REPONSE DES FORETS MEDITERRANEENNES FRANÇAISES AUX CHANGEMENTS CLIMATIQUES

RESPONSE OF FRENCH MEDITERRANEAN FORESTS TO CLIMATE CHANGE

GICC Programme 2003 Call for Research Proposals

End of Contract Report

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SUMMARY REPORT

(intended for users and public managers)

RESPONSE OF FRENCH MEDITERRANEAN FORESTS TO CLIMATE CHANGE

GICC 2003 CALL FOR RESEARCH PROPOSALS

Written by: J. Guiot, with: F. Guibal, R. Huc, L. Misson, S. Rambal, J.P. Ratte, M. Vennetier

GENERAL BACKGROUND

The Mediterranean biome (which is present on four continents) is rightly considered to be a biodiversity hotspot: whilst it only covers 2% of the earth's surface, it contains almost 20% of its total plant diversity[1]. The Mediterranean basin region provides a model for the study of global change (climate-induced and anthropogenic)[2] in that, from the bioclimatic point of view, it is situated in a transitional zone, the complexity of which is heightened by its topography and which makes it particularly sensitive to changes. The northern part of the basin is undergoing very different changes compared with the southern part[3], with a spreading of wooded areas caused by abandonment of land for farm use. Forests are crucial for preserving this biodiversity and providing essential ecosystem services such as soil protection, preservation of water resources and climate regulation[4]. Climate models predict significant warming and lower rainfall in the 21st century[5], which could trigger positive feedback on the climate by reducing ecosystem carbon capture.

The salient feature of the Mediterranean climate is the frequency and severity of extreme events (heat waves, heavy rain) and these are expected to increase over the next few decades[6]. The 2003 heat wave is a good example, which led to a 30% reduction in primary productivity in Europe and thus wiped out the equivalent of four years' carbon capture[7]. If this type of extreme event becomes the norm, it is important for us to understand how the French Mediterranean region's dominant forest types, namely Aleppo Pine and Holm Oak, will respond to the changes predicted by climate models[8]. From a more practical point of view, gaining a better understanding of how these species will shift in altitude in response to climate change may help managers decide on how best to manage these forests in order to mitigate the consequences of the anticipated changes to the extent possible.

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[1] Medail, F., 2006. Ecosystems: Mediterranean. Encyclopaedia of Ecology, S.E. Jorgensen (ed), Elsevier, Amsterdam, 14p.

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[3] Barbero, M. & Quézel, P. 1995. Desertification, desertisation, aridification in the Mediterranean region and global change. In: D. Bellan, G. Bonin & C. Emig (eds.), Functioning and dynamics of natural and perturbed ecosystems, Pp. 549-569.

[4] Eamus, D. et al., 2005. Ecosystem services: an ecophysiological examination. Australian Journal of Botany, 53(1): 1-19.

[5] Gibelin, A.L. & Deque, M., 2003. Anthropogenic climate change over the Mediterranean region simulated by a global variable resolution model. Climate Dynamics, 20(4): 327-339.

[6] Meehl, G.A. and Tebaldi, C., 2004. More intense, more frequent, and longer lasting heat waves in the 21st century. Science, 305(5686): 994-997.

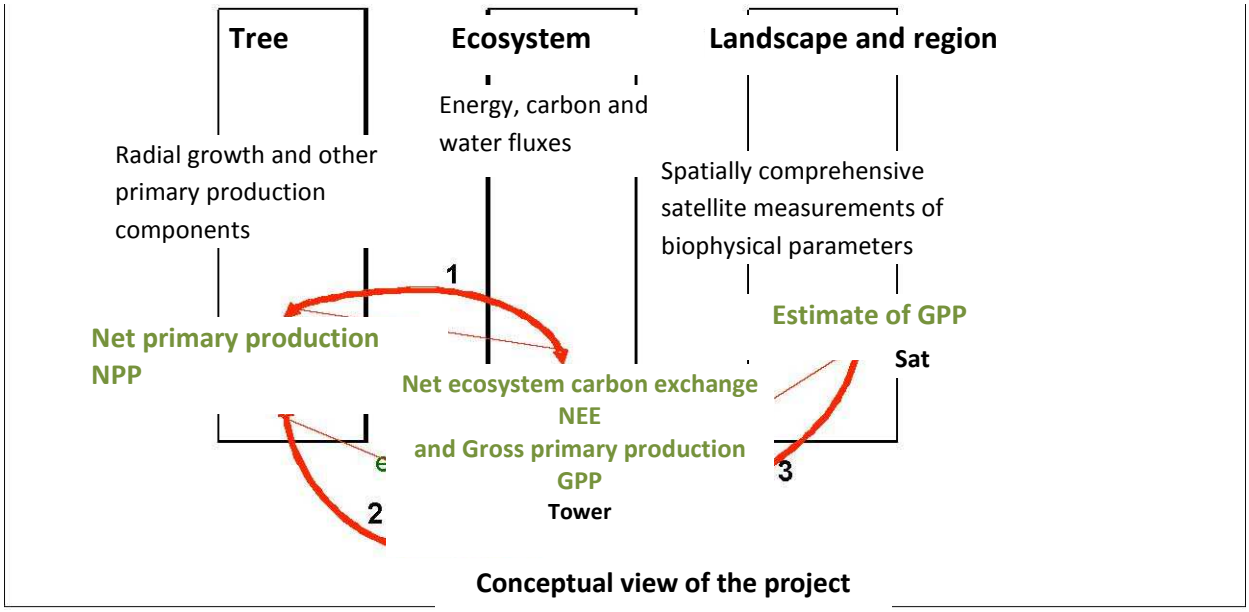
[7] Ciais, P. et al., 2005. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature, 437(7058): 529-533.

[8] IPCC, 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

It is in this climate change context between now and 2100 that the REFORME project hopes to make a contribution.

OVERALL AIMS OF THE PROJECT

The overall aims of the REFORME project are to examine how climate change and increased atmospheric CO_2 levels are affecting and will affect the productivity of Mediterranean forest species and the structure of landscapes. We also look at the future of the current stands in the face of alterations caused by climate change to disturbances and the effects on the landscapes and their diversity and structure. The model species chosen were Aleppo Pine and Holm Oak. The final aim is to provide forest managers and decision-makers with information about the future development of forest stands at a regional level, especially the evolution of landscapes, but also more accurate local information on the forests' future development, in accordance with their geographical locations and the characteristics of the environment in which they are growing (topography, soil, structure).



Conceptual view of the project

To achieve this overall aim, a data analysis strategy needs to be devised, based on both measuring stations and large spatial gradients and modelling. In particular, our approach is based on comparing different parameters associated with the carbon cycle (NEE, NPP, GPP) either measured by flux towers or modelled on the basis of satellite data.

In order to fine-tune our models, a large body of field data was measured and/or compiled. This allowed us to analyse the impact of climate on the establishment, growth and survival of the pines' aerial parts (stems, needles, flowers, fruit) and on the trees' annual growth (dendrochronological approach). This information should provide a clearer picture of the resource allocation processes (carbon, etc.) going on in the plant.

In terms of extreme events, we attempted to establish what the consequences of exceptional climate events are, such as extreme hot weather, drought and heavy snow, which regularly have a significant and sometimes lasting impact on the stands' productivity. These events are likely to become more frequent in the future and it is important to take them into account in vulnerability studies.

Finally, by using future climate scenarios (produced here by the ARPEGE model) and an annual tree growth model, we aimed to test the sensitivity of the two model species to climate change only and to changes in atmospheric CO_2 levels (fertilisation effect) in order to reveal how long it may be before the potential stresses start to have a lasting effect.

SOME ELEMENTS OF METHODOLOGY

Our approach was based on measurements made in stations equipped with sensors, field measurements consisting essentially of dendrochronological series and stem elongation measurements, and on three very different models.

1. Data Gathering and Experiment Plans

The Puéchabon site (CEFE-Montpellier), in the hinterland behind Montpellier, was set up to investigate the Holm Oak's behaviour. It has been part of the European carbon flux measurement network (Carboeurope) since 1988. It is equipped with a large number of sensors taking micrometeorological and ecophysiological readings, a flux tower and a rain exclusion device designed to investigate the impact of controlled water stress. Dendrochronological analyses of oaks were carried out within the framework of this project (IMEP).

The Lamanon site (INRA-Avignon), near Salon-de-Provence, was set up to investigate the behaviour of a mixed forest (pine, oak, box). It is equipped in a similar way to the Puéchabon site (with the exception of the flux tower and the rain exclusion device). Soil analyses, water potential and hydraulic conductivity are also carried out regularly, as well as stem and leaf area monitoring (CEMAGREF).

The Font-Blanche site (INRA-Avignon, IMEP-Aix, CEREGE-Aix), situated southeast of Aubagne, should have been equipped at the beginning of the project. For financial and administrative reasons, it was only equipped in Spring 2007. It is also a mixed forest site and has a flux tower. Growth measurements of aerial parts were carried out in the context of this project (CEMAGREF).

We also have a network of 21 sites where dendrochronological series (IMEP) were sampled prior to this project. These series provide data on thicknesses and density fluctuations throughout the year for the site's different representative trees.

2. Databases, Scenarios, Satellite Data

The CEFE-Montpellier database contains information on the distribution of the two model species across the 12 départements bordering the Mediterranean. The MODIS-TERRA database supplies the traditional indices associated with vegetation (NDVI, LAI, GPP …) at spatial resolutions from 250-1000m. Data on source rock and maximum soil water capacity are also available for the vegetation modelling.

Simulations provided by the Météo-France ARPEGE model (50km resolution) were geospatially referenced and downscaled to a 1km scale (CEFE-Montpellier). They provide the usual climate variables (temperature, precipitation, wind, radiation …) at a daily scale.

3. Vegetation Models

MAIDEN is a mechanistic tree growth model governed by meteorology and field data (CEREGE-Aix). The processes that are taken into account are essentially those of the water and carbon cycles. Its main purpose is to reproduce an annual parameter that is close to a tree growth ring (yearly biomass increase in the trunk), which can be done by simulating seasonal changes in carbon allocation in the different compartments: roots, leaves, trunk and storage reservoir, which ensures that a portion of the carbon is available for later years. This model was developed by Misson (2004)[9] but has been improved during this project. The model's various empirical parameters were estimated on the basis of the Puéchabon and Lamanon measurements and dendrochronological series, using highly efficient Bayesian algorithms. The model proved suitable for simulating mean annual growth of Aleppo Pine (averaged across the 21 sites) and that of the Puéchabon Holm Oak.

BILHY is a statistical model developed by CEMAGREF-Aix. It is based on floristic and forest mensuration data from a network of 350 sample plots representing the main ecological gradients, spread across the whole of limestone Provence. It is used to assess the water balance in forest environments and their potential productivity at scales ranging from regional (7000 km²) to local (tens of metres). This model has been reworked in the context of this project in order to set the project's research elements in a regional context.

The SIERRA model (CEFE-Montpellier) is essentially designed for environments with restricted water supplies subject to repeated disturbances such as fires. The model's basic principle is the use of functional biomass growth processes to simulate the succession of species. The model is used in the context of this project to calculate drought indices for the period 1970-2100.

RESULTS OBTAINED

1. Response of Holm Oak

The dendrochronological approach is a large temporospatial scale approach. It does not easily isolate the various factors that determine a tree's growth, but it incorporates wide variability, on the basis of which lessons can be drawn after the event. The measurements taken in Puéchabon are space and time restricted, but each growth parameter is measured separately. This leads to a very high process resolution, but over a limited number of years. Both approaches tend to provide converging responses on Holm Oak growth. It is the variability in April, May and June that dictates variations in growth (observed via dendrochronology) and carbon fluxes (observed via flux tower). This is a vital finding from this research, for both the dendrochronology and the micrometeorology communities. It will be interesting to test this result on Aleppo Pine as soon as the NEE data is available for Font-Blanche.

The dendrochronological approach could only be used on seven cross-dated stems out of 15 stems collected from the dominant species. The study showed us that the size of the sample from the Holm Oak must be greater than the size currently used in standard dendrochronology studies. Nonetheless, and this is both the cause of this lack of replication and an important finding of the analysis, variability in growth of the oak between individual subjects

[9] Misson, L. 2004. MAIDEN: a model for analyzing ecosystem processes in dendroecology. Canadian Journal of Forest Research, **34**, 874-887.

is high. It will be important to find out why this is: is it due to the method of reading the growth rings, the micro-environment, genetic variability, ...? This approach should therefore be pursued and will yield important findings.

Gross primary production (GPP), which is the total amount of CO_2 uptake by the plant during the photosynthesis process, is an important parameter in understanding how the tree assimilates atmospheric carbon. Satellite images such as those supplied by MODIS, are a useful tool for estimating this, but need to be adjusted. The main problems with satellite estimation of GPP are during the summer period, as drought in the Mediterranean region comes from the ground, not the air. There are also weaknesses in leaf area index (LAI) estimation, which MODIS systematically overestimates.

The effect of exceptional events such as the 2003 heat wave reduced *GPP* by 12% but without any major effect on ecosystem respiration. The defoliation suffered by the trees in 2005 in the wake of a caterpillar attack reduced *GPP* by 28% and ecosystem respiration by 11%, with a resulting 66% increase in NEE (and hence a 66% reduction in the carbon sink effect). It is interesting to note that a factor such as a caterpillar attack can have a greater impact on vulnerability than a series of droughts. Rising spring temperatures may lead to increased frequency of caterpillar attacks in future.

2. Response of Aleppo Pine

We demonstrated that morphogenesis and growth in Aleppo Pine are governed by the combined climate conditions of several successive years. Extreme climate events, in particular heat waves and intense droughts, have negative repercussions on growth lasting several years, and cumulative effects which we were able to measure following the 2003 heat wave and the three years of considerable drought that followed it. The weakening of the trees is seen in a 30 to 60% decrease in size of needles, number of needles produced, length of annual new growth on branches and fruit production. After three years of drought, polycyclic growth ceases almost completely.

We show that the productivity model for Aleppo Pine is highly sensitive to small rises in annual and seasonal temperature. These are reflected in significant alteration of the weight of dominant climate parameters in the model, mainly due to variations in the length and early onset of the vegetation season, and f how early the soil water reserves laid up in winter are used. This means that with warming, the trees would become considerably sensitive (negatively) to May and June temperatures, to which they were previously indifferent at moderate altitudes. The trees would also become more sensitive to lack of rain from May onwards, which extends the period of vulnerability to drought. Higher temperatures in the previous October would however be in their favour, allowing them to build up reserves at a later stage and possibly to continue their autumnal growth in height and diameter in the event of late polycyclic growth. We saw previously, however, that prolonged Spring droughts are a disadvantage for polycyclic growth.

3. Comparison between Aleppo Pine and Holm Oak

For the period 2003-2006, we note that growth in height and diameter decreases significantly after 2003. Many trees are dead or have dying tops (30% of the oaks and 20% of

the pines). The oaks have died back more in plots in which they were dominant and places where the soil is shallower, whilst the pines have died back more wherever there are fewer of them and where they are not as tall.

We observed that transpiration values in both pine and oak were much lower than potential evapotranspiration. There is generally a marked drop in transpiration at the beginning of the dry season, when water stress increases. The soil drought which occurs in the summer leads to a drop in baseline soil water potential. Gas exchanges are then halted by closure of the stomata. Among the mixed stands, we observe that this closure occurs earlier on during the dry season in pine than in oak. Pine therefore behaves like a species avoiding drought, whilst oak, due to its location under the canopy, functions throughout the summer with no apparent stress. Pine is also more susceptible as a species to xylem embolism than oak.

4. Vulnerability of Aleppo Pine and Holm Oak to climate change

Figure 1 simulates an aridity index (WSI) over time, based on the "Puéchabon" grid point in the Arpège simulation. It shows continuous linear increase in water stress and an increase in extreme events.

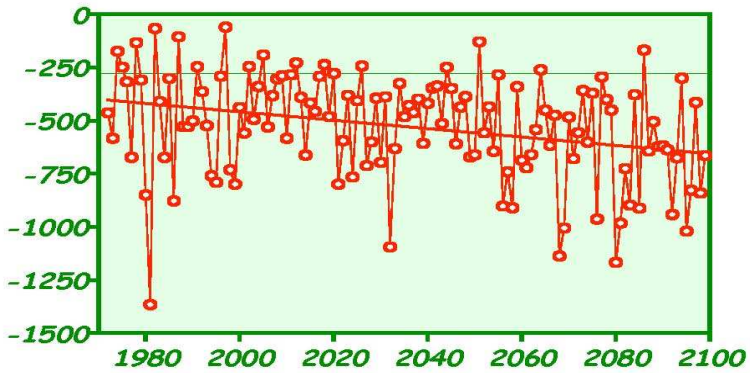


Figure 1. Development of WSI (water stress integral) according to climate change simulated by ARPEGE for the grid point closest to Puéchabon

A cumulative effect model and a model of recovery after extreme events were calibrated to adjust the dendroecological model forecasts, which regularly need to be calibrated to exclude the most extreme events, and are not capable of taking lasting reduction in leaf surface and deterioration of the trees' state of health into account. These adjustments, applied to the forecast for developments in Aleppo Pine productivity in the 21st century, showed a downward trend from the beginning of the century, which contradicts simulations that do not take this effect into account (Figure 2).

A link was established between Aleppo Pine productivity and water balance indices calculated by the model. We were therefore able to assess Aleppo Pine productivity in an average soil and its development over the 21st century, and upscale it to the regional scale. Since Aleppo Pine is particularly sensitive to local water balance parameters, there is a strong interaction between local water balance (soil and topography) and climate. In terms of wood production, we showed a drop of between 2.5 and 3.5 $m^3*ha^{-1}*year^{-1}$ for Font-Blanche, representing a loss of around 28%, and a drop of between 4 and 5.75 $m^3*ha^{-1}*year^{-1}$ for Lamanon, representing a 30% loss. Loss of total biomass production is in the same region.

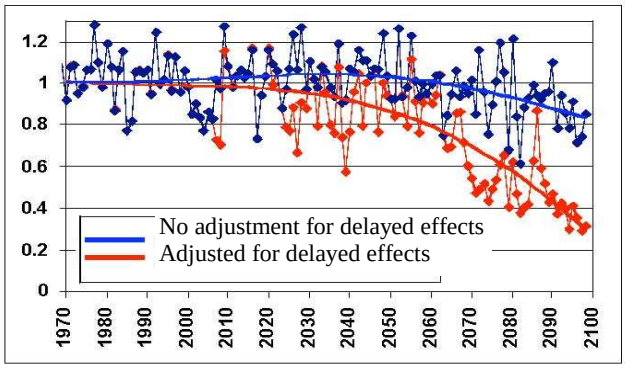


Figure 2: Productivity simulation (dendrochronology-based growth index) for Aleppo Pine in the 21st century. The sudden plunge after 2065 is due to more frequent occurrence of heat waves plus recurrent springtime droughts.

If the MAIDEN results are taken in isolation, there appears to be a discrepancy with the conclusions suggested by the measurements. The measurements show that drought causes considerable damage to Mediterranean forests, both to Aleppo Pine and to Holm Oak. The MAIDEN simulations show stable productivity throughout the first decade of the 21st century, in spite of the recorded droughts (Figure 3). Furthermore, if the fertilisation effect is taken into account, MAIDEN appears to show that it completely cancels out the climate change effect. If this were the case, the forests would have already benefited from this fertilisation. Between 1950 and 2000, CO_2 levels rose from 300 ppmv to 375 ppmv (+25%), but this does not appear to have boosted growth in the two species, which have remained highly sensitive to drought. It therefore seems that extreme but infrequent climate events have a greater impact that small but continuous changes in climate. Clearly, several of the MAIDEN model processes need to be reviewed or added to: carbon allocation, acclimatisation to CO_2 changes, organic material quality, delayed effects due to deterioration in the trees' state of health and reduction in leaf surface…

Another explanation relates to the ARPEGE simulations. The scenario used is not in complete agreement with the climate that has been recorded. Whilst the latter showed increasing aridity over the last few decades of the 20th century, the simulations suggest decreasing aridity over the same period, due mainly to a slight decrease in temperatures (0.5°C over the last 20 years of the 20th century) and stable precipitation levels. This may account for why the aridity simulated by ARPEGE is not high enough to show any increase before 2020 (the point at which it exceeds the 20th century values).

A comparison between the Holm Oak and Aleppo Pine simulations reveals interesting results (Figure 3). Both species reach a peak during the first decade of the 21st century, but the oak's productivity levels off at 1.8 $Tg*ha^{-1}*year^{-1}$, whilst the pine levels off at 5.7 $Tg*ha^{-1}*year^{-1}$, a difference of 3:2. Then, as the drought intensifies, productivity for both species decreases until the end of the 21st century, the first down to 1.3 $Tg*ha^{-1}*year^{-1}$ (72%) and the second down to 5.3 $Tg*ha^{-1}*year^{-1}$ (92%). So the pine appears to withstand water stress (taken in isolation) better. If fertilisation effect is taken into account, both species appear to withstand conditions much better, as by the end of the 21st century, the oak reaches mean productivity of 2 $Tg*ha^{-1}*year^{-1}$ (110%) and the pine 6.7 $kg*ha^{-1}*year^{-1}$ (118%). These values should be viewed as trends: under the ARPEGE-simulated climate, CO_2 fertilisation would

start to mitigate the aridity effect from the beginning of the 21st century onwards and pine should withstand conditions significantly better than Holm Oak.

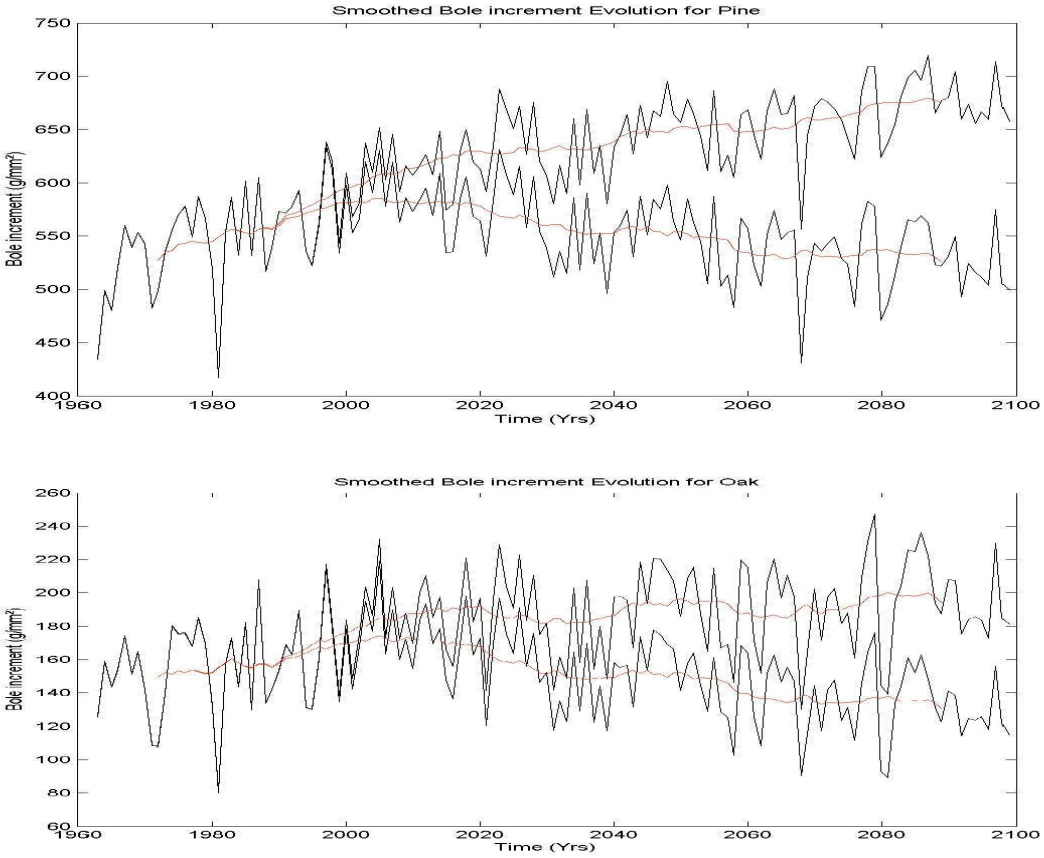


Figure 3: Mean annual production graphs for Aleppo Pine (top) and Holm Oak (bottom) in south-Eastern France, based on ARPEGE scenarios, with (top curve) and without (bottom curve) direct effect of atmospheric CO_2 level. The red lines represent a 20 year moving average.

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This positive growth trend is not confirmed by the recovery model (Figure 2), which takes delayed effects into account. However, the inclusion of delayed effects is statistical, which makes any extrapolation beyond the calibration limits problematic. Furthermore, it does not take CO_2 fertilisation into account. Our model is mechanistic but it does not as yet take into account the effects of extreme events in previous years. If we attempt to combine the two approaches from a qualitative point of view, the suggestion is that increased frequency of extreme events will decrease both species' productivity over the course of the 21st century (rather than increasing it, as MAIDEN suggests), but the fertilisation effect will allow them to withstand conditions more effectively.

PRACTICAL IMPLICATIONS, RECOMMENDATIONS, PRACTICAL WORK & PUBLICITY

1. Practical Implications:

There are both methodological and ecological practical implications.

From the point of view of methodology, our three modelling approaches have shown what directions need to be taken to achieve more exhaustive models of Aleppo Pine and Holm Oak vulnerability. Using the MODIS/GPP approach, wide areas can be included, covering all the species growing in them. There is still work to be done, however, to bring estimation of GPP via satellite image closer to reality in terms of the effect of droughts and leaf area index estimation. One of the avenues now open following the positive correlation between NEE and dendrochronological series for Holm Oak is to compare the two data types more systematically and quantitatively. The "delayed effect model" approach and the weakness of some of the MAIDEN results show that MAIDEN will need to be improved in terms of the following processes: carbon allocation, acclimatisation of photosynthesis to changes in CO_2, taking organic material quality into account, delayed effects due to deterioration in the trees' state of health and reduction in leaf area.

From the ecological point of view, our findings should be taken as indications of potential future trends in both species in response to climate change. As was anticipated, drought is the key factor that determines Mediterranean forests' productivity and vulnerability. The negative effect of this factor is heightened by the increase in frequency and severity of extreme events. The damage caused in an extremely hot year like 2003 is intensified by the two year continuation of water deficit, to such an extent that it takes several years for leaf area to be restored. Added to this, increased springtime temperatures can lead to caterpillar invasions (*Lymanthria dispar*), as occurred in 2006 in Puéchabon. This invasion had a much greater impact than the drought of 2003. A more frequent recurrence of successive droughts and parasite invasions is therefore to be feared, with much greater impacts. Whilst our modelling approach is not perfect, we can deduce that because of its fertilising effect, atmospheric CO_2 may mitigate reduced productivity in Mediterranean forests for a time, provided that the return period of extreme events give the forests time to recuperate. Finally, Aleppo Pine appears to withstand conditions better than Holm Oak.

2. Recommendations and Limitations:

Our findings are limited both in terms of the data and the models. Our measurements still do not cover optimal time periods. Nonetheless, some sound lessons can be drawn from them, as the last decade has seen a variety of extreme events that have allowed us to understand how pine and oak can respond to extreme climate variations. The dendrochronological data and stem elongation measurements are fairly exhaustive for Aleppo Pine, but are still limited for Holm Oak. There are still a number of gaps in the vegetation models, which will need to be gradually filled in the coming years. Our vulnerability studies are based on one scenario only, from a single climate model. They therefore do not have any forecasting value, but are indicative only. In order to complete the approach, we will need to use simulation ensembles from several different climate models to deal with climate trends probabilistically.

The following recommendations might be addressed to forest managers:

(1) **Opt for mixed pine/oak stands**. The dieback rate for pines is greater when they are the only species and in the same way, dieback rate for oaks is higher when the stand is more dense. A balanced mix is likely to increase their resistance. Furthermore, their differing strategies to cope with drought would increase the ecosystems' resilience in the face of climate change.

(2) **Thin stands out more vigorously** to reduce the amount of competition for available resources among individual trees.

(3) When thinning, **select the healthiest individuals**.

(4) **Opt for stands located at the higher altitudes in the zone in question**: climate change will entail less water stress in hilly regions than on plains.

3. Practical work and publicising the research:

The issue of climate change and its impact on Mediterranean forests requires forest managers to be trained. The participating team from CEMAGREF therefore organised a training day (15 May 2007) for 16 environmental engineers from the "Centres de la propriété Forestière" (Forest Estate Centres) in every region of France, as well as representatives of the National Forestry Office environment directorate. A presentation was given on the REFORME project's findings, a field visit (to the Sainte-Baume sample plots, with information about symptoms of water stress and dieback, especially on leaves and branches), and a discussion on preventive management methods.

The production of several accessible articles aimed at a wide lay audience including managers and the general public, has been another means of passing on the messages that have come out of this research. There have been a large number of activities aimed at the public over the last few years (see below).

During the process of the project, a station was built at Font-Blanche, to supplement the Lamanon station (the flux measurement station in particular). It will be put to use when additional funding obtained for the continuation of the project comes in from the National Research Agency (ANR) "Vulnerability: environment and climate" programme (see below).

PARTNERSHIPS THAT HAVE BEEN ESTABLISHED OR ARE BEING PLANNED OR CONSIDERED

A project entitled DROUGHT+ was submitted to the ANR Vulnerability, environment and climate programme by S. Rambal and L. Misson (CEFE) and will receive a grant of 730,000 Euros between 2007 and 2010. This project is the natural continuation of REFORME, as it aims to gain a better understanding of the effect of water stress on growth of Aleppo Pine and Holm Oak. The consortium is made up of the same teams as those working on REFORME.

The Puéchabon flux tower is part of the Carboeurope-IP programme. The flux data is entered online in the project's database every six months and is immediately available to the scientific community. The Puéchabon experimental platform and its rain exclusion device are affiliated with the IMECC project (Infrastructure for Measurement of the European Carbon Cycle). An initiative has been set up which will draw in external teams, in order to make optimum use of the platform. This is an Integrated Infrastructure Initiative (I3) under the 6th PCRD. We are external partners in the UE Nitroeurope project, involving: 1) continuous measurement of dry deposition and 2) soil microbiology "soil bioassay: The purpose of the simple soil bioassay is to provide best estimates of emission potentials for N_2O and other greenhouse gases on L1 sites. Data from the bioassays can then be used to assess the effects of N-input on nitrogen oxides emissions to reveal relationships between C and N fluxes and to

parameterize models".

The forest measurement stations are part of the « FORET » Regional Environment Observatory (ORE) coordinated by GIP ECOFOR, whose activities concern the functioning and processes of forest ecosystems, sustainable forest management and dissemination of forestry information. In this context, the REFORME project was presented at the information and discussion day entitled "the forest in the face of climate change: what we have learnt and remaining uncertainties" (15 December 2006), in which a large number of forest scientists and managers were involved.

Between September and December 2007, UR EMAX will be hosting a Spanish thesis student from the Departamento de Ecología, Facultad de Ciencias (Universidad de Granada). The purpose is to exchange information on measuring climate change impacts on the aerial parts of Aleppo Pine. Joint work will be undertaken at the Font-Blanche site, to compare and then harmonise protocols. This joint work began in March 2006 when a visiting delegation of Spanish researchers was welcomed at the site.

FOR FURTHER INFORMATION (SOME REFERENCES)

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LIST OF SCIENTIFIC PUBLICATIONS, PARTICIPATION IN SYMPOSIUMS, THESES, PUBLICITY ACTIVITIES, PARTICIPATION IN TRAINING AND MEDIA ACTIVITIES

1. Publications

PUBLISHED OR IN PRESS

- Vennetier M., Thaabet A., Gadbin-Henry C., Ripert C., Prevosto B., Borgniet L., Vila B., Guibal F., Ray R., Buron V.et Zanetti C. 2007 (Accepted). *Conséquences de la canicule et de la sécheresse 2003 sur les pins méditerranéens.* In Landmann G. (ed.) "Sécheresse et canicule 2003. Contribution des dispositifs de suivi et d'observation des forêts à la quantification des effets immédiats et à court terme". ECOFOR. (in press)

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- Gaucherel, C., Campillo, F., Misson, L., Guiot, J. and Boreux, J.J., subm. Parameterization of a process-based tree-growth model: comparison of optimization, MCMC and particle filtering algorithms. Ecological Modelling.
- Vila Bruno, Vennetier Michel, Ripert Christian, Chandioux Olivier, Liang Er-yuan and Guibal Frédéric, (Submitted to Annals of Forest Sciences). *Did global change already modify trees' productivity? Consequences for species distribution in the French Mediterranean forest.*
- Vennetier Michel, Ripert Christian, Maille Eric, Blanc Laurence, Torre Frank, Tatoni Thierry, Brun Jean-Jacques, (submitted to Annals of Forest Sciences): *A statistical water-balance model based on the flora for Mediterranean forested areas. Methodological finalization.*

IN PREPARATION

- Gaucherel, C., Guiot, J. and Misson, L., Potential distribution area of French Mediterranean forests in the 21st century. To be submitted to Ecology and Biogeography
- Thaabet A., Vennetier M., Gadbin-Henry C., Borgniet L., Vila B., Guibal F., (to be submitted to Canadian Journal of Forest Research). *Impact of scorching heat and drought on the growth and aerial morphology of Pinus halepensis.*
- Vennetier Michel, Ripert Christian, Chandioux Olivier, Rathgeber Cyrille, Brochiéro Fabien, Brun Jean-Jacques, Tatoni Thierry, (to be submitted to Plant Ecology). *Autecology of Pinus halepensis in France. The balance between global and local water balance in relation to climate change.*
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2. Contributions at Conferences

- Castro Jorje, Vennetier Michel, *et al.* 2007 (Accepted). *Forest Dieback in Europe: Climate Drivers, Symptoms, and Physiological Processes.* Annual meeting of the Ecological Society of America (9 August 2007).
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3. Theses already defended or underway

- Thabeet Ali : Impact de la canicule 2003 sur la croissance et l'état sanitaire de la forêt méditerranéenne. (Thesis defence scheduled for early 2008), M. Vennetier co-director.
- Sandrine Chauchard, « Structure et dynamique d'une forêt méditerranéenne dans un monde changeant », Université Montpellier II. (thesis defence November 2007), F. Guibal co-director.

4. Technical and publicly accessible articles

- Guiot, J., 2006. Les changements climatiques : que nous apprend le passé, Biofutur, 270, October 2006, 18-21.
- Vennetier M. Vila B., Liang E.Y., Guibal F., Ripert C., Chandioux O. -2007 (Accepted). Impact du changement climatique et de la canicule de 2003 sur la productivité et l'aire de répartition du pin sylvestre et du pin d'Alep en région méditerranéenne. Rendez-Vous

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- Vennetier Michel -2006. Quand les arbres disent le temps. Atmosphériques (revue Météo-France) Dec. 2006; 3p
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- Vennetier M., 2006. Impact du changement climatique sur les forêts de la Sainte Baume. *Pays Sainte Baume*, no. 18, p. 16-17
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- Rambal, S., 2006. Journal du CNRS, no.198-199, July August 2006, p. 8-9. Journal d'une forêt de laboratoire at *http://www2.cnrs.fr/presse/journal/2983.htm*

4. Public Conferences

- J. Guiot: changements climatiques et végétation : ce que nous apprend le passé, "Jeudis du CNRS" conference, 26 October 2006, Délégation régionale 12 du CNRS, Marseille
- S. Rambal : Maison de l'environnement de l'Hérault, Prades le Lez, public conference 27 April 18h « Les écosystèmes méditerranéens en danger ? »
- S. Rambal : Journée Ecologie, Environnement et Développement durable (EEDD), IUFM, Montpellier, 23 May 2007 « Changements climatiques et EEDD : le fossé global/local »
- F. Guibal : Participation in the *Fête de la Science 2006*, Village des Sciences, Europôle de l'Arbois, Aix-en-Provence, 9-15/10/2006 : « Dendrochronologie du domaine méditerranéen ».

5. Media Publicity

MICHEL VENNETIER

- Report on TF1's 20h news programme, 26 August 2006 1/2 day filming on 23 August.
- Report on Antenne 2's 20h news programme on 1Sept 2006 : 1 day filiming on 30 August.
- Live programme for France-Bleue Provence, 1/2hr on 27 May 2006
- Scheduled live programme for France-Culture on 16 July 2007 from 14h to 15h.
- 2 long articles in the periodical *La Provence* in 2006.

SERGE RAMBAL

- Radio France International, programme entitled "Le Monde Change" ("The World is changing"), broadcast on 18 September 2006. Interviews with Richard Joffre and Serge Rambal. Duration 19'30.
- TF 1 - 20h news programme, 16 August 2006, duration 2 mins.
- France 2 - 20h news, 29 august 2006, duration 2 mins.
- M6 -6 Minutes, Montpellier edition, 6 September 2006, duration 1 min.
- FR3 -Midi Pile, France3 Sud edition, 12 September 2006.
- Chaîne parlementaire Public Sénat "Paroles de Sciences" programme (10 May 18h45, duration 3 mins.

- L'Hérault du jour newspaper, 11 May 2007. pp. 3, Réchauffement en flèche de l'arc méditerranéen ("Warming shoots up around Mediterranean arch").
- VSD, 11-17 October 2006, p. 72-74 Au cœur d'une forêt laboratoire ("Inside a laboratory forest"
- Midi Libre, 30 August 2006 La forêt résiste, le buis jaunit ("The forest is resisintg, but the box trees are withering").
- Midi Libre, 31 August 2006 La sécheresse plombe l'avenir des pins du Midi ("Drought seals the fate of pines in the South).

6. Website

Médias-France public interest group is responsible for managing the project's website and has produced the template for the website presenting the Reforme project.

The provisional website can be found at: http://medias.cnrs.fr/reforme

The website comprises the following sections:

1. The project, with:

1.1 Summary

1.2 Data from the measurement sites (Puéchabon, Lamanon and Font-Blanche), the intensive measurements carried out (LAI, RAI, sap flow, biomass, continuous trunk growth, densitometry profile, lumen, cell dimensions, soil water content, quantity of water entering the soil, soil evaporation, understory transpiration), dendochronological data, climate simulations and databases (Format, Dendrodb, Modis, …) .

1.3 The methodology, with the ecophysiological models (Maiden, Sierra, Bilhy), scenarios for the 21st century and Aleppo Pine sensitivity

- 2. Important events (conferences, workshops, …)
- 3. Bibliographical references and downloadable documents (UNFCCC, Kyoto protocol, …)

4. List of the project's partners and their contact details,
5. A restricted area for partners, for document sharing
6. A list of the acronyms used

ABSTRACT

Mediterranean forests are crucial for preserving the rich biodiversity they contain and providing essential ecosystem services such as soil protection, conservation of water resources and climate regulation. Climate model simulations predict significant warming for the 21st century and decreased precipitation levels, with a significant increase in extreme events which could considerably reduce the forests' productivity. The primary aim of REFORME was to quantify these impacts in order to help forest managers make appropriate decisions. To achieve this, we adopted a strategy based on measurements in experimental forest stations (Puéchabon, Lamanon), large temporospatial scale dendrochronological data and a set of vegetation models (MAIDEN, SIERRA, MODIS/GPP, BILHY). The vulnerability studies were based on scenario B2 (relatively moderate) of the Météo-France ARPEGE model. The principal findings were as follows:

Climate variability in April, May and June dictates variability in Holm Oak radial growth and carbon flux. In this respect, the flux measurements and dendrochronological data match very closely. At a wider scale, we show that satellite images such as those supplied by MODIS are a useful tool for estimating Mediterranean forest productivity, but need to be adjusted for certain systematic skewing. In 2005, Puéchabon suffered a caterpillar invasion which had a greater impact than successive droughts on the oak's vulnerability. This problem needs to be taken into account in studies on vulnerability studies to climate change, as increased springtime temperatures may lead to increased frequency of these attacks in future.

For Aleppo Pine, the 2003 heat wave is also a good model for the impact of climate warming. A 30 to 60% reduction was seen in needle size, number of needles formed, length of annual new growth on branches and fruit production. Polycyclic growth ceased almost completely after 3 years of drought. The BILHY model showed a loss of wood production in the region of 28% for Font-Blanche and 30% for Lamanon.

A comparison between the MAIDEN simulations for Holm Oak and Aleppo Pine showed that both species reach a growth peak during the first decade of the 21st century, the pine showing three times more productivity. As drought levels then intensify, productivity for both species goes down until the end of the 21st century, by 28% for the oak and 8% for the pine (BILHY shows a less significant drop), the pine appearing to withstand water stress better. If fertilisation effect is taken into account, both species appear to withstand conditions much better (with a slight increase in productivity). A statistical approach conducted at the same time showed the importance of the delayed effect of extremes in previous years, which are capable of accumulating exponentially after several successive events, via their effects on the trees' health and defoliation. This delayed effect therefore has the potential to considerably reduce the fertilisation effect. Aleppo Pine, no doubt because of its capacity to close its stomata earlier on, appears more capable than the oak of withstanding the conditions.

Our findings have limitations, related both to the data and to the models. Our measurements do not yet cover optimal time periods. There are still a number of gaps in the vegetation models, which will need to be filled in the coming years. Finally, our vulnerability studies are based on one scenario only (B2) from a single climate model. They therefore have no forecasting value, but are indicative only. In order to complete this approach, it will be necessary to use ensembles of simulations from several different climate models in order to deal with climate probabilistically.

KEY WORDS

MEDITERRANEAN FORESTS, VULNERABILITY TO CLIMATE CHANGE, DROUGHT, TREE GROWTH, CO_2 FLUX, FERTILISATION, EXTREME EVENTS, HOLM OAK, ALEPPO PINE

(Authors' original English Abstract)

The Mediterranean forests are critical to preserve the high biodiversity which characterizes them and to provide essential ecosystem services, such as soil protection, water resources conservation and climate regulation. The climatic models simulate, for the 21th century in that region, a significant warming and a reduction of rainfall, with a significant increase of extreme events, which can considerably reduce the forest productivity. Quantification of these impacts to help the forest manager to take appropriate decisions was the main objective of REFORME. To reach it, we adopted a strategy based on measurements in forest experimental station (Puéchabon, Lamanon), of tree-ring data at broad spatiotemporal scale and a hierachy of vegetation models (MAIDEN, SIERRA, MODIS/GPP, BILHY). The vulnerability studies have been based on the B2 scenario (comparatively moderate) by the model ARPEGE of Météo-France. Main acquired results are the following:

The climate variability from April to June drives the variability of the radial tree-ring increment of the evergreen oak and of the fluxes of carbon. There is a very good convergence between flux measurements and dendrochronology. At a broader scale, we showed that remote sensing images such as they are provided by MODIS is a good tool to estimate the productivity of the Mediterranean forests, but it must be corrected for some systematic biases. Puéchabon was subjected in 2005 to a caterpillar attack with more effects than successive droughts on the vulnerability of the oak. This phenomenon must be taken into account in vulnerability studies to climatic change, because the increase of the spring temperature risks to induce a decrease of the return period in future.

For the Aleppo Pine, the heat wave of 2003 is also a good model for the impact of climatic warming. There was a reduction from 30 to 60 % of the size of needles, of the number of the needles formed, of the length of the annual shoot on branches and fructification. The polycyclism disappeared almost entirely after 3 years of drought. The model BILHY showed a loss, in terms of wood production, about 28 % for Font-Blanche, and for Lamanon a 30 % loss.

The comparison of MAIDEN simulations between the oak and the pine showed that both species arrive at a maximum of growth during the first decade of the 21th century, with a three times stronger productivity for the Alep pine. Then, drought becoming more important, the species see their productivity diminishing till the end of the 21th century, of 28 % for the oak and 8 % for the pine (smaller values than with BILHY). The latter therefore seems to resist better to water stress. If we take into account the fertilisation effect by CO_2, both species seem to resist much better (with a productivity slightly increased). A statistical approach conducted in parallel showed the importance of the delayed effect of the extremes of the previous years. The latter are able, by degrading the health state of the tree and by subsequent defoliation, to exponentially cumulate with several successive events. This delayed effect has therefore the potentiality to attenuate the fertilisation effect. Finally Aleppo Pine, likely by its capacity to early close its stomatae, seems to better resist than evergreen oak.

Our results have limitations linked together to data and to models. Our measurements still do not cover optimum periods of time. The vegetation models have some more lacunae which must be filled up progressively in future. Finally, our vulnerability studies are based on

a single scenario (IPCC-B2) of a single climatic model. They therefore do not have value of prediction but simply of indication. It will be necessary, to complete this approach, to use simulation ensembles from several climate models to deal with the climate evolution under probabilistic forms.

KEY WORDS

MEDITERRANEAN FORESTS, VULNERABILITY TO CLMATIC CHANGE, DROUGHTS, TREEGROWTH, CO_2 FLUX, FERTILISATION, EXTREME EVENTS, EVERGREEN OAK, ALEPPO PINE