsening of the annual climatic water deficit at each of the three sites. Only the Mirecourt site will have a roughly zero balance in the DF.

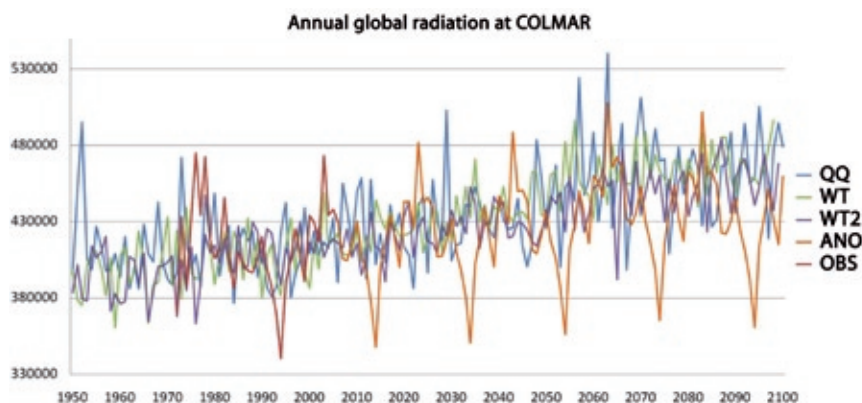


**Figure 2:** annual climatic water deficit (rainfall-ET<sub>0</sub>) in the RP, NF and DF at Colmar (top left), Dijon (top right) and Mirecourt (bottom). ARPÈGE A1B. WT downscaling method. The ET<sub>0</sub> is calculated without correcting for the CO<sub>2</sub> (cf. MODELS section).



## Global radiation

At Colmar, we see a continuous increase in the global radiation over the course of the 21<sup>st</sup> century. In the RP, the mean annual global radiation is 408 000 (WT method) to 411 000 (QQ method) J/cm<sup>2</sup>/yr, or 1 120J/cm<sup>2</sup>/day on average. In the DF, the mean annual global radiation is 447 000 (QQ method) to 466 000J/cm<sup>2</sup>/yr, or 1 250J/cm<sup>2</sup>/day on average. This radiation “supplement” of 130J/cm<sup>2</sup>/day, together with the higher temperatures, explains the significant increase in potential evapotranspiration (ET<sub>0</sub>). At Dijon, the radiation levels are slightly less (1 100J/cm<sup>2</sup>/day in the RP and 1 260J/cm<sup>2</sup>/day in the DF), but the trend is identical.



**Figure 3:** change in the annual total global radiation (J/cm<sup>2</sup>/yr) from 1950 to 2100 at Colmar. A1B scenario. Standard downscaling methods: ANO, WT and QQ, to which were added the WT2 method (cf. CLIMATE section) and the data observed for the RP.

## A reminder of the current agricultural production in the North-East zone (Source Agreste)

Crops	Area (ha)	% UAA	Yield t/ha
Soft wheat	644 716	0.17	66
Oilseed rape	307 214	0.08	30
Grass leys	227 879	0.06	71
Grain and seed maize	224 618	0.06	93
Forage and silage maize	137 060	0.04	116
Vines	47 989	0.01	85
Sunflower	42 698	0.01	27
Sorghum	284	0.00	49
Durum wheat	215	0.00	54
.../...			
<b>Total</b>	<b>1 632 457</b>	<b>0.42</b>	

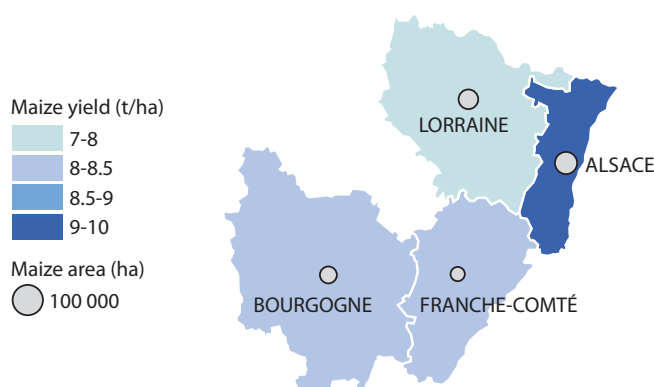
The crops studied in the CLIMATOR project cover 42% of the UAA of the North-East zone. This includes 35 488 professional farms, and 48 517 small farmers and partners. The total number employed in farming is 77 141 AWUs. The value of the raw and processed plant products was 4.55 billion euros in 2008.



## B Main impacts of climate change on maize in the North-East zone

We distinguish the sites of Colmar and Dijon, where maize yields tend to fall (from the NF with the WT downscaling method and in the DF for the ANO and QQ methods), from Mirecourt, where grain maize, whose yield was erratic in the RP, becomes a profitable crop in the future (fig. 5). Yields will also stabilise at Dijon.

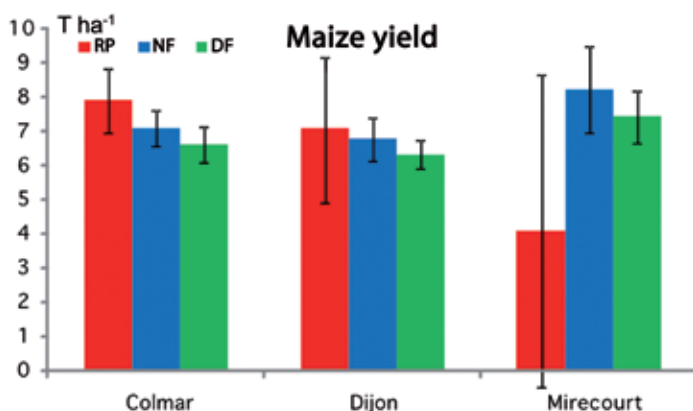
These results however are accompanied by an increase in irrigation of about 50mm between the RP and the NF, but no further increase between the NF and the DF. Hence one expects average amounts of about 200mm at Dijon and 100mm at Mirecourt.



**Figure 4:** current areas and yields of maize in the North-East zone (means 2000-2007). Source Agreste.

Maize will be able to be grown more easily in rotation\*, which requires earlier harvesting than in monoculture. In fact grain drying, which was necessary in 8 years out of 10 at Colmar and 9 years out of 10 at Dijon in the RP, will no longer be necessary in the future. These rotations will also be possible in the DF at Mirecourt.

In order to maintain, or indeed increase yields at Colmar and Dijon, the use of long-term varieties and earlier sowing (by about one day every four years on average) are recommended. The estimated increase in water applications as a result of the varietal change is small – about 10-20mm.



**Figure 5:** change in grain maize yields (variety Mériabel, soil 1, WT downscaling method) between the three periods, with the year-to-year variability\*.



### C Main impacts of climate change on oilseed rape in the North-East

The falling risk of frost in the future during autumn and winter (fig. 5) is a bonus for the rape crop in the North-East, where yields increase significantly everywhere: by about 0.7 and 0.9t ha<sup>-1</sup> for the NF and DF respectively at Colmar and Dijon, and more than twice that at Mirecourt (1.4 and 2.5t ha<sup>-1</sup> for the same periods) for the WT downscaling method.

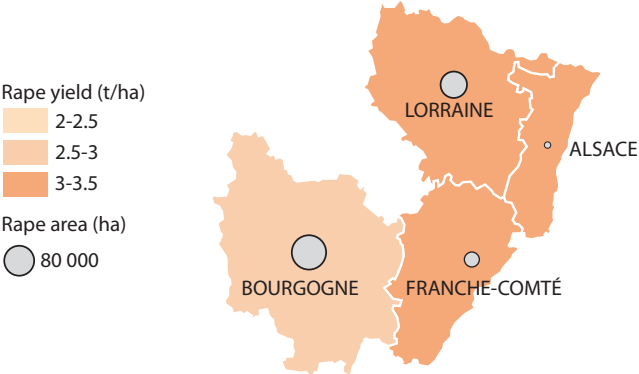


Figure 6: current areas and yields of rape in the North-East zone (means 2000-2007). Source Agreste.

However the downscaling methods can give results of different magnitude (fig. 7), since they differ basically in their treatment of the variability (cf. CLIMATE section) which determines, in particular, the occurrence of low minimum temperatures. This being so, it would be wise to trust the most pessimistic method.

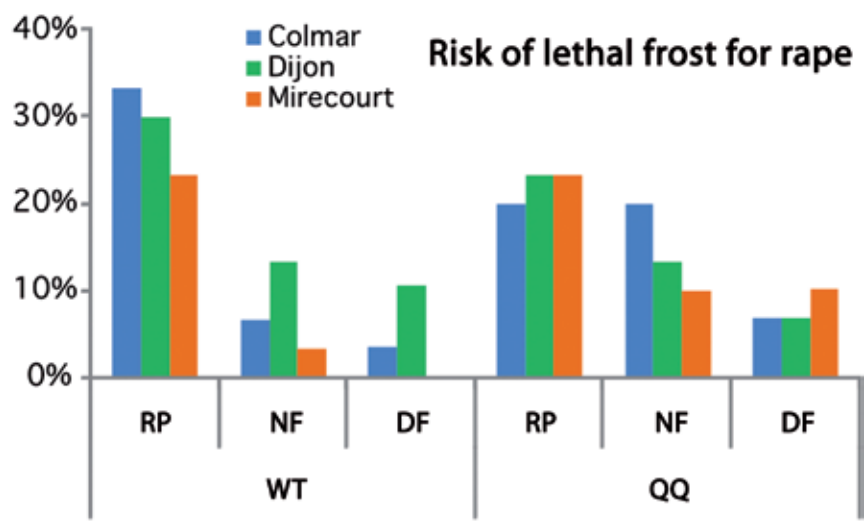
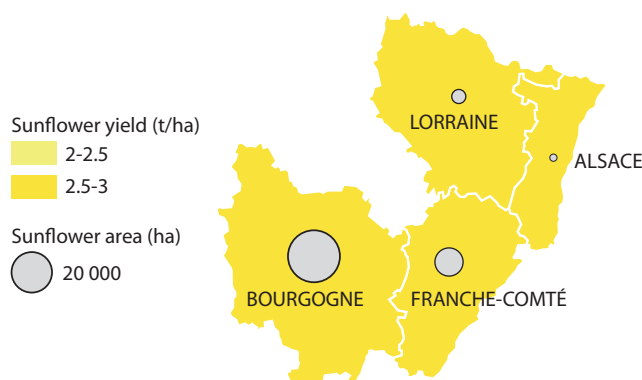


Figure 7: change in risks of lethal frosts for rape for the two climate downscaling methods.

In order to limit the damaging effects of soil drying which could become severe during the vegetative phase it could be necessary to defer sowing, or to use "starter" irrigations, especially at Colmar. For the same reasons, it would also be preferable, in future, to use varieties with rapid stem elongation like Olphi.

## D Main impacts of climate change on sunflower in the North-East

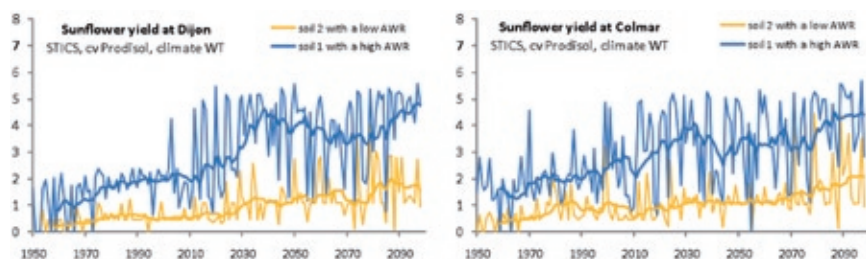
The North-East region seems favourable to growing sunflower for two reasons. Firstly, at its northern boundary (Mirecourt), the crop will be able to be grown as part of cereal rotations because of the warming.



**Figure 8:** current areas and yields of sunflower in the North-East zone (means 2000-2007). Source Agreste.

Secondly, in the zones where it can already be grown (Dijon, Colmar), one can expect better yields in favourable years (fig. 9).

However in rainfed conditions and on soils with a low AWR\*, these gains will remain limited. In the DF it will be possible to use long-term varieties which will be capable of higher yields.

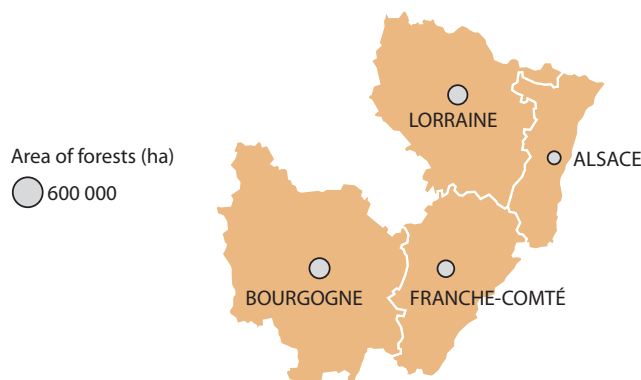


**Figure 9:** change in sunflower yield at Dijon and Colmar for a soil with a high AWR (226mm) and a soil with a low AWR (104mm). Simulations for a rainfed cereal rotation (SWSgW) with the WT climatic downscaling method. For each series the annual data and a 10-year running mean are shown.

## E Main impacts of climate change on forests in the North-East zone

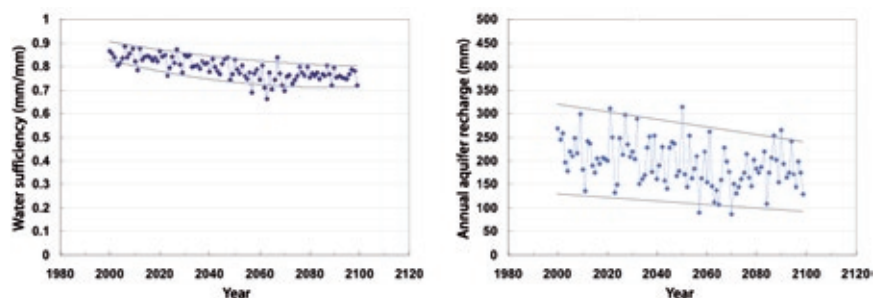
The behaviour of forest canopies is strongly controlled by water stress, especially during the growing season (spring and summer).

The climate changes modelled for the A1B scenario (with crop models\* BILJOU and GRAECO) predict a decline in the water sufficiency of trees (fig. 11a) over the coming century.



**Figure 10:** current areas and yields of forest in the North-East zone (means 2000-2007). Source Agreste.

Aquifer recharge is affected, with a trend showing a loss of 50mm by 2100 (fig. 11b) compared with the RP.



**Figure 11:** regional mean (Colmar, Dijon, Mirecourt) for the change in water sufficiency ETR/ET0 (left) and aquifer recharge of pines (right) (45-year rotation, soil 3) with the confidence interval (95%) due to the downscaling method.



# Climate change in the Centre-East zone: the main agricultural and forest impacts

Frédéric Levrault, Jean-Louis Durand,

Nadine Brisson, Alexandre Bosc

Regions concerned:

- **Auvergne**
- **Limousin**
- **Rhône-Alpes**

Study sites: Clermont-Theix, Saint-Étienne



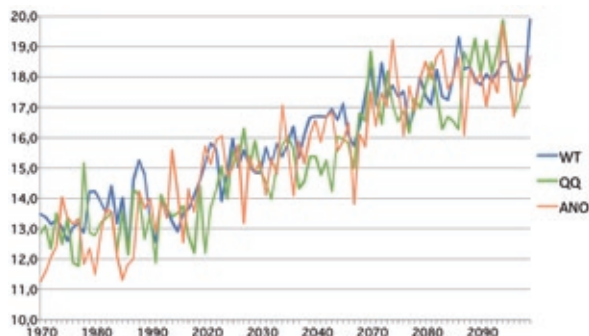
Land use	Area (ha)	% TA	Usable agricultural area	Area (ha)	% TA
Total area (TA)	8 819 404		Farms	3 860 550	
Woods and forests	2 953 648	0.33	Arable land	1 457 922	0.38
Total UAA	4 124 512	0.47	Permanent grassland	2 287 244	0.59
Others	1 741 245	0.20	Permanent crops	115 398	0.03

*Increased temperatures and a worsening of the annual climatic water deficit, a big increase in grassland production in the DF, more opportunities for the sorghum and sunflower crops, a slight fall in the water sufficiency of forest which will not affect its yields in the NF; these are the main trends revealed for the Centre-East zone.*

## A Some striking facts about climate change\* in the Centre-East zone

### Temperatures

At the two sites\* concerned (Clermont-Theix and Saint-Étienne), the mean annual temperature will increase slightly more markedly than the mean trend for the 12 sites studied: 1.5°C between the RP\* and the NF\*; 3.0°C between the RP and the DF\*. In the DF, the mean annual temperature of these two sites (14.0°C) will be higher than that observed in the RP at Toulouse (13.3°C) or Avignon (13.1°C), the two warmest of the 12 sites studied. In this zone, an important temperature issue for cultivated species is the warming, notably in the foothills.



**Figure 1:** changes in the mean annual temperature (°C) from 1970 to 2100, at Clermont-Theix. A1B scenario\*. Downscaling methods: ANO, WT and QQ\*.

### Precipitation and evapotranspiration

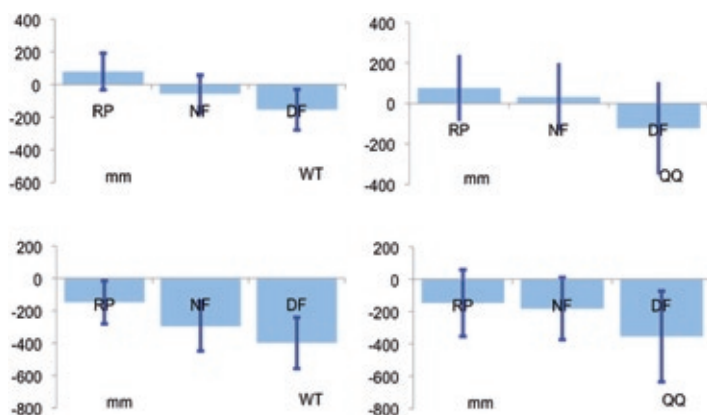
Clermont-Theix and Saint-Étienne are the two most well-watered sites in our study, with 1 022mm annual total rainfall. In the future, these two sites can expect one of the biggest reductions in precipitation: 110mm between the RP and the NF; 183mm between the RP and the DF. In spite of this big fall, Clermont-Theix and Saint-Étienne will remain the two most well-watered sites in our study, with 912mm of total annual rainfall in the NF and 839mm in the DF.

A significant increase in evapotranspiration (ET0\*) is found at Clermont-Theix and Saint-Étienne, whichever the downscaling\* method. The increases in the annual totals (30-year means) are:

- at Saint-Étienne, from 70 to 95mm between the RP and the NF and from 180 to 240mm between the RP and the DF;
- at Clermont-Theix, from 50 to 70mm between the RP and the NF and from 140 to 175mm between the RP and the DF.

Averaged over the WT and QQ downscaling methods, this represents a mean increase of 0.5-0.6mm per day between the RP and the DF. We have not studied the distribution between seasons of this increase, but the periods of high evaporative demand (spring and summer) will account for a large fraction of the increases.

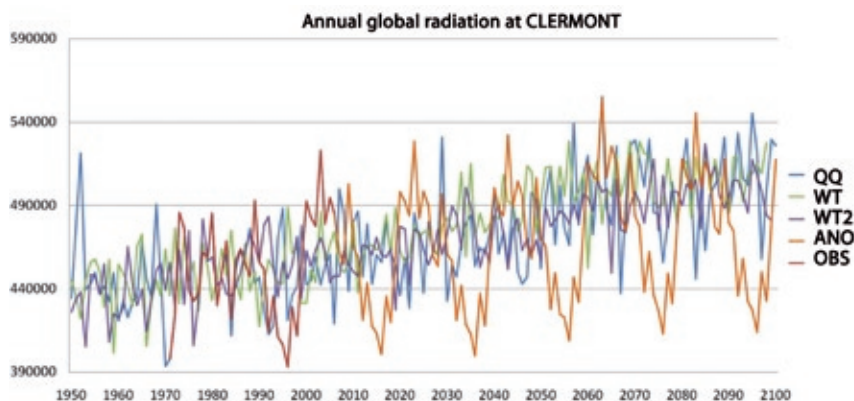
The concomitance of the reduction in rainfall and the increased evapotranspiration will lead (fig. 2) to a worsening of the annual climatic water deficit.



**Figure 2:** annual climatic water deficit (rainfall-ET0) in the RP, the NF and the DF at Clermont-Theix (above) and Saint-Étienne (below). ARPEGE A1B. Downscaling methods: WT and QQ.

## Global radiation

At Clermont-Theix we observe a continuous increase in global radiation over the whole period of study (1970-2100). In the RP, the mean annual global radiation is 451 000 (WT method) to 455 000 (QQ method)  $\text{J}/\text{cm}^2/\text{yr}$ , or 1 240  $\text{J}/\text{cm}^2/\text{day}$  on average. In the DF, the mean annual global radiation is 490 000 (QQ method) to 506 000 (WT method)  $\text{J}/\text{cm}^2/\text{yr}$ , or 1 365  $\text{J}/\text{cm}^2/\text{day}$  on average. This radiation "supplement" of more than 100  $\text{J}/\text{cm}^2/\text{day}$  explains the significant increase in potential evapotranspiration (ET0). At Saint-Étienne, the levels of global radiation are 466 000 (QQ method) and 467 000 (WT method)  $\text{J}/\text{cm}^2/\text{yr}$  in the RP and 514 000 (QQ method) to 545 000 (WT method)  $\text{J}/\text{cm}^2/\text{yr}$ . The daily radiation supplement is 100  $\text{J}/\text{cm}^2/\text{day}$ .



**Figure 3:** change in the annual total global radiation ( $\text{J}/\text{cm}^2/\text{yr}$ ) from 1950 to 2100 at Avignon. A1B scenario. Standard downscaling methods: ANO, WT and QQ, to which were added the WT2 method (cf. CLIMATE section) and the data observed for the RP.



**A reminder of current agricultural production in the Centre-East zone**  
(Source Agreste)

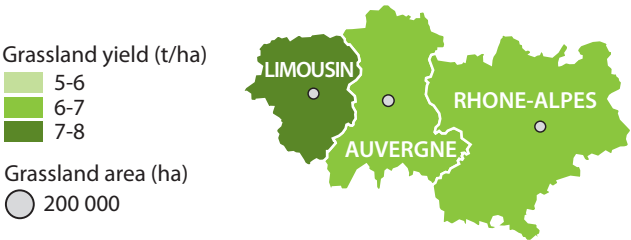
Crops	Area (ha)	% UAA	Yield t/ha
Grass leys	529 550	0.14	67
Soft wheat	258 619	0.07	57
Grain and seed maize	168 912	0.04	88
Forage and silage maize	110 483	0.03	107
Vines	59 497	0.02	66
Sunflower	51 991	0.01	25
Oilseed Rape	36 889	0.01	28
Sorghum	10 733	0.00	60
Durum wheat	8 083	0.00	42
.../...			
<b>Total</b>	<b>1 234 755</b>	<b>0.32</b>	

The crops studied in the CLIMATOR project cover 32% of the UAA of the Centre-East zone. This includes 50 901 professional farms and 67 440 farmers and their associates. The total number of workers represents 99 304 Annual Work Units. The value of raw and processed agricultural plant products was 2.87 billion euros in 2008.



**B Main impacts of climate change on grassland in the Centre-East zone**

The region is diverse in climatic terms, notably because of the pronounced topography. For the cold semi-mountainous zones, it is the increasing temperatures during climate change which profoundly modify production conditions and make possible harvests which are sometimes impossible at present.

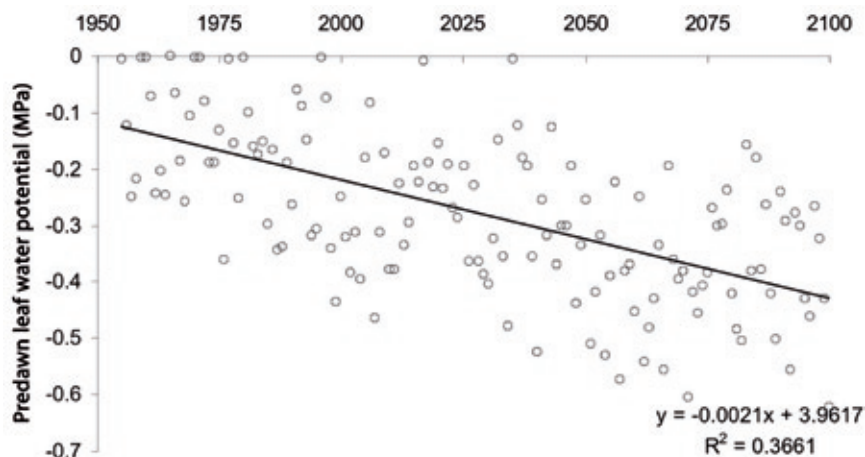


**Figure 4:** current areas and yields of grassland in the Centre-East zone (Means 2000-2007). Source Agreste.

The two crop models\* PASIM and STICS used here agree in predicting these changes, although they are always smaller with PASIM. The harvest of an additional cut and the increase in yields at the end of winter and the beginning of spring lead us to expect large yield increases towards the end of the century.

This increase, already considerable in the near future, will be about 100% or nearly so towards the end of the 21<sup>st</sup> century with the QQ downscaling method and slightly less with weather data simulations from the WT method.

One of the consequences of these big yield increases while rainfall is declining (fig. 5), would be a trend towards limitation by nitrogen availability due to plants taking up nitrogen and water from different depths, which would be easily corrected by increasing nitrogen applications if necessary.



**Figure 5:** worsening trend in the annual water deficit at Clermont-Theix for tall fescue with the A1B scenario and the WT downscaling method The basic leaf water potential measures the water stress “experienced” by the vegetation.

The data obtained for the Saint-Étienne station contrast strongly with the previous ones. At this station, the severe summer water deficits predicted by the WT downscaling method would reduce the annual yield of the species most sensitive to drought –perennial ryegrass.



## C Main impacts of climate change on sorghum in the Centre-East zone

Although our results show that in the DF, the hills of Clermont-Theix could grow sorghum with perfectly respectable average yields of 4.5-6t ha<sup>-1</sup>, depending on the soil, we are more interested in the Limagne, represented as regards altitude by the Saint-Étienne site.



**Figure 6:** current areas and yields of sorghum in the Centre-East zone (means 2000-2007). Source Agreste.

In spite of the deteriorating water sufficiency\*of the crop, with means of ETR/ETM\* of 0.89, 0.85 and 0.83 for the RP, NF and DF respectively (for soil 1, the deep silt), there is no significant change in sorghum yields (for the short-term variety Friggo), as shown by figure 7.

From the NF, it should be profitable to switch to longer-term varieties, like Fulgus, which would allow a substantial yield increase (fig. 7).



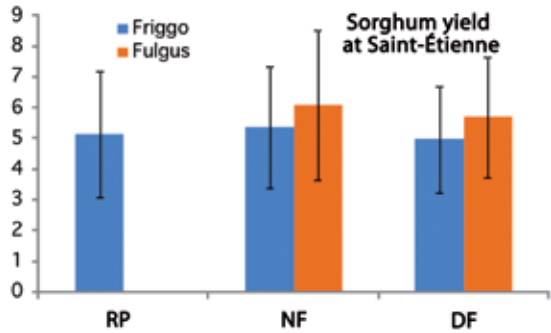


Figure 7: change in yield of grain sorghum at Saint-Étienne for soil 1 (deep silt) with the varieties Friggo and Fulgus (when it has time to mature). The variability\* indicated includes the year-to-year variability and that between climate downscaling methods.

D Main impacts of climate change on sunflower in the Centre-East zone

The Limagne seems like a possible place to grow sunflower, where the deep soils (e.g. soil 1 in figure 8) can compensate for the spring and summer droughts which reduce yields on shallow soils.

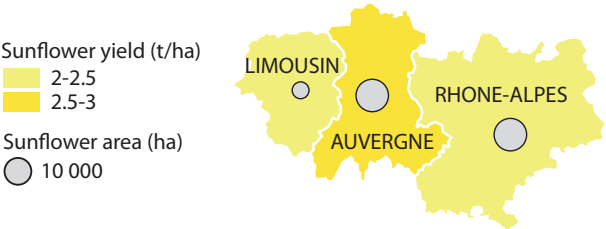


Figure 8: current areas and yields of sunflower in the Centre-East zone (means 2000-2007). Source Agreste.

Also, early sowing and the use of long-term varieties from the NF would allow yield increases of about 0.5t ha<sup>-1</sup> on average.

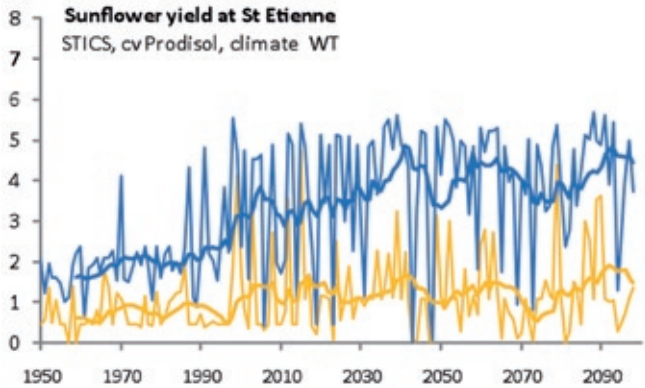


Figure 9: change in sunflower yield at St-Étienne for a soil with a high AWR (226mm) and one with a low AWR (104mm). Simulations for a rainfed cereal rotation\* (SWsgW) with the WT downscaling method. For each series the annual data and a 10-year running mean are shown.

## E Main impacts of climate change on forest in the Centre-East zone

The behaviour of forests is strongly controlled by the water status, especially during the growing season (spring and summer).



*Figure 10: current areas of forest in the Centre-East (means 2000-2007). Source Agreste.*



The climate changes modelled in the case of the A1B climatic scenario (using the crop models\* BILJOU and GRAECO) predict a slight fall in the water sufficiency of trees (fig. 11 left). Aquifer recharge is generally maintained over the period 2000-2100 (fig. 11 right).

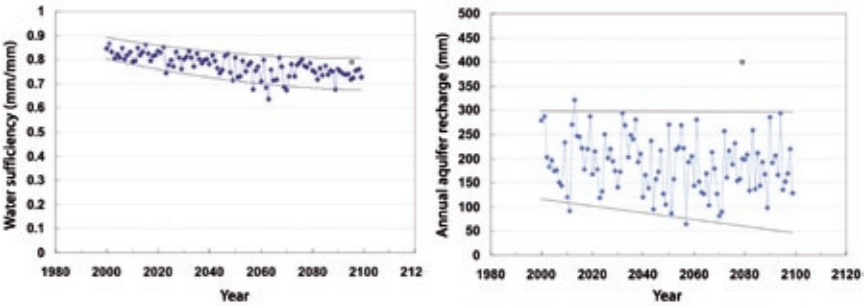


Figure 11: regional mean (Clermont-Ferrand, Saint-Étienne) of the change in water sufficiency ETR/ET0 (left) and the aquifer recharge for a pine forest (right) (45-year rotation 45, soil 3) with a confidence interval (95%) due to the downscaling method.



For this region, a fall in average yields is only predicted for the distant future (fig. 12), and even then smaller than in the lowland areas, with a yield loss of 4 and 16% for Clermont and Saint-Étienne respectively.

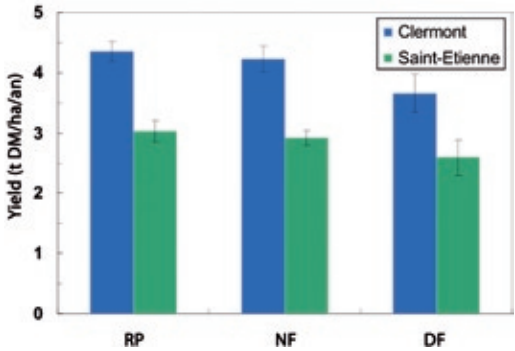


Figure 12: change in yield of pines (45-year rotation, soil 3, WT downscaling method) between the three periods, with the year-to-year variability.



# Climate change in the South-West zone: the main agricultural and forest impacts

**D6**  
South-West

Frédéric Levrault, Nadine Brisson,  
Philippe Pieri, Alexandre Bosc

Regions concerned:

- **Aquitaine**
- **Midi-Pyrénées**
- **Poitou-Charentes**

Study sites : Bordeaux, Lusignan and Toulouse



Land use	Area (ha)	% TA	Usable agricultural area	Area (ha)	% TA
Total area	11 337 680		Farms	5 559 746	
Woods and forests	3 555 218	0.31	Arable land	4 011 087	0.72
Total UAA	5 932 928	0.52	Permanent grassland	1 215 019	0.22
Others	1 849 534	0.16	Permanent crops	333 565	0.06

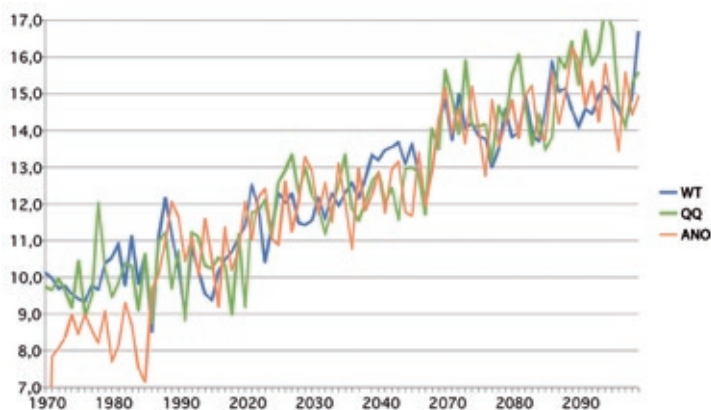


*A severe reduction in rainfall, a decline in irrigated maize yields with the current cultural practices (more marked in the south of the zone), maintenance of sorghum yields in the DF, little change for sunflower, movement to the north of the zone of temperatures favourable to merlot quality, a fall in forest yields, these are the main trends revealed for the South-West.*

## A Some striking facts about climate change\* in the South-West zone

### Temperatures

The predicted change in temperatures is identical for the three sites\*: + 1.4°C between the RP\* and NF\*; + 2.7°C between the RP and DF\*. This warming is slightly less than that for the mean of the 12 metropolitan sites (+ 1.44°C between the RP and NF; + 2.83°C between the RP and DF). Of the twelve sites studied, Toulouse retains the highest mean annual temperature, in the RP (13.3°C), the NF (14.7°C) and in the DF (16.0°C). The change in maximum temperatures is quite remarkable, especially in the south of the zone: thus at Toulouse, the number of heat stress days (with a maximum daily temperature > 25°C) during the months of May and June goes from 15 days in the RP to 21 days in the NF and 35 in the DF, i.e. it more than doubles.



**Figure 1:** change in the mean annual temperature (°C) from 1970 to 2100 at Toulouse. ARPÈGE\* A1B\*. Downscaling methods: ANO, WT and QQ\*.

## Precipitation and evapotranspiration

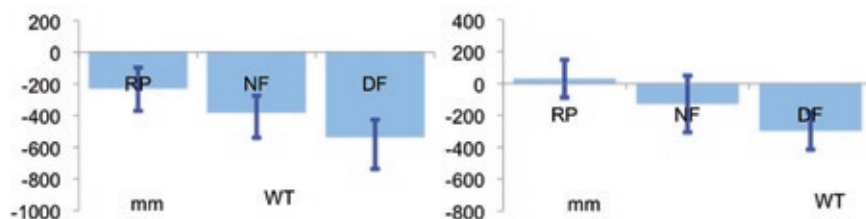
The South-West zone is characterised by one of the biggest reductions in total annual precipitation, especially in the DF: 73-146mm between the RP and the NF\* and 182-219mm between the RP and the DF\*. The decline in rainfall is most marked in the north of the zone, thus bringing the situation at Lusignan closer to those of Bordeaux and Toulouse. Of the twelve metropolitan sites studied, it is at Lusignan that we see the largest drop in total annual precipitation: 146mm between the RP and the NF and 220mm between the RP and the DF. In the DF, of the twelve sites studied, Toulouse will receive the lowest total annual precipitation: 474mm instead of 657mm in the RP.

A significant increase in the potential evapotranspiration (ET0\*) is seen at Bordeaux, Lusignan and Toulouse, whatever the downscaling method\*. The increases in the annual totals (30-year means) are:

- from 70 to 80mm between the RP and the NF and from 140 to 175mm between the RP and the DF with the WT downscaling method;
- from 75 to 90mm between the RP and the NF and from 220 to 230mm between the RP and the DF with the QQ downscaling method.

This represents (as a mean of the WT and QQ methods) a mean increase of 0.5-0.6mm per day between the RP and the DF. We have not studied the distribution between seasons of this increase, but the periods of high evaporative demand (spring and summer) will account for a large fraction of the increases.

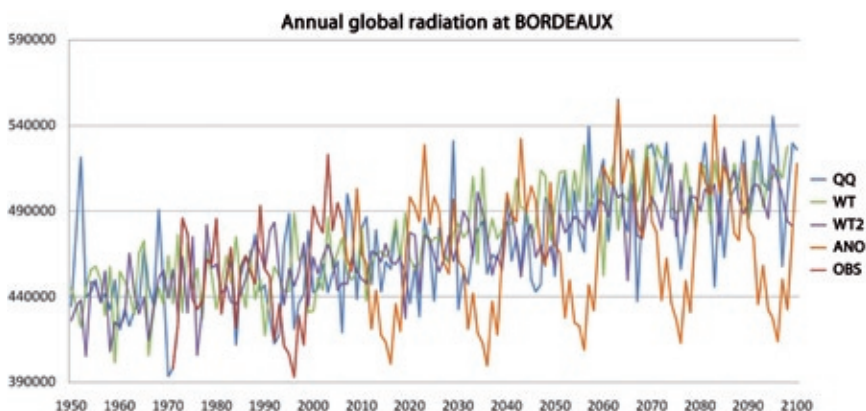
The concomitance of the reduction in rainfall and the increased evapotranspiration will lead (fig. 2) to a worsening of the annual climatic water deficit.



**Figure 2:** annual climatic water deficit (rainfall-ET0) in the RP, the NF and the DF at Toulouse (left) and Lusignan (right). ARPÈGE\* A1B\*. WT downscaling method.

## Global radiation

In the RP the mean annual global radiation at Toulouse is 485 000 (QQ method) to 487 000 (WT method) J/cm<sup>2</sup>/yr, or about 1 330J/cm<sup>2</sup>/day on average. A gradual increase is observed throughout the 21<sup>st</sup> century. In the DF, the mean annual global radiation reaches 544 000 (QQ method) to 553 000 (WT method) J/cm<sup>2</sup>/yr, or about 1 500J/cm<sup>2</sup>/day on average. At Lusignan the same trend is observed, with mean daily values from about 1 230J/cm<sup>2</sup>/day in the RP and about 1 375J/cm<sup>2</sup>/day in the DF. This increase in radiation of more than 150J/cm<sup>2</sup>/day explains the marked increase in the potential evapotranspiration (ET<sub>0</sub>).



**Figure 3:** change in the total annual global radiation (J/cm<sup>2</sup>/yr) from 1950 to 2100 at Bordeaux. ARPÈGE\* A1B\*. Standard downscaling methods: ANO, WT and QQ, to which were added the WT2 method (cf. CLIMATE section) and the data observed in the RP.

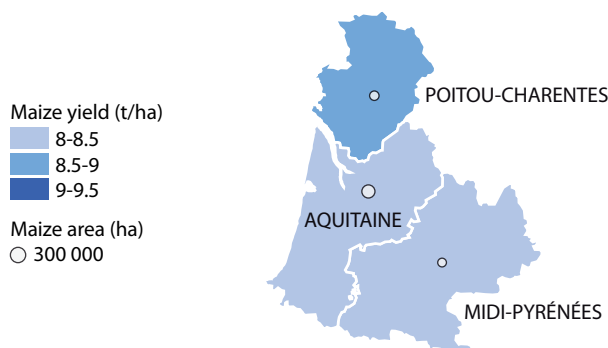
## A reminder of current agricultural production in the South-West zone (Source Agreste)

Crops	Area (ha)	% UAA	Yield t/ha
Grass leys	843 369	0.15	70
Grain and seed maize	741 350	0.13	85
Soft wheat	664 826	0.12	60
Sunflower	389 867	0.07	23
Vines	270 967	0.05	90
Forage and silage maize	175 370	0.03	116
Oilseed rape	140 806	0.03	31
Durum wheat	136 424	0.02	50
Sorghum	38 896	0.01	55
.../...			
<b>Total</b>	<b>3 401 875</b>	<b>0.61</b>	

The crops studied in the CLIMATOR project cover 61% of the UAA of the South-West zone. This includes 74 716 professional farms and 96 180 farmers and their associates. The total number of workers represents 159 736 Annual Work Units. The value of raw and processed agricultural plant products was 7.52 billion euros in 2008.

## B Main impacts of climate change on maize in the South-West

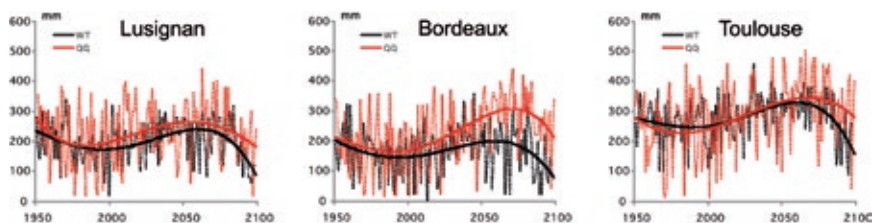
Everywhere in the South-West the yields of irrigated maize look likely to decrease if there is no change in varieties. This fall is about  $1\text{ t ha}^{-1}$  in the NF and  $1.6\text{ t ha}^{-1}$  in the DF for Toulouse and Bordeaux; slightly less for Lusignan.



**Figure 4:** current areas and yields\* of maize in the South-West zone (means 2000-2007). Source Agreste.

The reason is to be found in the phenology\* and in the reduction of the grain-filling phase which, because of the warming, is notably shorter: by about 10 days in the NF and 15 days in the DF. At the same time the irrigation water requirements increase until 2070 and, from then on, fall (fig. 5) because of the reduction in the lifespan.

Although this trend is identical for the two extreme downscaling methods, we see at Bordeaux a difference in the size of the increase. The fact remains that present levels of irrigation will be exceeded in the NF.



**Figure 5:** change in irrigation water requirements for a maize monocrop (varieties Méribel at Lusignan and DKC5783 at Bordeaux and Toulouse) on a deep silty soil (soil1) for the two climatic downscaling methods WT and QQ, smoothed with a 4<sup>th</sup>-order polynomial.

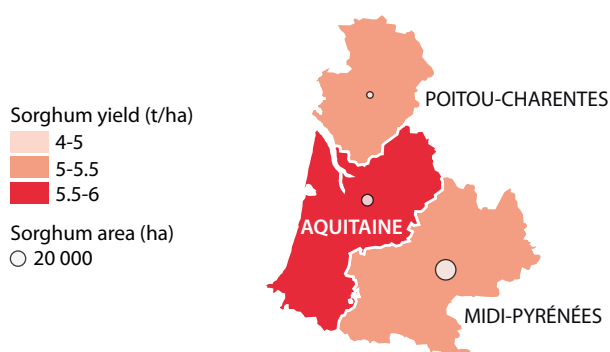
Bringing forward sowing, which is already effective, could continue at a rate of about one day every four years. Unfortunately it will not reduce irrigation requirements because of a combination of climatic factors favouring the increase in demand. In this context, the choice of soils is crucial: there is a difference of 70-100mm in irrigation between a soil with an AWR of 100mm and one with an AWR of 200mm. Only the use of longer-term varieties would allow maize yields to be maintained at their present level in the South-West, and that would increase irrigation water consumption even more. This suggests that we should seek alternative solutions.



## C Main impacts of climate change on sorghum in the South-West

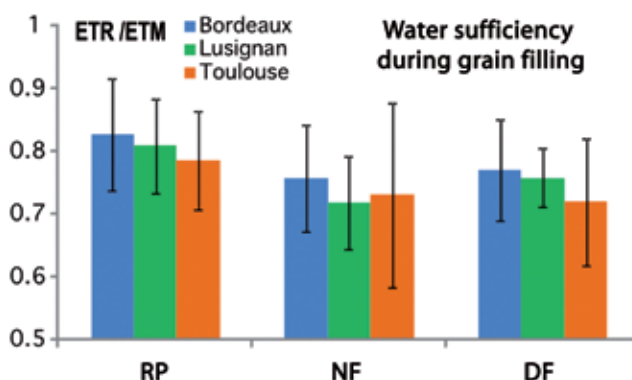
Rainfed sorghum suffers water stress\*, especially during the grain-filling phase. Yet the rainfall deficits predicted by the climate models\* will exacerbate this stress (fig. 7) and lead to a yield reduction in the NF of 0.6-1.0t ha<sup>-1</sup>.

However the situation will improve between the NF and the DF in Bordeaux and Lusignan sites, where escape\* (advancement\* of phases) and avoidance\* (low leaf area index\* and deep rooting) appear to combine to improve the water sufficiency\* of sorghum. Conversely at Toulouse, water sufficiency continues to worsen between the NF and DF



**Figure 6:** current areas and yields of sorghum in the South-West zone (means 2000-2007). Source Agreste.

Hence the yields in the DF will return to levels comparable with the RP: 5.4t ha<sup>-1</sup>(± 1.6) at Bordeaux and 4.5 (± 1,8) at Lusignan. At Toulouse it is the greater year-to-year variability in the water sufficiency\* which causes the average yield to fall: 4.2 (± 2.2).



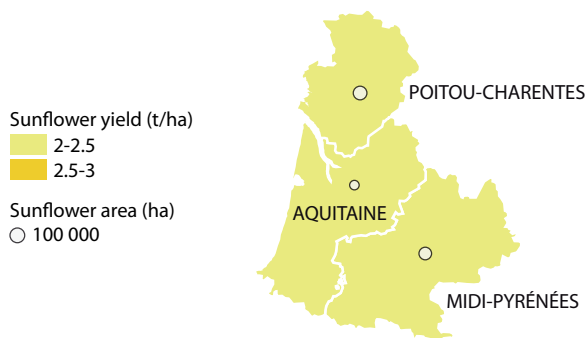
**Figure 7:** change in the water sufficiency\* of grain sorghum (variety Friggo at Lusignan and Fulgus at Bordeaux and Toulouse, soil 1) between the 3 periods, with an indication of variability including year-to-year and that due to the climate downscaling method.

Growing sorghum in less harsh conditions would be a way of greatly improving its yields. For example irrigating it to 50% of its water requirements would double yields at Toulouse for roughly 180mm water applied. Moreover without starter irrigation, earlier sowing, which would assist the crop to escape later drought, will be limited in the DF by the dryness of the seed-bed in spring.



## D Main impacts of climate change on sunflower in the South-West

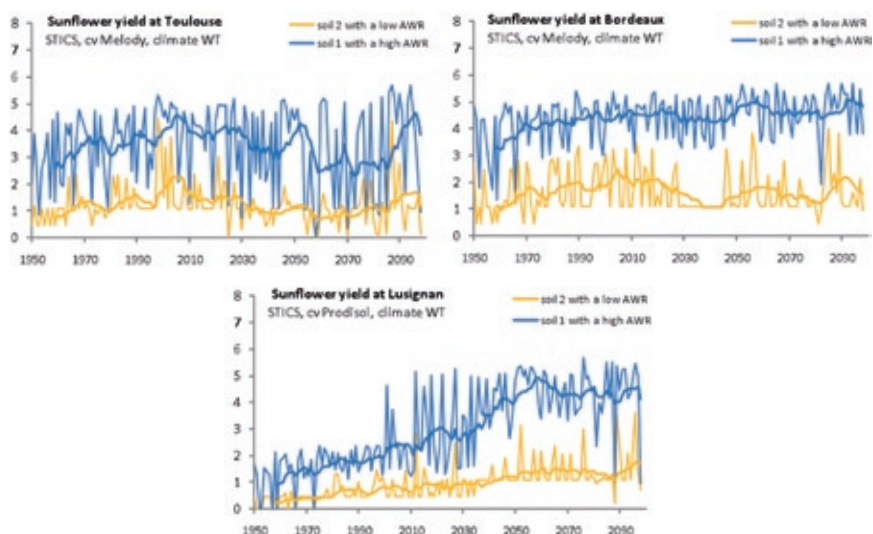
Without changes in varieties or relocating it from rather poor soils, the sunflower crop will change little, being subject to large year-to-year variability (fig. 9).



**Figure 8:** current areas and yields of sunflower in the South-West zone (means 2000-2007). Source Agreste.

This is because of a counterbalance between the benefits of increasing atmospheric CO<sub>2</sub> and the adverse effects of water stress, which are particularly severe on soils with a low AWR\* (fig. 9).

Geographical displacement towards the north (Lusignan) or onto richer soils offer prospects of substantial yield improvement.

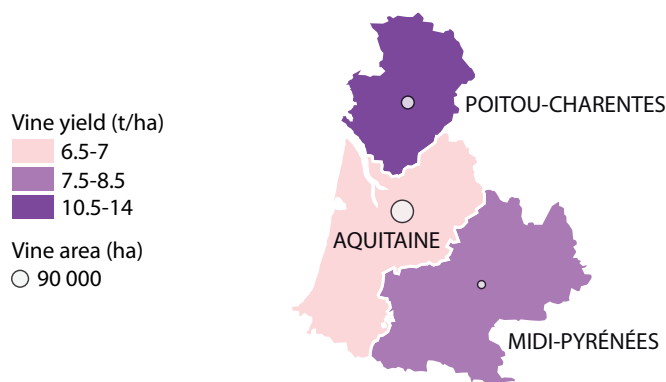


**Figure 9:** change in sunflower yield at Toulouse, Bordeaux and Lusignan for a soil with a high AWR (226mm) and one with a low AWR (104mm). Simulations for a rainfed cereal rotation (SWSgW) with the WT downscaling method. For each series the annual data are shown, together with a 10-year running mean.

Without changing soil, earlier sowing, which could take place from the end of March in the NF, would help quite a lot with escaping drought, but the most effective solution without doubt would be to use starter irrigation or supplementary irrigation during the vegetative phase.

## E Main impacts of climate change on vines in the South-West

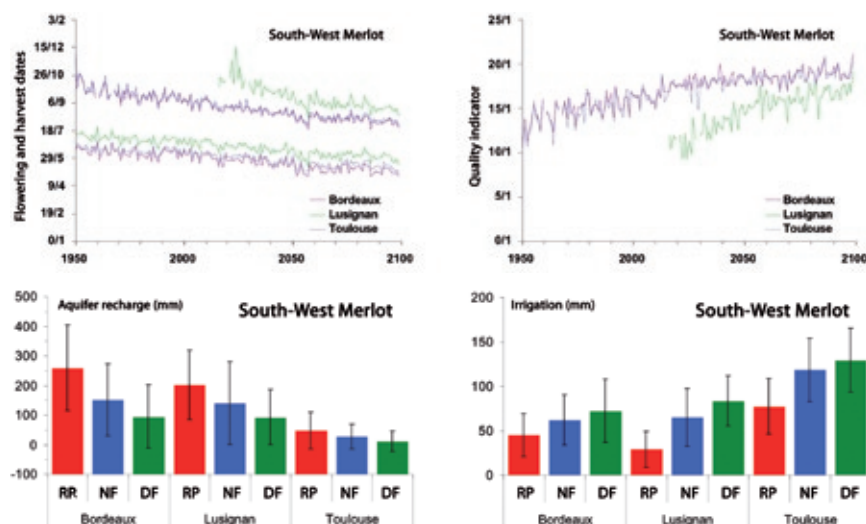
The South-West region is represented in CLIMATOR by three sites, two of which have a tradition of viticulture, and a third, Lusignan (half-way between Cognac and the Val-de-Loire), which already could, given suitable varieties, soils, and management systems.



**Figure 10:** current areas and yields of vines in the South-West zone (means 2000-2007). Source Agreste.

Vines in this region should follow very similar trends to those predicted generally, with a very clear advancement of development (fig. 11), a very large increase in temperatures during the maturation phase (fig. 11), a stability of water sufficiency until harvest and a very marked reduction in water transferred to the aquifer (fig. 11).

These trends are clear whichever weather pattern is simulated, but the QQ downscaling method predicts much more variability than the WT method.



**Figure 11:** change at the three sites in the zone; upper left: dates of flowering and harvest; upper right: quality index (minimum temperature during maturation); lower left: aquifer recharge; lower right: irrigation requirements (30% of ETM) – A1B scenario – WT downscaling method – Soil 1.

Irrigation requirements should increase, even with a low-input strategy (maintenance of ETR/ETM\* at at least 0.3, buried drip-feed system) because of the post-harvest water deficit (fig. 11). The simulations also show that the Lusignan climate should soon become suitable for merlot, with a temperature regime quite favourable for quality (fig. 11).



## F Main impacts of climate change on forests in the South-West

The behaviour of forest canopies is strongly dependent on the water status, particularly during the growing season (spring and summer).

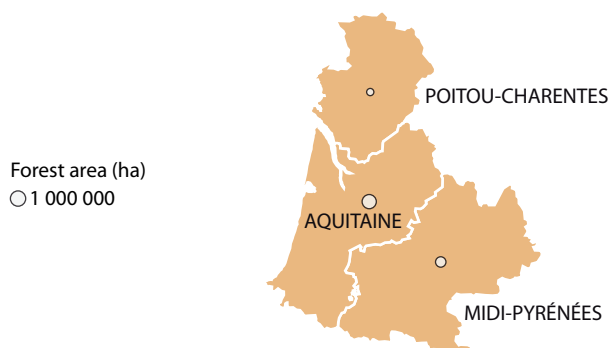


Figure 12: current areas of forest in the South-West zone (means 2000-2007). Source Agreste.

The increase in temperature (and hence the  $ET_0$ ) and in the rainfall predicted by the climate models (A1B scenario) leads (with the BILJOU and GRAECO models) to a reduction in the water sufficiency of trees (fig. 13a). The expected consequences of this increased water stress are a big decrease in aquifer recharge (of 125mm/yr in the DF) (fig. 13b) and a reduction in mean yields (fig. 14).

This fall in yield, small for Bordeaux in the distant future (7%), will reach 23% for the other two regional sites. These trends will be even greater on deep soils.

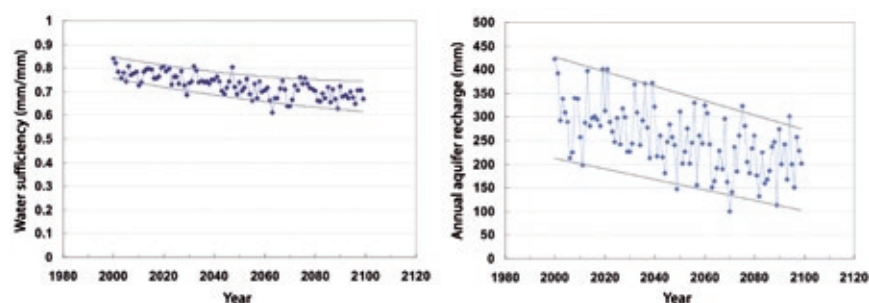


Figure 13: regional mean (Bordeaux, Lusignan, Toulouse) of the change in water sufficiency  $ETR/ET_0$  (left) and aquifer recharge of pines (right) (45-year rotation, soil 3) with a confidence interval (95%) due to the downscaling method.

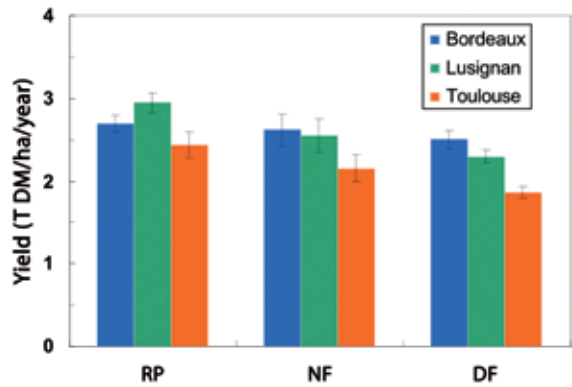


Figure 14: change in yields of pines (45-year rotation, soil 3, WT downscaling method) between the 3 periods, with the year-to-year variability.





# Climate change in the South-East zone: the main agricultural and forest impacts

**D7**  
South-East

Frédéric Levrault, Marie-Odile Bancal,  
Philippe Pieri, Alexandre Bosc



## Regions concerned:

- **Languedoc-Roussillon**
- **Provence-Alpes-Côte d'Azur**

Study site : Avignon

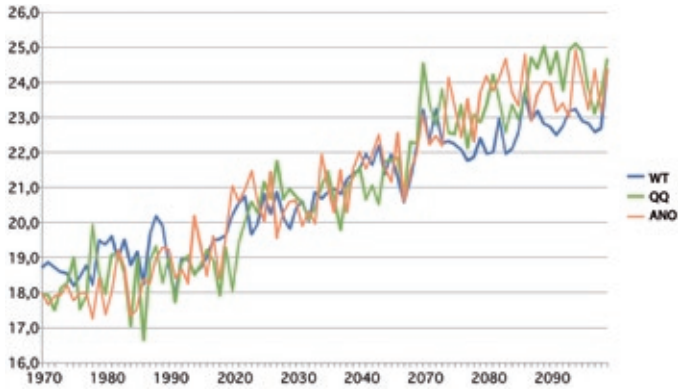
Land use	Area (ha)	% TA	Usable agricultural area	Area (ha)	% TA
Total area (TA)	5 956 502		Farms	1 665 124	
Woods and forests	2 212 196	0.37	Arable soils	502 417	0.30
Total UAA	2 080 968	0.35	Permanent grassland	696 149	0.42
Others	1 663 338	0.28	Permanent crops	466 558	0.28

*Severe decline in the annual climatic water deficit (rainfall-ET0), a slight lowering of the water sufficiency of vines, a slight yield reduction for rainfed wheat but an increase if irrigated, increased variability in aquifer recharge under forests and a reduction in their yields; these are the main trends revealed for the South-East region.*

## A Some striking facts about climate change\* in the South-East zone

### Temperature

In the NF\*, the increase in the mean annual temperature at Avignon (+1.4°C compared with the RP) is close to the average for the 12 study sites\* (+1.44°C). In the DF\*, the warming (+2.7°C compared with the RP\*) is less marked than that of the mean for the 12 sites (+2.83°C). At these two dates, the South-East zone remains, however, with the South-West zone, one of the warmest in metropolitan France. It is also in this zone that the change as regards high temperatures is significantly very damaging for cultivated species. Thus the mean number of heat stress days (with a maximum temperature > 25°C) during the months of April to June goes from 27 in the RP to 36 in the NF and 48 in the DF, i.e. almost a doubling.



**Figure 1:** change in the mean annual temperature (°C) from 1970 to 2100 at Avignon. A1B scenario\*. Downscaling methods\*: ANO\*, WT\* and QQ\*.

### Precipitation and evapotranspiration

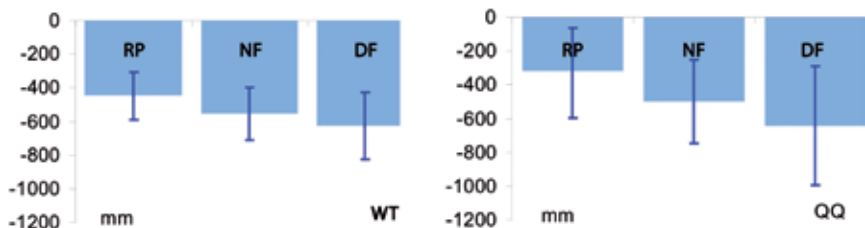
The South-East zone is likely to suffer one of the biggest reductions in total annual rainfall: 109mm at Avignon between the RP and the NF and 182mm between the RP and the DF. The total annual precipitation (NF: 730mm; DF: 657mm) however remains higher than those of the sites of Toulouse, Bordeaux, Lusignan, Colmar, Rennes and Versailles, both in the NF and the DF, indicating the maintenance of a Mediterranean rainfall pattern.

A detectable increase in the potential evapotranspiration (ET0\*) at Avignon is found, whichever downscaling\* method is used. The annual total (30-year means) thus goes:

- from 1 038mm/yr in the RP to 1 097mm/yr in the NF and to 1 147mm/yr in the DF with the WT downscaling method;
- from 1 032mm/yr in the RP to 1 127mm/yr in the NF and to 1 270mm/yr in the DF with the QQ downscaling method.

This represents (as a mean of the WT and QQ methods) a mean increase of 0.5mm/day between the RP and the DF. We have not studied the distribution between seasons of this increase, but the periods of high evaporative demand (spring and summer) will account for a large fraction of the increases.

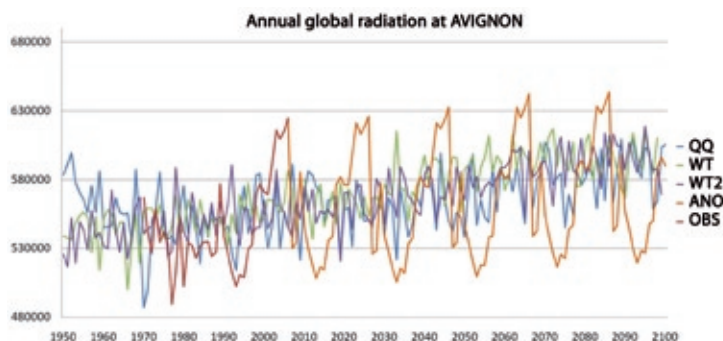
The concomitance of the reduction in rainfall and the increased evapotranspiration will lead (fig. 2) to a worsening of the annual climatic water deficit.



**Figure 2:** annual climatic water deficit (rainfall-ET0) in the RP, the NF and the DF at Avignon. ARPEGE A1B\*. Downscaling methods: WT (left) and QQ (right).

## Global radiation

At Avignon we see a continuous increase in global radiation over the whole period of the study (1970-2100). In the RP, the mean annual global radiation is 545 000 (QQ method) to 552 000 (WT method) J/cm<sup>2</sup>/yr, or 1 500J/cm<sup>2</sup>/day on average. In the DF, the mean annual global radiation is 585 000 (QQ method) to 595 000 (WT method) J/cm<sup>2</sup>/yr, i.e. a mean of 1 620J/cm<sup>2</sup>/day. This radiation “supplement” of more than 100J/cm<sup>2</sup>/day, together with the temperature increase, explains the significant increase in potential evapotranspiration (ET<sub>0</sub>).



**Figure 3:** change in total annual global radiation (J/cm<sup>2</sup>/yr) from 1950 to 2100 at Avignon. ARPÈGE A1B. Standard downscaling methods: ANO, WT and QQ, to which were added the WT2 method (cf. CLIMATE) and the data observed on the RP.



### A reminder of current agricultural production in the South-East zone

(Source Agreste)

Crops	Area (ha)	% UAA	Yield t/ha
Vines	373 095	0.22	73
Hard wheat	146 374	0.09	35
Grass leys	100 477	0.06	52
Sunflower	28 774	0.02	21
Grain and seed maize	10 133	0.01	71
Soft wheat	9 787	0.01	37
Oilseed rape	6 962	0.00	24
Sorghum	3 033	0.00	53
Forage and silage maize	2 477	0.00	93
.../...			
<b>Total</b>	<b>681 111</b>	<b>0.41</b>	

The crops studied in the CLIMATOR project cover 41% of the UAA of the Centre-East zone. This includes 30 156 professional farms and 36 317 farmers and their associates. The total number of workers represents 76 216 Annual Work Units. The value of raw and processed agricultural plant products was 4.5 billion euros in 2008.



## B Main impacts of climate change on vines in the South-East

The South-East region, represented in CLIMATOR by the Avignon site, already has a wine-growing tradition using the grenache variety which is very typical of regional vineyards.

In this region vines will follow similar trends to those predicted generally, with a very clear advancement of development (fig. 5a), a very big increase in temperatures during the maturation phase (fig. 5b) and stable or slightly worsening water sufficiency\* conditions until harvest. At Avignon, there will be very irregular transfer of water to the aquifer, rather than a steady but perceptible trend as in the other regions (fig. 5c).

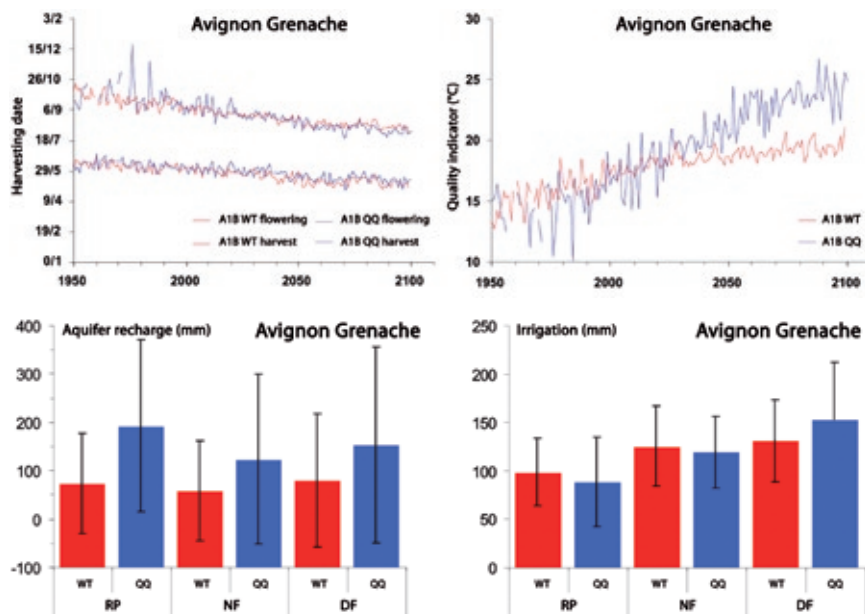
These trends are clear whichever weather pattern is simulated, but the QQ downscaling method leads to higher variability than WT and in particular a very big difference in minimum temperatures during maturation (fig. 5b).

Irrigation requirements should increase, even with an economical strategy (maintaining ETR/ETM\* above 0.3, buried drip system), mostly because of the post-harvest water deficit (fig. 5d).



**Figure 4:** current areas and yields of vines in the South-East zone (means 2000-2007). Source Agreste.





**Figure 5:** change from 1950 to 2100, at Avignon, of four climatic and agronomic variables associated with the growth\* and development of vines; above left: flowering and harvest dates; above right: minimum temperatures during maturation; below left: PERCOL\*; below right: irrigation requirements. A1B scenario. Downscaling methods WT and QQ. Variety : grenache.

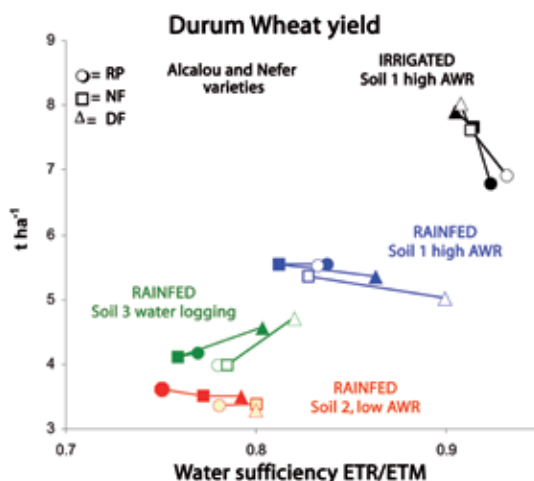
## C Main impacts of climate change on wheat in the South-East

The south, the main region producing durum wheat, accounts for nearly 39% of French production. In spite of this, the yields\* there are the lowest, with a mean of  $3.5 \text{ t ha}^{-1}$ , far behind the South-West ( $5 \text{ t ha}^{-1}$ ) and Centre-North ( $6.2 \text{ t ha}^{-1}$ ) zones.



**Figure 6:** current areas and yields of durum wheat in the South-East zone (means, 2000-2007). Source Agreste.

Figure 7 shows that, for a rainfed crop (SWSgW rotation\*), a favourable change appears to the water sufficiency during grain filling. This increase is mostly due to the adjustment in the stress which occurs during the vegetative phase of growth by a reduction in the leaf area index\*, a classic escape phenomenon which improves the water conditions at the end of growth, but reduces the number of grains and the yield.



**Figure 7:** change in durum wheat yield with the water sufficiency according to the variety (Alcalou in colour and Nefer in white), soil type and method of management (WT climatic downscaling method, STICS model).



One should add the increase in heat stress towards the end of growth: the number of heat stress days in spring is on average 37 for the RP, 58 for the NF and 83 for the DF (cf CLIMATE section). Hence, for soils 1 and 2, with very different AWR\*, the yields fall or remain unchanged in the DF, indicating that the increase in CO<sub>2</sub> and the water sufficiency\* during grain filling are not enough to raise the average yield level between the RP and the DF. Soil 3 is an exception, thanks to the reduction in waterlogging problems due to the decline in rainfall in the DF (of about 80mm/yr).

For an irrigated crop (MWRW), we find that yields tend to increase in the NF and DF despite a slight fall in water sufficiency. This is due both to better conditions during the vegetative phase, thanks to irrigation, and to an earlier sowing, thanks to the preceding crop of rape, which results in flowering 5 days earlier on average than in the rainfed rotation, and limits the heat stress at the end of growth.

## D Main impacts of climate change on forests in the South-East zone

The behaviour of forest canopies is strongly dependent on the water status, particularly during the growing season (spring and summer).



Figure 8a: current areas of forest in the South-East zone (means 2000-2007). Source Agreste.

The climatic changes modelled for the A1B climatic scenario for Avignon using the BILJOU and GRAECO models predict only a small reduction in the water sufficiency of trees (fig. 9a), already low for the reference period. Aquifer recharge is generally maintained over the period 2000-2100 (fig. 9b), with a very high year-to-year variability.

For this region, a reduction in mean yields of 8% in the NF and 16% in the DF is predicted by the GRAECO model (fig. 10).

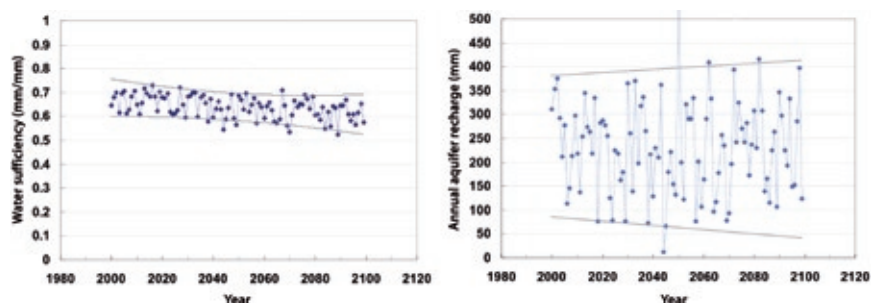
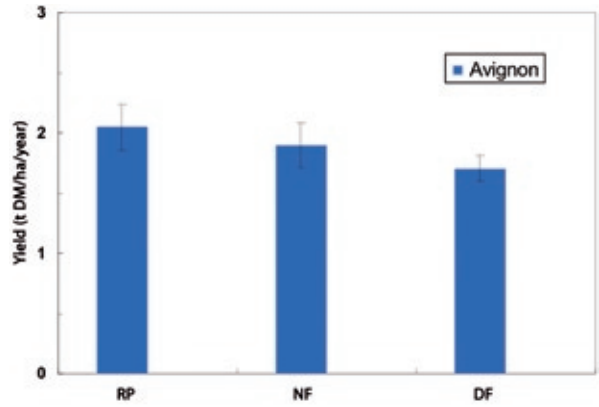


Figure 9: change in the water sufficiency (ETR/ETO) (left) and in the aquifer recharge under pine forest (right), at Avignon (45-year rotation, soil 3) with confidence interval (95%) due to the WT downscaling method.



*Figure 10: change in the yield of pines (45-year rotation, soil 3, WT downscaling method) between the 3 periods, with the year-to-year variability.*





# Climate change in the West Indies: the main agricultural impacts

Jorge Sierra



## Regions concerned:

- **Guadeloupe**
- **Martinique**

Zones analysed: Guadeloupe  
East and north of Basse-Terre (the Basse-Terre plain).

*An increase in temperatures but also of rainfall, a reduction in the yields of C4 species (sugar cane, maize) and maintenance of yields in the near future of C3 species (bananas), increase in nitrate concentrations in leaching waters if fertilisation is increased, decline in the soil organic matter due to increased mineralisation; these are the main trends revealed for the West Indian zone.*

## A Some striking facts about climate change\* in the West Indies zone

A: Annual; D: Dry season (January-June); R: Rainy season (July-December)

Period	Mean daily temperature °C			Rainfall mm/yr			Solar radiation MJ/m <sup>2</sup>		
	A	D	R	A	D	R	A	D	R
1970-99	24.8	24.3	25.4	2050	900	1150	18.1	18.4	17.7
2020-49	25.8	25.2	26.4	2500	1200	1300	16.7	17.0	16.3
2070-99	27.1	26.6	27.5	3500	1600	1900	15.1	15.8	14.5

**Table 1:** ARPEGE A1B\* scenario, QQ downscaling (cf. CLIMATE section).

Firstly we need to point out that the uncertainties\* about climate change, especially in Guadeloupe, are greater for rainfall than for temperature (cf. CLIMATE section). According to the scenario analysed, the climate of the Basse-Terre plain will become hotter and wetter. Compared with the present situation, the temperature will increase by 1°C in the NF and by 2.3°C in the DF\*. This increase applies both to the dry season and the rainy season. The annual rainfall will also increase steadily, by 22% in the NF and 70% in the DF. The increase will be relatively larger in the dry season: 33% in the NF and 75% in the DF. Because of the greater cloud cover, the solar radiation reaching the crops will fall by 8% in the NF and by 18% in the DF.

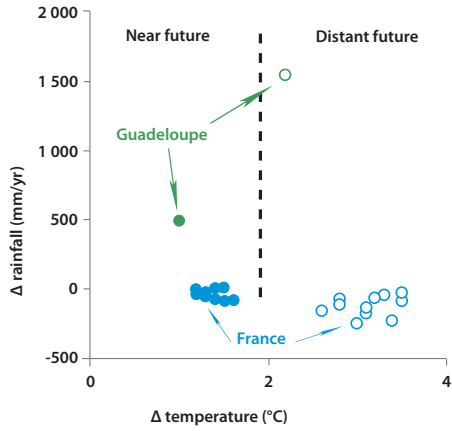


Figure 1: climate change in mainland France and in the Basse-Terre plain (CNRM A1B).

For the two periods analysed, the increase in temperature in the Basse-Terre plain will be the least among the sites studied. The opposite is true for rainfall.

B A reminder of the current agricultural production  
(Source Agreste 2007)

Crop	Area(ha)	Agricultural yield (tonnes/ha)	Fraction of the UAA in Guadeloupe (%)
Sugar cane	6 000	65	17
Bananas	2 000	25	6

The cropping systems studied in CLIMATOR represent 23% of the 2006 UAA of Guadeloupe and 75% of the UAA of the zone analysed (fig. 2).

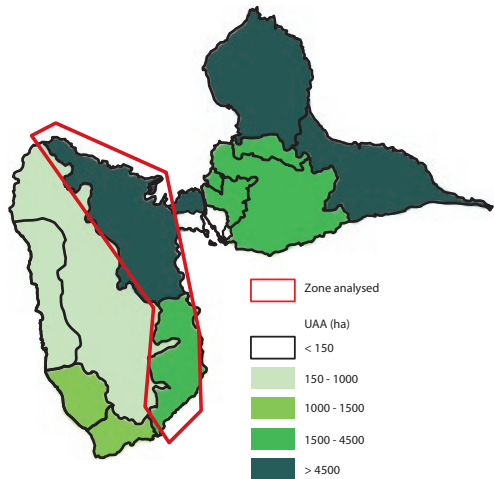


Figure 2: UAA in each zone in Guadeloupe.



## C Effects of climate change on some cropping systems in the Basse-Terre plain

### Sugar cane

The results are for the variety B69566, without irrigation, fertilised with 150kg N/ha/yr and mechanically harvested.

The yields\* of cane will decline both in the NF (by 14%) and in the DF (by 23%) (fig. 3). The reduction in sugar yield will be even greater due to a lower sugar content at harvest: 16% and 32% less in the NF and DF respectively. These results should be attributed to the shortening of the growth cycle\* (due to the temperature increase) and to the reduction in solar radiation. The increased CO<sub>2</sub> is of little benefit to cane, being a C4\* plant.

### Bananas

The results are for the variety Grande Naine, without irrigation and fertilised with 400kg N/ha/yr (50kg at planting and 25kg every ten days until flowering).

The fall in yields should be small in the NF (1%), and greater in the DF (7%) (fig. 3). For this crop, there is partial compensation between the positive effect of CO<sub>2</sub> (bananas being C3\* plants) and the shortening of the growth cycle, caused by increasing temperature. The reduction in the solar radiation should not significantly affect banana yields.



### Maize

The results are for the Guadeloupan variety Spectral, without irrigation and fertilised with 150kg N/ha/yr.

Of no great importance in Guadeloupe, maize is an important food crop in the tropics. Because of this, and because it is an example of a very short-term crop (three months) we decided to do some tests on the effect of climate change on it. The results obtained (fig. 3) and the climatic factors involved are similar to those mentioned for sugar cane (maize is a C4 plant).



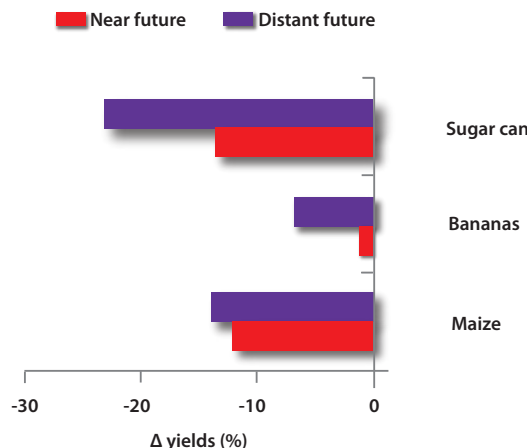


Figure 3: effect of climate change on yields.

## D Some major agro-environmental challenges from climate change in the Basse-Terre plain

### Water quality (nitrate concentration)

The increased rainfall will not necessarily cause more nitrate leaching into aquifers, provided that fertiliser rates are not increased. This is due to the capacity of the soils of the region, notably in the banana-growing zone, to retain some of the nitrate. On the other hand if this retention capacity were to become saturated as a result of excessive fertiliser application, an increase in the leaching of nitrates and of their concentration in the drainage water would ensue.

### Soil organic matter

Figure 4 shows that the organic matter would decline over time, regardless of the crop considered. On average, the reduction is 7% in the NF and 13% in the DF. This is due partly to the acceleration of mineralisation\* due to the temperature increase and partly to the reduction in returns as crop residues.

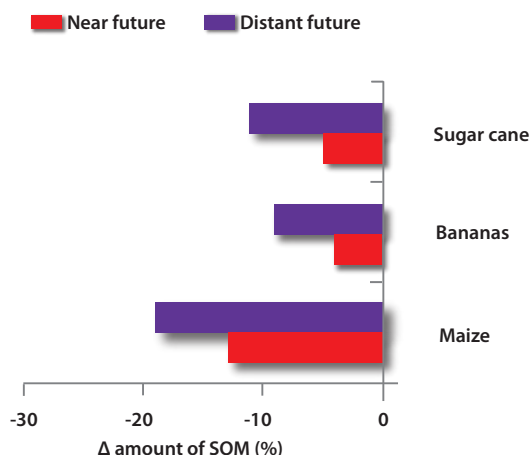


Figure 4: effect of climate change on the quantity of soil OM.

## Adaptations identified

There is no “one” strategy of adaptation to cope with climate change, but some measures to take into consideration to alleviate and/or avoid the harmful aspects (for example the effect of temperature on the lifespan) and to profit from the beneficial aspects (for example CO<sub>2</sub> and extra dry-season rainfall). In this respect, the increase in crop biodiversity (rotations, crops and associated varieties, leguminous crops, mixed cropping and livestock) would help to minimise the risks and diversify the sources of income. At the same time, these practices help to protect the soil by reducing the risk of degradation and by increasing the input of organic matter into the soil. More widespread use of plant mulches (which cool the soil) and the application of composts, would also help to maintain soil organic matter content.

From the point of view of the cropping calendar, the aim would be to shift the growing cycle towards the periods when the climate is most favourable to production (for example the wetter dry season). For example it might be a case of avoiding exposure to limiting factors (rainy season temperature) or even prolonging the growth cycle, which would lead to an increase in potential yields.

Genetic improvement has an essential role to play in the adaptation, both as regards varieties with higher temperature thresholds and in the increase in harvest indices (i.e. to increase the efficiency of conversion of biomass into yield), notable for short-term species, such as market garden crops.

## New farming possibilities introduced by climate change

Tuberous plants (C3) could be grown more, notably in the north of the region analysed, without the problems associated with the use of Chlordecone. Earlier planting dates, by taking advantage of the photoperiodic effect and the prolongation of the vegetative period, would favour the later growth of the tuber. Crops like maize and market garden crops, which are very susceptible to water stress, could be grown with the help of the improved water supply, provided that one could be sure of having varieties adapted to the higher temperatures.



### What you need to remember

- ✓ Of the export crops, sugar cane seems to be the most affected by climate change: it should not benefit from the increase in CO<sub>2</sub> concentration and would suffer from the effect of the temperature on shortening the growth cycle. Short-term crops, such as vegetables, would be particularly affected by the temperature increase because of the reduction in the periods of growth and filling of harvested organs. The most problematical environmental aspect concerns soil degradation due to the loss of organic matter.

### What needs further study ...

- ✓ Most of the currently-available crop models\* do not contain sufficiently precise hypotheses about the changes in risks from pests and diseases to include them in a more complete adaptation scheme. This includes the growth of weeds, fungal diseases and insect pests in a warmer, wetter climate. Also, the climatic scenarios do not take account of changes in the hurricane risk (frequency, intensity, and geographical distribution in the Caribbean). These two factors could greatly affect bananas and the considerations mentioned above for this crop. Regarding diseases, we need to improve our knowledge of changes in the pathogens already present in Guadeloupe and also on the migration and introduction of new plant pests.
- ✓ There is currently a wide scientific debate about the importance of thermal adaptation of soil micro-organisms and its effect on the degradation of the organic matter. This subject began to be explored about ten years ago in temperate countries, but very little information is available yet for tropical soils. The meaning of such adaptation concerns the reduction of the consequences of the increased temperature on organic matter content. It is essential to increase our knowledge of this topic to decide whether climate change will cause a severe loss of quality in Guadeloupan soils.

