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The response of European forests to the change in summer temperatures: a comparison between normal and warm years, from 1996 to 2006.

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An eddy covariance tower in Norunda (Sweden). Credit photo: Sarah Loudin

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Master degree thesis in
Physical Geography and Ecosystem Analysis

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Abstract

With the forecasted increase of summer temperatures over Europe, the carbon balance of forests – photosynthesis (GPP), ecosystem respiration and Net Ecosystem Exchange - in likely to change. In this thesis, the photosynthesis and the respiration of six European forests were studied from 1996 to 2006, in order to see how they react to abnormally warm summer temperatures. The parameters used are temperature, vapor pressure deficit and soil water content, precipitation and net radiation. The eddy covariance technique was used to obtain the data. Linear regression was used to find trends and correlations between the various parameters. Common responses can be found between the six forests, depending on common features they share, such as phenology (evergreen or deciduous), foliage (needleaved or broadleaved) and location in Europe (the six forests were distributed in Sweden, Germany, France and Italy).
This study shows that the most marked changes in GPP during very warm years are found in deciduous forests. Evergreen forests are characterized by their respiration, which is less sensitive to temperature than those of deciduous forests. Moreover, it was found that the NEE is more often negative (respiration is higher than GPP fluxes, and CO_2 is released by the forests) in needleleaved forests than in broadleaved forests. The location also plays a role in the carbon balance of the forests, as respiration is higher in the northern sites. It is less obvious for GPP, for the highest value are found in the central Europe forests (France and Germany).
These findings show that if temperatures keep increasing during the summer, both respiration and GPP will be impacted, and marked changes are likely to be seen in the carbon balance.

Key-words : Eddy covariance, Gross Primary Product, Ecosystem respiration, summer temperatures

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1- Introduction

During the summer 2003, a wave of abnormal warmth beat down on Europe and caused the death of 70 000 people (Robine et al., 2007). In Italy, almost 20000 persons died. It is now remembered in some countries, like in France where thousands of people died too, as “the deadly summer” (Besancenot et al., 2006). This heat wave also had strong effects on the environment, particularly on forests which had to endure a level of temperatures and water stress barely known before (Luterbacher et al., 2004; Besancenot et al., 2006; Garcia-Herrera et al, 2010). In order to understand better how these forests have reacted during this summer, and in a more general way, how forests react when they are confronted to abnormally high temperatures, heat waves and possibly resulting droughts as in 2003, six sites will be here studied, through the measurements of the exchange of CO_2, and the analysis of photosynthesis and respiration.

A heat wave can be defined in many different ways. In a general way, it is an extended period (in term of days) of unusually high air temperature (or heat stress), which causes modifications and disturbances for human societies (Robinson, 2000) and the environment.

More specifically, other definitions exist, based on the distribution of temperatures, thresholds and percentiles (Meehl and Tebaldi, 2004), but this thesis will focus more on the entire summer, rather than on some specific days or weeks. Indeed, under the three summer months (June, July and August), CO_2 exchange between the atmosphere and the canopy is higher, as both uptake and release are larger with higher temperature and higher light availability. In this way, it will be easier to see clear changes in photosynthesis and ecosystem respiration. The effects of temperature increase and heat wave are also more interesting during this period.

In the southernmost sites, where temperatures are particularly high and where water is scarce, heat waves often lead to droughts, which can be defined as the combination of low water supply (for example due to the lack of rainfall) and/or a high rate of water loss (due to high temperatures, which provoke high evaporation) (Jones, 1998).

Consequently, it will be referred in this thesis to an “abnormally warm summer” when temperature is at least 1.5 °C warmer than the mean of the mean summer temperature of the rest of the available years for one site, and when there possibly is a heat wave (the summers 2003 and sometimes 2006, but also 1997 for Norunda).

Throughout this thesis, it will be attempted to determine the effect of abnormally high summer temperatures on six forests in Europe, by focusing on their carbon balance. Indeed, the Net Ecosystem Exchange (NEE) of CO_2 between terrestrial ecosystems and the atmosphere is the result of the difference between the incoming fluxes of CO_2, absorbed by the forests and contributing to the photosynthesis, or Gross Primary Production (GPP); and the outgoing fluxes of CO_2, which correspond to the ecosystem respiration (Aubinet et al., 2005). Amplitude and timing of the assimilatory and respiratory processes thus determine the seasonal pattern of the CO_2 fluxes (Falge et al., 2002). GPP is strongly dependent on light and on temperature in summer, when plant growth is the highest, whereas respiration is strongly dependent on temperature and soil moisture (Falge et al., 2002). In this way, these three drivers will affect the carbon balance, but here we will mainly focus on two of them, temperature and soil moisture.

The study of the CO_2 fluxes over forests is made thanks to their responses to year-to-year changes in temperature, because their consequences are important for the ecosystem carbon balance (Randerson et al., 1999). For instance, higher temperatures can lead to greater evaporative demand, but also to a change in the photosynthesis pattern and water stress (increase or decrease). In terrestrial ecosystems, the cycles of carbon and water are strongly linked (Zierl et al., 2007). Indeed, water supplies impact terrestrial ecosystems, for example respiration and photosynthesis, which are dependent on local water availability. But terrestrial ecosystems also affect the local water budget, through evapotranspiration (Zierl et al., 2007). In this way, it is interesting to focus on both temperatures and water as main actors of the CO_2-cycle in forests.

The study of the carbon balance over European forests also has to be linked with the ongoing climate change that is being experienced since the last century (IPCC 2007). It is very likely that nowadays, the concentration of CO_2 in the atmosphere is higher than it has ever been in the last 650 000 years (Jansen et al., 2007), and it keeps rising. In 2008 the mean global CO_2 concentration peaked at 385.34 ppm (CDIAC, 2012), which represents an increase of more than 90 ppm since the dawn of the industrial revolution, around two centuries ago (Baldocchi et al., 2001). The main causes for this increase, and for the climate warming that is very likely to follow, are the anthropogenic emissions of CO_2, coming from fossil fuel burning and deforestation.

The role of the terrestrial biosphere, particularly of forests, in mitigating or delaying the quick rise of CO_2 concentrations in the atmosphere, is crucial. Indeed, the land biosphere (excluding the deforested parts) absorbs about one quarter of the fossil fuel emissions (Aubinet et al., 2005).

The state of the terrestrial biosphere and atmosphere has already experienced a lot of alterations in the past century (Baldocchi et al., 2001), and the coming changes are important for humanity, but difficult to forecast. One can expect a greater warming and larger changes in the hydrological cycle (IPCC 2007), which will impact greatly on ecosystems. The mechanisms which regulate carbon pools and fluxes are not yet well understood, and their functioning, vulnerability to climate change and evolution in the future remain uncertain (Carboflux). Many scientists agree to say that the role of forest is likely to change with global warming (Valentini et al., 2000). For example, a future increase in temperatures is expected in temperate ecosystems to enhance GPP and CO_2 sequestration. But too high temperatures, linked with the decrease of water availability, are likely to lead to a 30 per cent reduction in GPP over Europe, as well as a strong net source of CO_2 over European forests (Ciais et al., 2005). More frequent and extreme heat waves and drought in Europe may even offset the effects of the lengthening of the growing season and the mean warming of temperatures, causing the increase of positive carbon-climate feedbacks strength (Ciais et al., 2005). Indeed, with the increase of temperature, the CO_2 uptake by forests is reduced; there is then more CO_2 in the atmosphere, which contributes to the increase of temperature. Different studies showed that in a near future, the release of CO_2 by some forests could be so large that any human attempts to reduce CO_2 emissions would be offset (Carbo Europe IP). Other showed that the balance between respiratory and assimilatory processes is very likely to be affected by an increase of temperatures, especially in summer (Falge et al., 2002). Still according to Falge et al., (2002), these shifts might affect the potential sequestration of future ecosystems, but also the stability of the CO_2 stored in forests.

That is why trying to understand how the carbon budget of a forest is regulated is important, as well as which parameters are at stake. Identifying the role that forests play in the changes in CO_2 fluxes from terrestrial ecosystems will permit to have a more precise idea of how these same forests will react when confronted to global warming and a high increase of temperatures (Randerson et al., 1999).

These uncertainties give rise to the following questions:

[1] To which extent the increase of temperatures in summer is going to affect the uptake and the release of CO_2 of forests in Europe?
[2] Do forests react differently to normal and abnormally warm summer temperatures depending on their characteristics?
[3] Will a GPP and respiration gradient be seen depending on the location of the sites?

These questions are important, for the progressive shift of climate has a strong impact on meteorological conditions and physiological activity, both parameters which govern CO_2 fluxes and ecosystem processes (Falge et al., 2002).

2- Background

2.1- The response of deciduous and evergreen forests to temperature changes

The behavior of deciduous and evergreen, broadleaved and needleleaved forests in Europe and in the world has been the subject of studies in the past. It is interesting to see how much the response of forests, when confronted to abnormally high temperatures, differs from what is expected during normal conditions.

2.1.1- Common behavior

The net CO_2 exchange of forests is the result of the balance between photosynthesis and respiration, which means that there is a strong interrannual variability within each site, but also between sites (Falge et al., 2002). Deciduous and evergreen forests share some main particularities about the storage and release of CO_2. Under stable conditions, CO_2 release (positive fluxes of CO_2) is always observed at night, while there is no photosynthesis; whereas CO_2 uptake (negative fluxes of CO_2), due to light assimilation, is observed during the day, and it often dominates the carbon balance at this moment (Aubinet et al., 2005). Nevertheless, during leafless period (mostly winter) in deciduous forests, CO_2 release dominates the carbon balance (Valentini et al., 2000).

Some important differences also characterize these forests. Thus, the reason a broad range of deciduous and evergreen, broad-leaf and needle-leaf forests have been chosen is because they react differently to the vagary of climate. Their respiration and gross primary product, as well as the role they play in the carbon cycle, as a sink or a source, make that they are likely to react differently to a future climate change.

2.1.2- Gross Primary Production

GPP depends on different parameters: temperature, air humidity and water potential of both leaves and soil, light and nitrogen availability. These primary factors control photosynthesis at the leaf level. At the stand level, the leaf area density and the structure of the canopy are additional factors (Lindroth et al., 2008). Some major factors affect the seasonal course of the ecosystem's GPP. They can be the length of the growing season, the meteorological conditions, the seasonal differences in the Leaf-Area Index (LAI) or the physiological capacity of tree species (Falge et al., 2002).

The quantity of CO_2 stored in the canopy varies greatly between sites and different types of forests. In some studies, CO_2 uptake is said to be dependent of the latitude, and CO_2 uptake will increase following the decrease of the latitude (Valentini et al., 2000). It means that a priori GPP differences between the northernmost site of this study, Norunda (60° 05' N) in Sweden, and the southernmost site, Castelporziano (41° 45' N) in Italy, are likely to result from climate particularities, and one could expect to see a latitude gradient between the six sites chosen for this study. But other parameters which control GPP exist, for instance in the temperatures or in the differences in the quantity and the quality of the soil. Nevertheless, during abnormally warm summers, a decrease in GPP is expected in most of the forests, despite the differences in heat wave and drought duration and intensity (Ciais et al., 2005) between sites.

Moreover, it is known that deciduous and evergreen forests do not have the same amount of carbon uptake and release. For example, relatively large rates of CO_2 uptake have been reported for boreal deciduous forests, whereas small uptake and release have been reported over boreal conifer forests (Baldocchi et al., 2000). It will be interesting to see how the six forests that will be studied react, compared to the responses documented in the literature.

2.1.3. Respiration

The ecosystem respiration contributes to 20-40% of the annual atmospheric CO_2 input (Bond-Lamberty et al., 2004). It is divided between the autotrophic respiration (the respiration by the plant, due to its metabolism) and the heterotrophic respiration (the respiration of soil decomposers). It is important to differentiate them, as roots and soil organisms might respond in a different way to temperatures changes (Bond-Lamberty et al., 2004). Nevertheless, measurements to differenciate autotrophic and heterotrophic respiration are difficult to perform. For example, values of 10 % to 90 % for the autotrophic part have been reported in forests ecosystems, but much of this variability is due to problems in method to calculate respiration (Bond-Lamberty et al., 2004). As no data is available to differentiate them, here in this thesis the global ecosystem respiration will be studied.

Because microbial and plant respiration is stimulated by warmer temperatures, global ecosystem respiration is expected to increase during very warm summers. Nonetheless, respiration was found in Ciais et al. (2005) study to decrease, in parallel with GPP, during the summer 2003 in European forests.

Respiration patterns also reveal a large influence of climate zones (temperate, boreal, Mediterranean, etc.). A contrario, the influence of the lifeform (deciduous or coniferous) seems to be secondary when explaining the seasonality of the respiratory processes (Falge et al., 2002). For example, Valentini et al. (2000) reports that boreal forests seem to have a higher respiration than other forests in Europe, as boreal soils contain a larger amount of root and labile soil organic matter, which favors rapid decomposition, and consequently the release of CO_2. The same authors also report that in their studies on European forests, the ratio respiration versus temperature is not very significant. From this they deduce that the mean annual air temperature may not be an important parameter to drive forest respiration. It will be interesting to see if this statement applies to the followed studied sites for the summer period.

More generally, it will be interesting to see for each site if these relationships can be observed, and if not, try to find which other parameter can be the main driver of the seasonality and the photosynthesis and respiration processes.

2.1.4. The behavior of the leaves

It has been reported that with high temperatures, broad leaves might become a lot warmer than the air (up to 20 degrees for some species), which lead to the closure of the leaf guard cells (the stomata), in order to avoid dehydration (Oke, 1978). As the water loss but also the cooling of the leaf is cut, thermal stress becomes higher and might cause leaf cells damages (Oke, 1978). On the contrary, needle leaves' geometry (small size, low leaf surface/mass ratio) prevents them to store a lot of heat, and favors their respiration and heat release to ambient air by convection and long-waved radiation (Oke, 1978). Moreover, needle leaves are narrow, which make them avoid large amount of evaporation. In this way, the needle leaf temperature of is closer to the air temperature, compared with broad leaves (Campbell and Norman, 1998; Jones, 1992). Broadleaved forests are thus said to react more markedly to high temperatures, and see their GPP being more affected.

Moreover, a leaf remains alive if the average net GPP is positive, and if the water potential of the leaf is high enough to enable its metabolism to work. It is very likely that with very high temperatures and a marked decrease of water availability (which can be seen through Soil Water Content (SWC), but also through Vapor Pressure Deficit, or VPD), leaves might start to die (Campbell and Norman, 1998).

The six forests chosen in Europe for this thesis are thus hypothesized to react differently to the abnormally high temperatures in summer. That is why the parameters that were evocated above will be the main tool to analyze forests' behavior.

2.2- Eddy covariance

The eddy covariance method is a technique used to measure and compute turbulent fluxes, such as heat, water or gases, within the atmospheric boundary layer, that is to say between the atmosphere and the terrestrial ecosystems (Fluxnet). It is made at the ecosystem scale (Papale et al., 2006; Burba and Anderson 2007). Thanks to this technique, direct estimates of the amplitude and the phasing of various ecosystem processes such as GPP or respiration can be made, as well as settings of the seasonal patterns of these processes (Falge et al., 2002). The eddy covariance technique can be used for different purposes (Burba and Anderson 2007). As Baldocchi et al. (2001) defines it, it determines the exchange rate of CO_2 across the atmosphere-biosphere interface, by measuring the covariance (how much two variables change together) between variations in vertical wind velocity and the CO_2 mixing ratio. The eddy covariance technique is based on the high frequency measurements (10-20 Hz) of the vertical wind speed and CO_2 concentration above plant canopy (wind forms turbulent eddy flux) (Aubinet et al., 2005; Papale et al., 2006). In order to know the vertical movements of fluxes of gas concentration, temperature and humidity, towers are used to measure the speed of the vertical air movements and the characteristics of each air parcel moved by the eddies (Burba and Anderson 2007). Fluxes from the covariance between wind speeds and CO_2 mixing ratio are derived using two general statements: first, the density fluctuations are assumed to be negligible and second, the mean vertical flow is also assumed to be negligible for horizontal homogenous terrains. Fluxes obtained with the eddy covariance technique can then be derived in order to obtain hourly and daily data for the CO_2 fluxes (Burba and Anderson, 2007).

The members of the micrometeorological community have assessed the net ecosystem CO_2 exchange as "the sum of eddy covariance measurements and the storage of CO_2 in the underlying air" (Baldocchi et al., 2000). To perform these measurements in the six sites, a three-axis sonic anemometer and a fast response infrared gas analyzer are used (Papale et al., 2006). Assuming a

perfect turbulent mixing, measurements are integrated over periods of half an hour, which enables to calculate carbon and water fluxes and balances from daily to annual time scale (Papale et al., 2006).
This technique was used for the first time in 1951 (Aubinet et al., 2005), and since then it has been more and more implemented, especially during the two last decades. At present, it is now applied in more than 500 sites throughout the world (Aubinet et al., 2005).

Figure1: photo of an eddy covariance tower in Norunda, Sweden (Sarah Loudin).

The eddy covariance technique is more accurate when the atmospheric conditions, such as wind, temperature or humidity, are steady. For example, measurements might become unreliable or unavailable when performed during precipitation or icing (Curtis et al., 2002).
Moreover, the underlying vegetation has to be homogeneous, and the eddy covariance tower must be situated on a flat terrain (Baldocchi, 2003). Measurements are also more accurate when the canopy roughness and the source (or sink) strength are homogeneous over the studied area (Baldocchi et al., 2000). But even when these parameters are respected, the eddy covariance method must take into account the measurements of CO_2 atmospheric storage, flux divergences and advection, as well as turbulences regime. Thus, significant storage is observed only during periods of low turbulence and low advection (Aubinet et al., 2005).

In spite of the very precise measurements it can provide, the eddy covariance method is not perfect, and measurements errors or deviations can happen. These errors can be due to the intermittent and light winds at night, which create insufficient turbulent mixing. Under these conditions, non-turbulent transport processes, which become significant, are not taken in account by the eddy covariance technique (Aubinet et al., 2005). Thereby advection becomes an important term in the flux balance, which can in these conditions be miscalculated (Papale et al., 2006). Errors can be also due to the wrong measurements of the CO_2 storage in the air space and in the soil below the measurement height, and of the night-time drainage of CO_2 out of the canopy volume due to advection. The measurement of ecosystem respiration is thus underestimated (Baldocchi et al., 2000; Baldocchi, 2003; Aubinet et al., 2005). Moreover, rain can be a disturbing factor for measurements, as it can directly affect the functioning of the eddy covariance system, and thus the data quality (Falge et al., 2002)

Different methods can then avoid or reduce these problems. Averaging CO_2 flux measurements over long periods (day to years) enable to reduce accidental sampling errors (Baldocchi, 2003).

Empirical corrections can be applied to compensate this underestimation, based on the CO_2 flux measurements obtained during windy periods. However, these corrections remain difficult to apply, as they depend on the relative importance of storage and advection of every different site (Aubinet et al., 2002).

Moreover, the eddy covariance technique has some drawbacks that should be taken in account when analyzing and discussing the data. As most of the measurement technique, eddy covariance is not completely reliable and influences the quality of the data (in a minor way though). Indeed, the GPP and respiration values that are found with eddy covariance are indirectly obtained. Eddy covariance measures the NEE. To obtain the GPP, respiration is measured at night, when there is no uptake of CO_2 by the forests, but only a release. Based on the respiration data, these parameters are derived and used in a simple model. In this way, GPP (the difference between NEE and respiration) is obtained (Reichstein et al., 2005). Modeling, instead of directly measuring these values, brings some uncertainties over the data obtained and the real responses to temperature. Indeed, obtained data are influenced by the model assumptions (Reichstein et al., 2005), and it might happen that with this indirect way to obtain data, analysis get biased. For example, the Reichstein et al. (2005) model used for this correction does not set the temperature sensitivity of respiration. But the most important factor to look at here, that is to say how sensitive the respiration is to temperature, is determined from observations, and not from an a priori estimate.

But, despite of these limitations, the eddy covariance technique probably is the best method to study the response of ecosystems confronted to climate change (Aubinet et al., 2005), that is also why it was chosen to build this thesis.

3- Methodology

3.1- Choice of the sites

To complete this study, six sites were chosen in Europe. The latitude and longitude range was on purpose chosen to be large (see figure 2), so that it will be easier to observe differences in the phenology and vegetation types between forests, as well as a possible latitude gradient. Thus, two sites were chosen in Italy: Castelporziano, close to Rome, and Roccarespampani, 130 kilometers north-west of Rome. Despite of their relative closeness, one of them is an evergreen broadleaved forest, the other one is deciduous broadleaved. Two sites were chosen in France, Le Bray, close to Bordeaux, and Hesse-Sarrebourg, close to the German border. One site was chosen in Germany: Tharandt-Anchor, close to Dresden. Finally, one site was chosen in Sweden, Norunda, north of Uppsala.

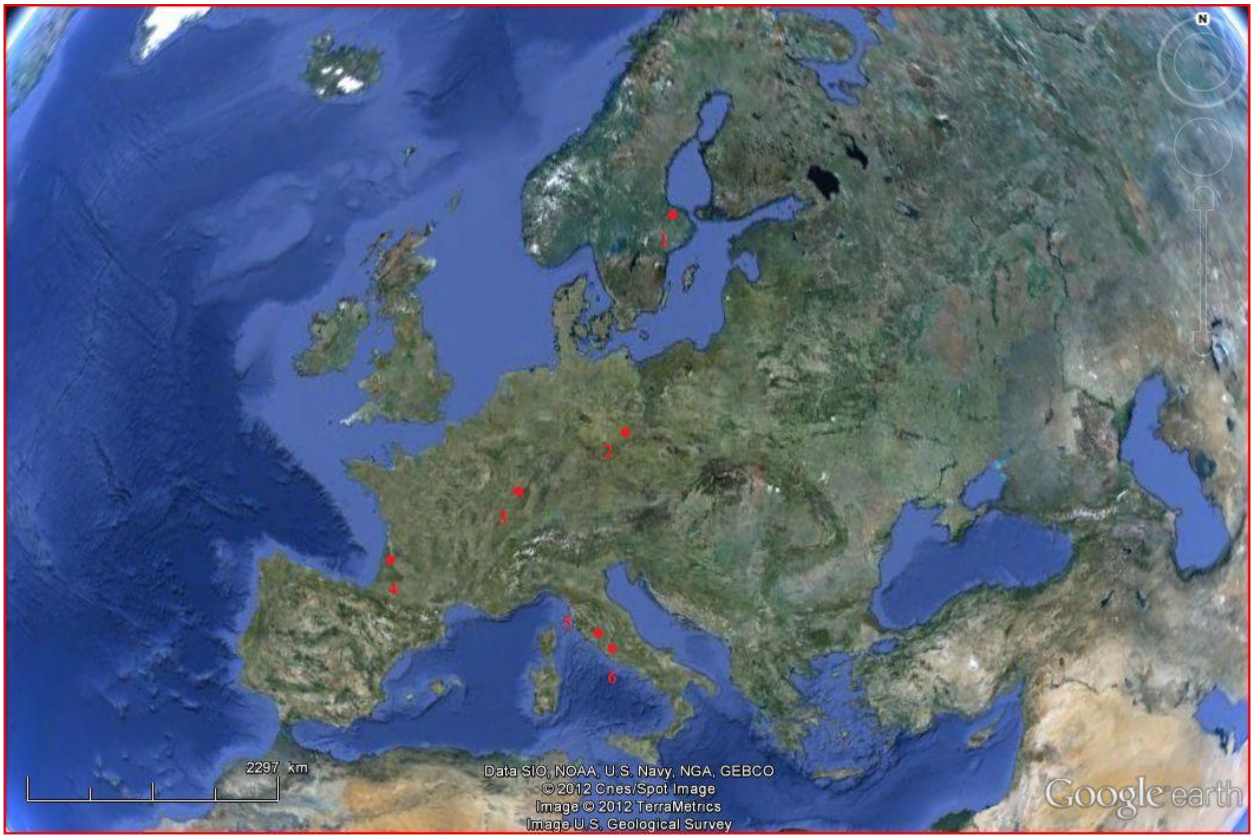


Figure 2: Google Earth map of the six sites: Norunda (1), Tharandt-Anchor (2), Hesse-Sarrebourg (3), Le Bray (4), Roccarespampani (5) and Castelporziano (6)

Every site has its own characteristics: They are influenced by different climate (oceanic, mediterranean, continental and boreal). They are all forest, evergreen or deciduous, broadleaved or needleleaved, but they all correspond to different species.

Table 1 (section 3.2.1) shows all the characteristics of the six sites. Four of them are evergreen forests, two of them are deciduous forests; three of them are broadleaved forests and three of them are needleleaved. This broad range might enable to find more easily differences and common characteristics between the sites.

3.2- Fluxnet, Fluxdata and data analysis

3.2.1Presentation of the sources

First of all, the online data base Fluxnet was used to collect the main characteristics of each site and make a selection (see above).

Fluxnet, as defined on the website homepage is a “network of regional network”, which was built in order to “coordinate regional and global analysis of observations from micrometeorological tower sites” (Fluxnet). It belongs to one of the NASA’s (National Aeronautics and Space Administration) Terrestrial and Ecology Program’s department, ORNL DAAC (Oak Ridge National Laboratory - Distributed Active Archive Center). The network gathers more than 500 flux towers throughout the world (whereof around 140 work at present), operating on a long-term (since the early 1990’s for some European sites) and continuous basis (Baldocchi et al., 2001). Among all the sites, more than 60 are situated in Europe, distributed in 17 countries (Carboflux).

The first step was to choose a large selection of sites in Europe, and then to check their availability on Fluxnet, as well as their characteristics. All the chosen sites present at least six years of data available, and sometimes nine or ten years (Roccarespampani, Hesse-Sarrebourg and Tharandt-Anchor). Once the six sites were found, data were extracted on Fluxdata, the website where datasets for every Fluxnet tower are stored. Daily data were chosen, for they were considered to be interesting and complete enough to analyze and find results. The data, when extracted, were already ready to work with: all the gaps were filled, and the format was adaptable to excel. The available parameters for the set of data were large: the variables mentioned before were found there, but there were also data about potential evapotranspiration, soil heat flux, sensible and latent heat flux, reflected radiation, wind direction or wind speed. These parameters were not analyzed in this thesis, but in some occasions they were used to have a general idea of the meteorological and physical conditions of a summer.

One change was brought to the set of data, concerning the SWC. For five of the sites, the data were said to be measured in m^3 m^{-3}, which corresponded to unrealistic measurements. Indeed, when using m^3 m^{-3}, the quantity of water in the soil was way too high. It was particularly visible for the mediterranean sites, where SWC does not reach such values (e.g. for Roccarespampani, the values ranged between “14.5” (in 2003) and “34.0” (in 2006)). It was thus assumed that the data for these five sites corresponds to the percentage of water contained in the soil (which is made of water, air and soil particles). The data was in m^3 m-^{3} in Norunda only, that it why it was multiplied by 100 for all the available years, in order to obtain the same range than for the other sites.

Table 1: Description of the six European sites. Sources: Fluxnet, Euroflux, Aubinet et al., 2005

Site	**Norunda**	**Tharandt-Anchor**	**Hesse-Sarrebourg**	**Le Bray**	**Roccarespampani**	**Castelporziano**
Country	Sweden	Germany	France	France	Italy	Italy
Latitude	60° 05' N	50° 58' N	48° 40' N	44° 42' N	42° 23' N	41° 45' N
Longitude	17°28' E	13° 34' E	07° 05' E	00° 46' W	11° 51' E	12° 22'E
Climate	Temperate-boreal transition	Temperate continental	Mediterranean, montane	Oceanic	Mediterranean, montane	Mediterranean, montane
Elevation (m)	45	380	300	60	120-190	3
Mean annual temperature (°C)	5,5	7,5	9,2	13,5	14,4	15,3
Annual precipitation (mn)	527	820	885	900-950	876	550
Stand characteristics						
Phenology type	Evergreen	Evergreen	Deciduous	Evergreen	Deciduous	Evregreen
Foliage	Needleleaved	Needleleaved	Broadleaved	Needleleaved	Broadleaved	Broadleaved
Dominant species	*Pinus sylvestris* , *Picea abies*	*Picea abies*	*Fagus sylvatica*	*Pinus pinaster*	*Quercus cerris*	*Quercus ilex*
Other species			*Quercus petraea, Tilia cordata, Betula alba*			
Understorey species	Worthleberry & lingonberry, mosses	Wavy hair-grass	European hornbeam	Purple moor grass	Ruscus, Hawthorn	Evergreen shrubs
Stand age (year)	100	108	35	25-35	0-20	30
Canopy height (m)	25	26	13	15-20	1 to 14	10 to 15
LAI (projected) (m2/m2)	5	7,6	5.5 to 7.8	2.6 to 5.5	4	3,4
Stem density (/ha)	600 stem. Ha-1	480	3800	500-600	600	1500
Wood increment (m3/ha/a)	5 m3. ha-1. yr-1	?	2,6	18	?	3,3
Soil characteristics						
Soil type	Sandy podzolic glacial till	Brown earth (rhyolith)	Gleyic luvisol	Podzolic	Cambisol	Sand
Soil depth (cm)	> 100	150	160	70	50-70	45
Available year	1996 to 1999, 2003, 2005	1996 to 2006	1997 to 2006	1996 to 1998, 2000, 2003 to 2006	2000 to 2006	1997 to 2006

3.2.2. Method to analyze the dataset

Two software packages were used, Excel 2007 (Microsoft Corporation, Redmond, US) and SPSS (Statistical Package for the Social Sciences; IBM, New-York, US). The data were analyzed with the help of different formulas and statistics tools. The maximum, minimum and mean of daily and summer temperatures were used, as they show very well the seasonal and interrannual stability or changes in GPP, respiration, NEE, SWC or VPD values. The standard deviation of the data was also used. The standard deviation describes the spread, or the deviation, of values around the mean. It corresponds to the square root of the variance (Till, 1984). The variance, which was not used here but which is part of the standard deviation calculation, is the "average squared deviation of the observations for the mean". (Rogerson, 2010). Standard deviation was used to describe the variability of the values around the summer mean. In this way, one can easily see if the data are all close to a same value, or if they are spread around the mean and do not seem to follow a special trend. The use of the standard deviation was associated with use of the coefficient of determination R^2, which is the proportion of variability in a data set (Wikipedia). The R^2 ranges between 0 and 1. The higher it is, the higher the relationship between the two studied parameters is. It was very useful for the analysis of the data, and will thus be broadly used. The reason for this is that it permits to see easily if a relationship exists between two parameters.

Linear regression was used to give an idea of the trend followed by the data. It permits to interpret the charts, by giving a direction to the patterns the values shows, which is not always obvious to see. It is also easier to say if a linear relationship exist between the two parameters that were analyzed. The linear regression was though used carefully, as in some cases, a couple of values that do not follow the general trend can modify it. The value of the slope was also used, for it permits to see how sensitive a parameter is to another.

A comparison was then done between all the sites, in order to see if their common features could explain their responses.

The following parameters, all coming from the Fluxnet data, will be used to analyze the data: the air Temperature (T), the GPP, the ecosystem respiration, the SWC, the VPD, the precipitation.

4- Results

4.1- Overview

In this part of the thesis, it will be looked at the results drawn from the analysis of the data. First, the GPP of the six forests will be analyzed, during a normal summer, and then during an abnormally warm summer. The same will be done for the ecosystem respiration. Secondly, the results found will be analyzed through the prism of common features between sites: are forests reacting in a similar way because of the evergreen/deciduous factor, the needleleaved/broadleaved factor (vegetation types) and/or the latitude gradient (climatic zones)? Beforehand, the mean temperature and the mean SWC of every site for every available year will be presented.

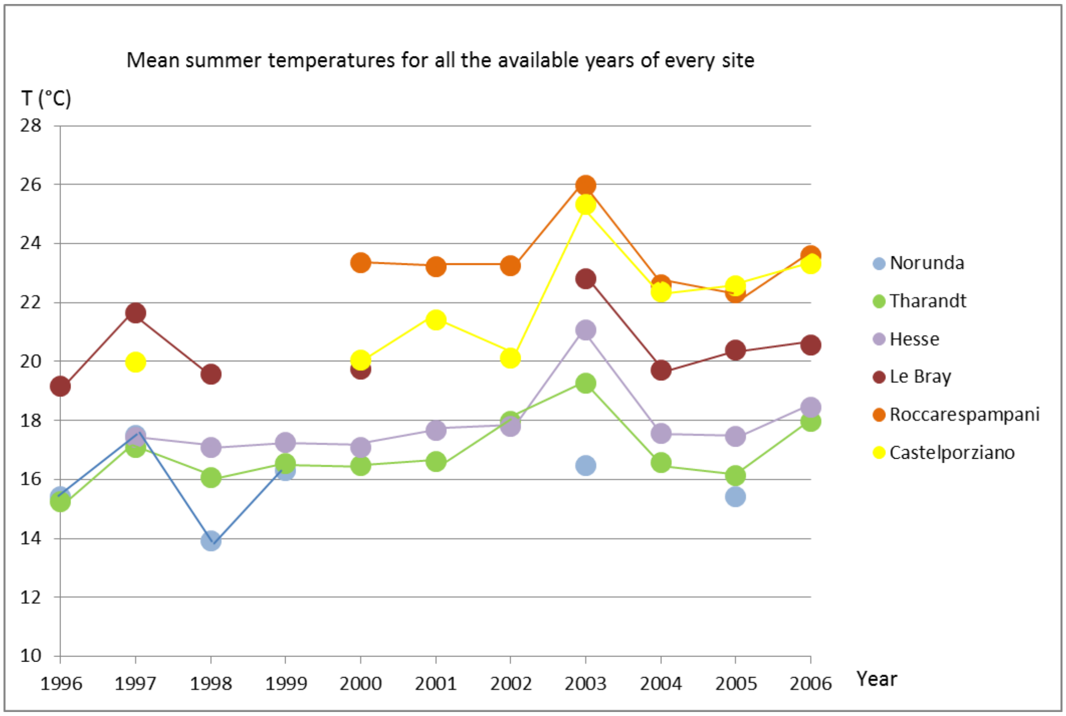


Figure 3: Mean summer temperatures for all available years of the six studied sites.

Figure 3 shows that 2003 indeed is a very warm year in Europe, as well as 1997 for some forests, and to a lesser extent, 2006 too. It also shows that the gradient of temperature through Europe is captured by the selected sites, as, in a general way, the more northern a site is, the lower the temperature is, which explains the study of the latitude gradient.

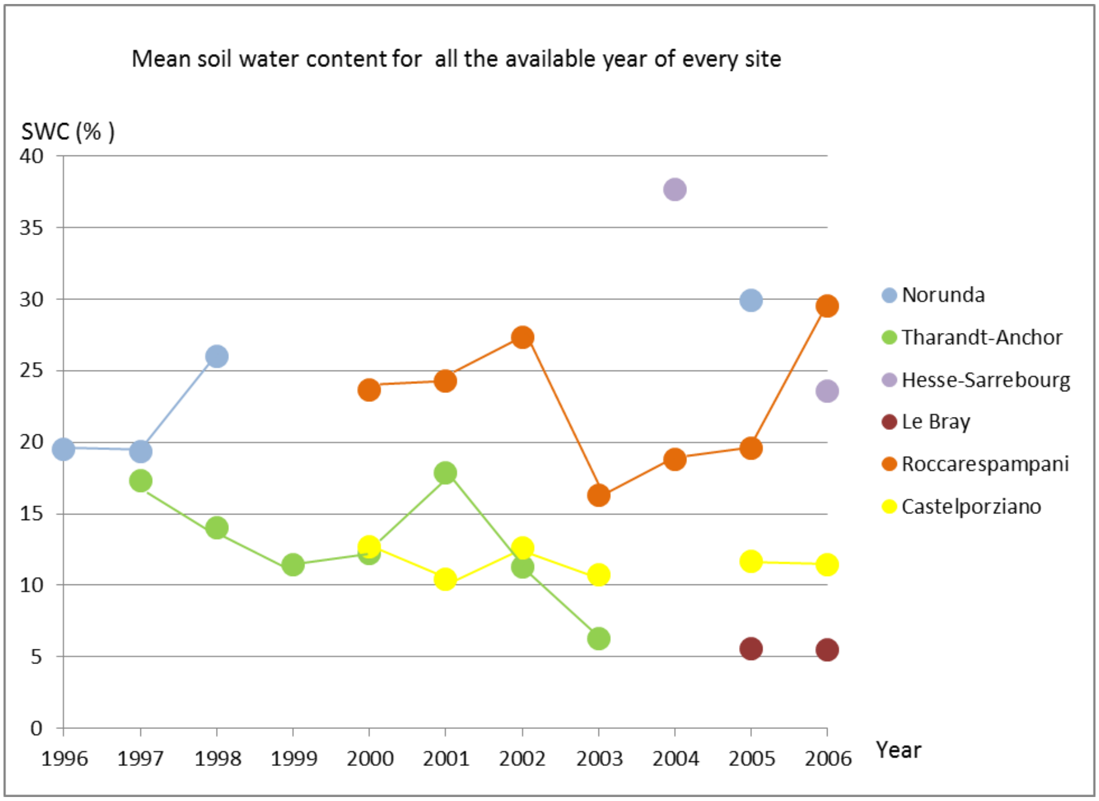
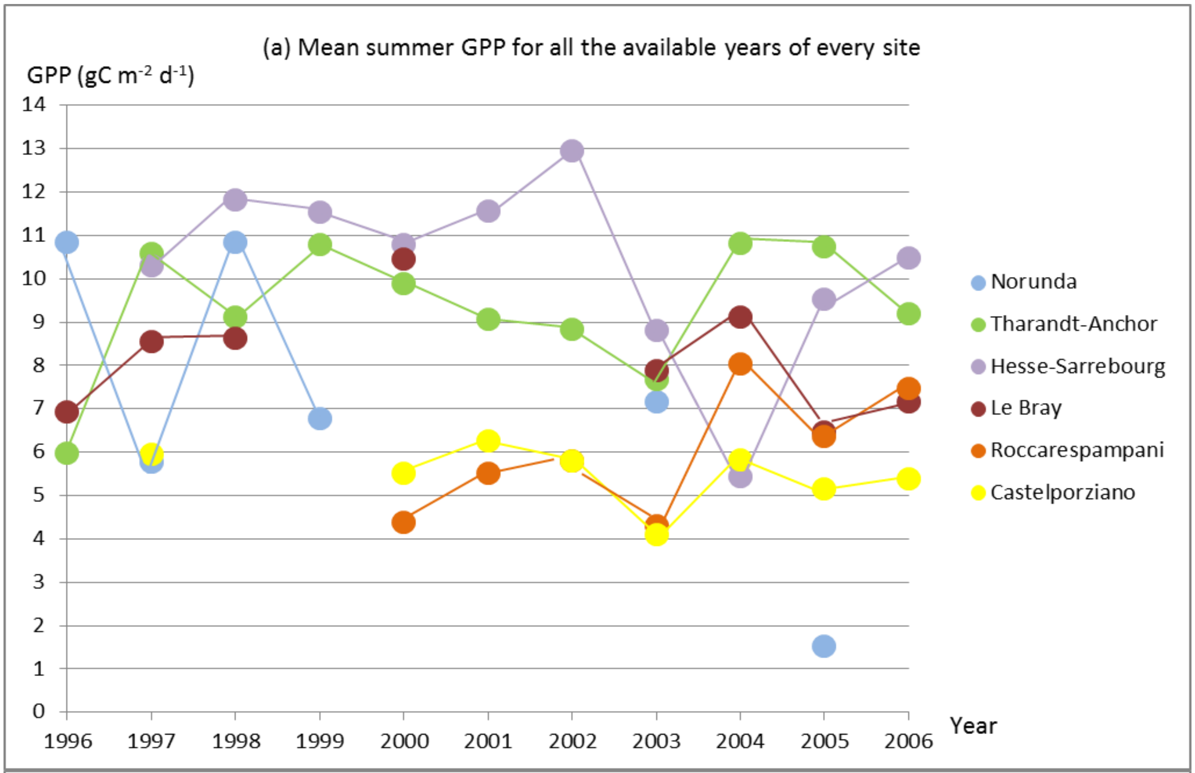


Figure 4: Mean summer SWC for all the available year of the six sites (% of the soil composition).

It can be seen in Figure 4 that there is a somewhat different response of the SWC for the year 2003 and 2006, which can be linked to the heat wave of these two years, as seen in figure 3. Here SWC cannot be compared between sites, as it represents a percentage of water in the soil, which depends on the soil type. For example, a podzolic soil like in Le Bray can contain a lot of water, whereas a sandy soil like in Castelporziano is characterized by an excellent drainage, and contain thus less water.

Figure 5a and 5b below will also be used as references for the analysis of the GPP and respiration of the six sites. They show that the abnormally warm summers of 1997, 2003 and 2006 have a strong effect on GPP and respiration of the forests. Nevertheless, the response of GPP seems much clearer than that of respiration, for it shows clearly that nearly all sites are affected. But it seems on Figure 5b that in 2003, only the two Italian sites show somewhat of a response.


(a) Mean summer GPP for all the available years of every site

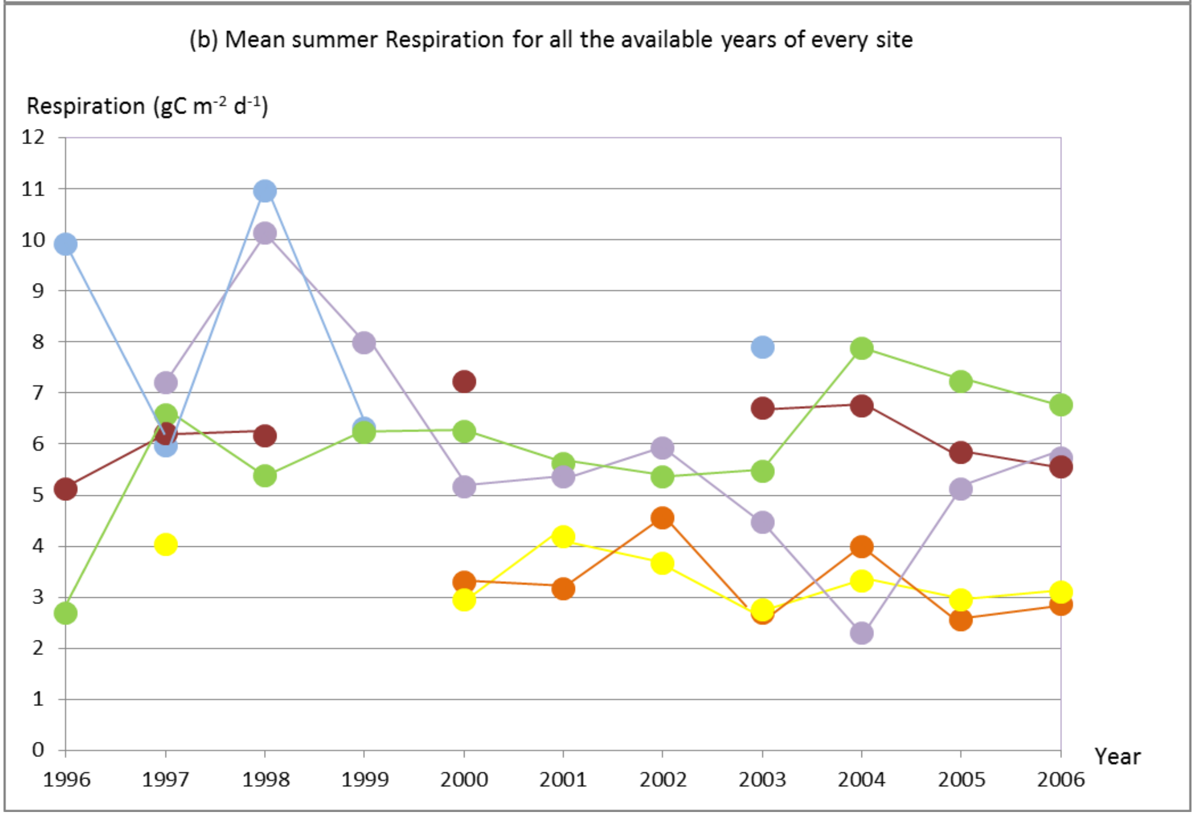

(b) Mean summer Respiration for all the available years of every site

Figure 5: Mean summer GPP (a) and respiration (b) for all the available years of every studied site

4.2- Summer normal and abnormally high temperatures effects on GPP and respiration

4.2.1. Normal summer temperatures effects on GPP

Temperature is one of the main parameters to affect the functioning of photosynthesis. During a normal summer, GPP is either increasing following the increase of temperature or staying constant, in the same range, or decreasing.

The increase of GPP with the increase of temperature during a normal summer can be seen for example in the site of Tharandt-Anchors, during the year 2005 (Table 2). The mean temperature for this summer is 16.1 °C, which corresponds to an average mean for a summer in this site. The mean of all the summer mean temperatures is 16.9 °C, with a standard deviation of 1.1 °C, which places the summer 2005 in a close range to the general mean.

Table 2: Comparison of the mean summer temperature (Celsius degrees) for all available years in Tharandt-Anchor

Year	Number of days	Minimum Temperature	Maximum Temperature	Mean Temperature
1996	92	8.64	21.92	15.2571
1997	92	7.07	23.81	17.0954
1998	92	8.26	26.55	16.0687
1999	92	9.67	24.13	16.5539
2000	92	9.02	27.69	16.4843
2001	92	6.60	26.18	16.6050
2002	92	11.35	25.02	17.9594
2003	92	11.33	27.81	19.2686
2004	92	10.67	23.48	16.5621
2005	92	6.79	25.97	16.1427
2006	92	6.53	28.32	17.9753

Figure 6a shows that for this summer, GPP is increasing following the increase of temperature. Maximum values for GPP are found for temperatures between 15 °C and 22 °C (except a couple of high GPP values, around 10 °C), and never go above 16 gC m^{-2} d^{-1}. The minimum value when daily temperatures are the lowest (6.8 °C) is 7.63 gC m^{-2} d^{-1}, and the minimum value when daily temperatures are the highest (around 25°C) is 12.94 gC m^{-2} d^{-1}. This last observation shows that, during a normal summer in Tharandt-Anchor, the higher temperatures are, the higher GPP minimum values are, as seen on Fig. 6, where the lower limit follows a clear slope and is plainly visible.

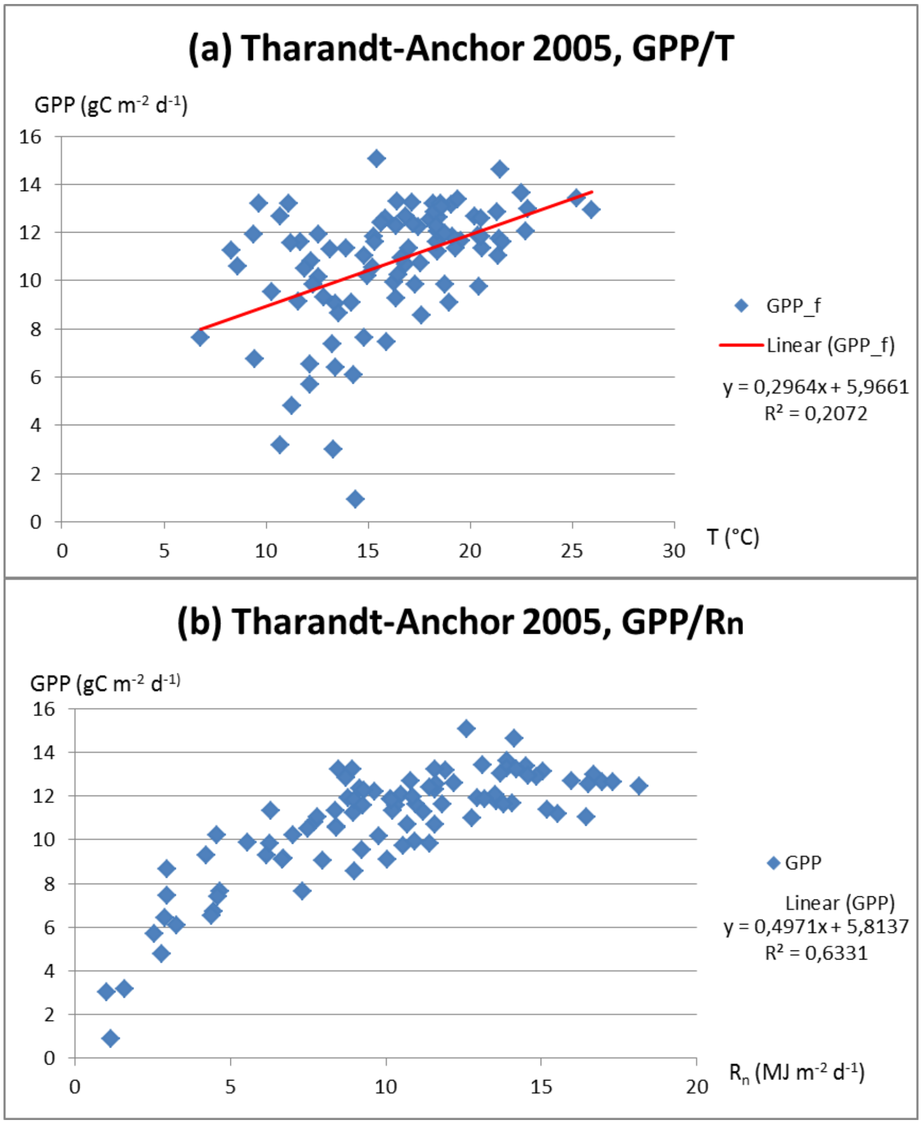


Figure 6: Daily GPP related to daily temperature (a) and daily GPP related to the Net Radiation (b) in Tharandt-Anchor during the summer 2005.

GPP values are also strongly correlated to light. Figure 6b shows that the higher the amount of daily net radiation is, the higher GPP is. The high R^2, 0.6, confirms that the correlation between the two is important. The evolution of the GPP according to light let see the shape of an exponential curve; after around 12 MJ m^{-2} d^{-1}, GPP stops increasing, and on the contrary slowly starts to decrease, which can be related to the fact that large amounts of light can lead to very high temperatures.

This response during normal summers can be found in two other sites: Norunda and Hesse-Sarrebourg, that is to say in the northern sites. An explanation for this common behavior is related to the adaptive characteristics to the species. Indeed, ecosystems are adapted to these ranges of temperatures, which are part of the environment characteristic. When soil moisture and the amount of precipitation also are normal, this response appears to be typical for these sites (Oke, 1978).

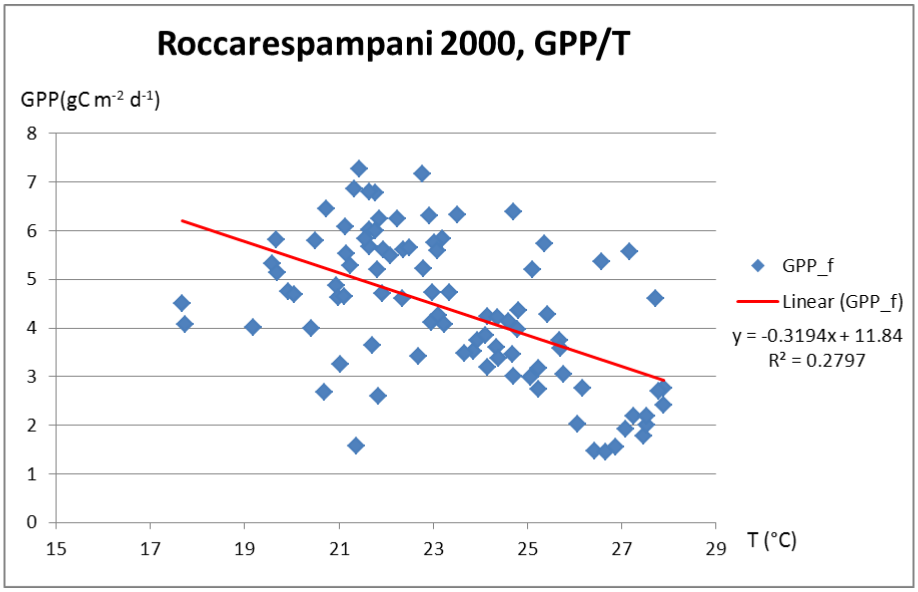


Figure 7: GPP related to temperature in Roccarespampani, during the summer 2000.

The three southernmost sites, Le Bray, Castelporziano and, as seen on Figure 7, Roccarespampani, show a decreasing GPP following the increase of temperature during almost all the normal summers, probably because summer temperatures there are already very high (see Figure 3) and are enough to impact the forests metabolism.

4.2.2- Abnormally high summer temperatures effects on GPP

During a summer when temperatures are abnormally high, GPP can respond in two different ways in the observations.

First, it can increase, because higher temperatures stimulate photosynthesis. Temperature tends to become more optimal for the development of photosynthesis, which is stimulated. This case can be found in only one site, Norunda, for example in 1997. The mean of the mean summer temperatures for all the available years in Norunda is 15.8 °C, and the mean temperature during the summer 1997 is 17.5 °C, which is 1.7 °C higher than all the other summers. Figure 8a shows that a short-term trend seems to appear as, within the summer, GPP seems to increase following the temperature increase. The mean GPP is 5.76 gC m^{-2} d^{-1}, with a standard deviation of 1.63 gC m^{-2} d^{-1}, which is the lowest of the standard deviation for every year in Norunda. On the long-term, compared to 1996 and 1998 which are two normal years in term of temperatures, GPP is almost twice as low (Fig. 5a; mean GPP values for these two years are respectively 10.83 and 10.84 gC m^{-2} d^{-1}). GPP values are thus abnormally low, as well as their variability. It means that high temperatures are negatively impacting photosynthesis. Nevertheless, the R^2 is here quite low (0.04), which means that temperature is not the main factor to drive GPP. The impact of light is more important than that of temperatures, as seen on figure 8b, where the R^2 is 0.2. The negative value than can be seen on Figure 8a can be explained by the fact GPP is indirectly obtained by an equation, and sometimes some errors can occur (section 2.2).

The other major parameter which controls photosynthesis, soil moisture, is not to be relevant in the case of Norunda, as the site is particularly wet (Halldin et al., 1999). Nevertheless, as 1997 was a very dry year for Norunda, it is possible that SWC has become lower than usual, which would have limited both GPP and respiration.

Figure 8a also shows that during the three hottest days of the summer 1997, GPP values are not as high as during cooler days, for example when temperature is between 12 and 20 °C. During a normal summer, GPP normally increases following the increase of temperatures. When temperatures are abnormally high, the optimum for photosynthesis is reached, and higher temperatures seem to lead to a stable GPP (values are included in a certain range, here between 4 and 8 gC m^{-2} d^{-1}), and to the beginning of a decrease). It is interesting to see on Figure 8b that the low GPP values (those beyond 3 gC m^{-2} d^{-1}) corresponds to days with a low amount of net radiation (probably due to a cloudy sky).

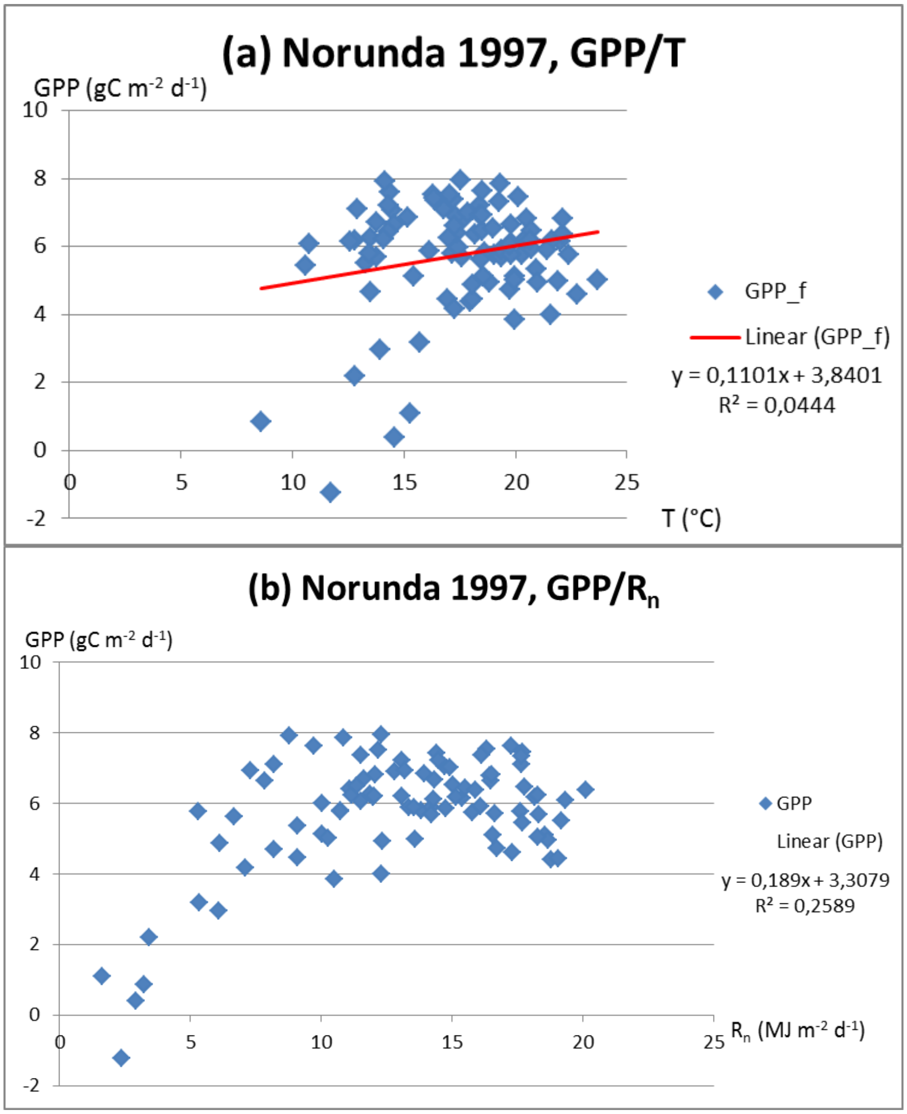


Figure 8: GPP related to temperature (a) and GPP related to the net amount of radiations (b) in Norunda, during the summer 1997.

The second possible behavior of forests when temperatures are abnormally high is a marked decrease of GPP, possibly preceded by an also marked increase. This situation was found in the majority of the sites (Tharandt-Anchor, Hesse-Sarrebourg, Le Bray, Roccarespampani and Castelporziano) during the hottest summers, especially in 2003. One (among many available) example is found during the summer 2003 in the forest of Hesse-Sarrebourg.

We can see on the Figure 9a that the highest values for GPP (around 16 gC m^{-2} d^{-1}) can be found for the middle temperature values. The four highest GPP values are thus found for temperatures between 20 and 20.5 °C. GPP values are very variable (between 2 and 16 gC m^{-2} d^{-1}) for low and middle temperatures. Around 24 °C, a threshold seems to be crossed. Beyond 24 °C, GPP suddenly decreases, and values become low again, approaching 2 gC m^{-2} d^{-1}) during the hottest day (29.3 °C).

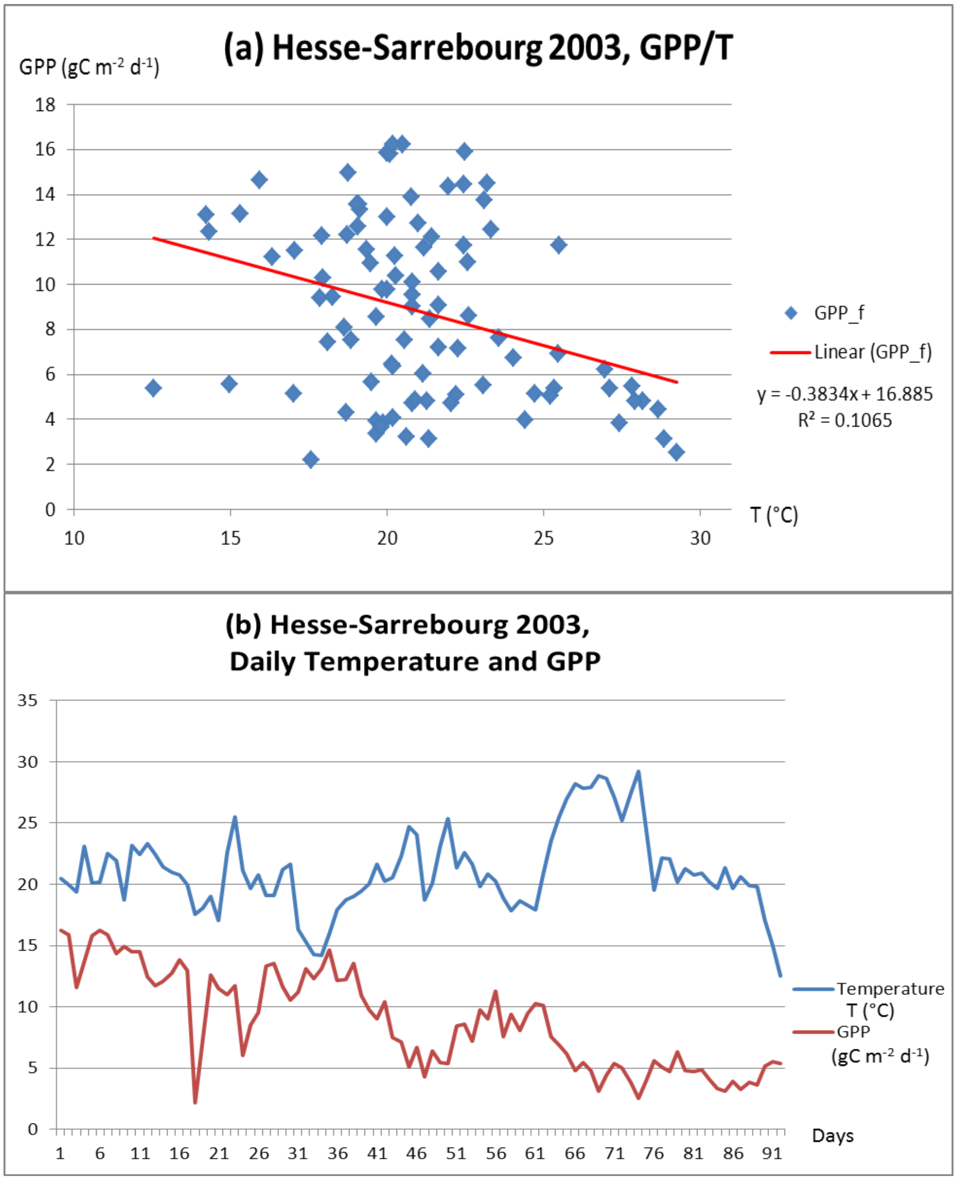


Figure 9: GPP related to temperature (a) and Temperature and GPP evolution day per day (b) during the summer 2003 in Hesse-Sarrebourg.

In parallel of this behavior, Figure 9b shows that, during the same summer, the highest GPP values are found at the beginning of June, while the lowest are reached at the end of August (except for one value, the 18th of June). In between, GPP is decreasing, following a saw tooth curve. Figure 9b also shows that this GPP trend throughout the summer is not exactly fitting to the temperature one, which mean that temperature is not the only driver of the GPP response. Another driver might be the water availability. No SWC data are available for the summer 2003 in Hesse-Sarrebourg, but Vapor Pressure Deficit shows that the GPP is indeed linked to the water parameter (Figure 10).

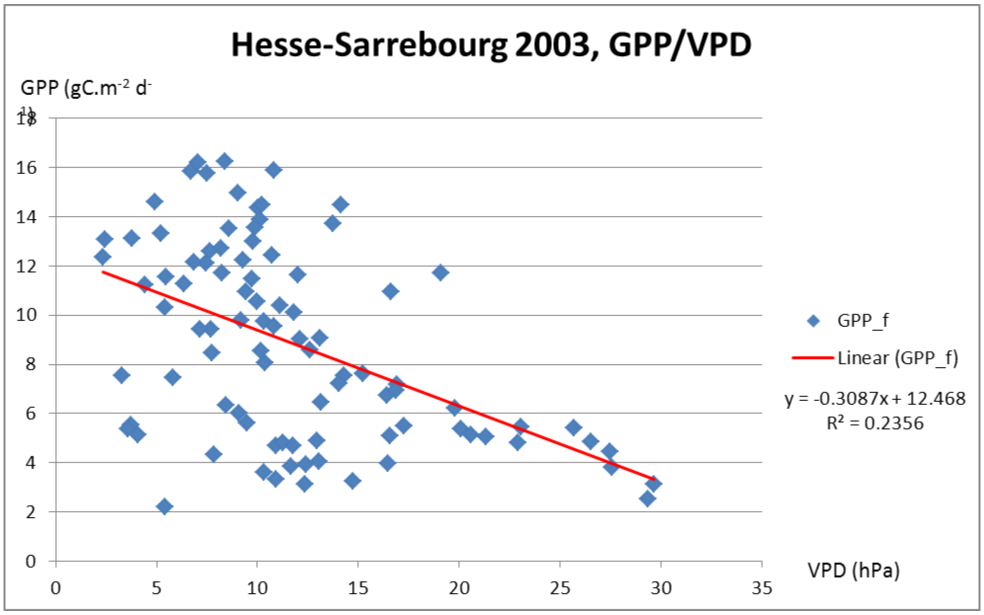


Figure 10: GPP related to the Vapor Pressure Deficit during the summer 2003 in Hesse-Sarrebourg

These graphs can be explained by the behavior of the stomata when confronted to high and abnormally high temperatures, as well as low soil moisture or low VPD (especially during a drought). Stomata are leaf cells that open or close in in such a way that the balance between CO_2 uptake and water loss is optimized (Jones, 1992). When temperature is beyond the optimum for photosynthesis, that is to say beyond the normally encountered temperature range, and when soil moisture is particularly low, stomata get closed, in order to avoid water evaporation (Jones, 1992). But as Jones adds, the magnitude of the response depends then on the vapor pressure.

Within an abnormally warm summer, the five sites showed a decrease of GPP following the increase of temperatures, but other parameters, in particular soil moisture (strongly influenced by precipitation, but also by temperature) and light availability, might also influence the change of GPP. It is thus not possible here to affirm clearly to what extent temperature is responsible for the decrease of GPP.

Even if it is difficult to say precisely which site will have its GPP more affected by the very likely increase of temperatures induced by climate change, some sites still show more marked changes than others. It is the case for Hesse-Sarrebourg and Roccarespampani (especially during 2003). The case of Roccarespampani is even more interesting that it is the site which shows the highest values for the slope, which means that it is where the GPP is the most sensitive to the changes in temperatures.

In a more general way, when SWC values are available, it can be seen that the link with GPP is quite strong in some sites during abnormally warm summers, especially when there is a drought. A good example can be found, again, in Roccarespampani in 2003 (Figure 11).

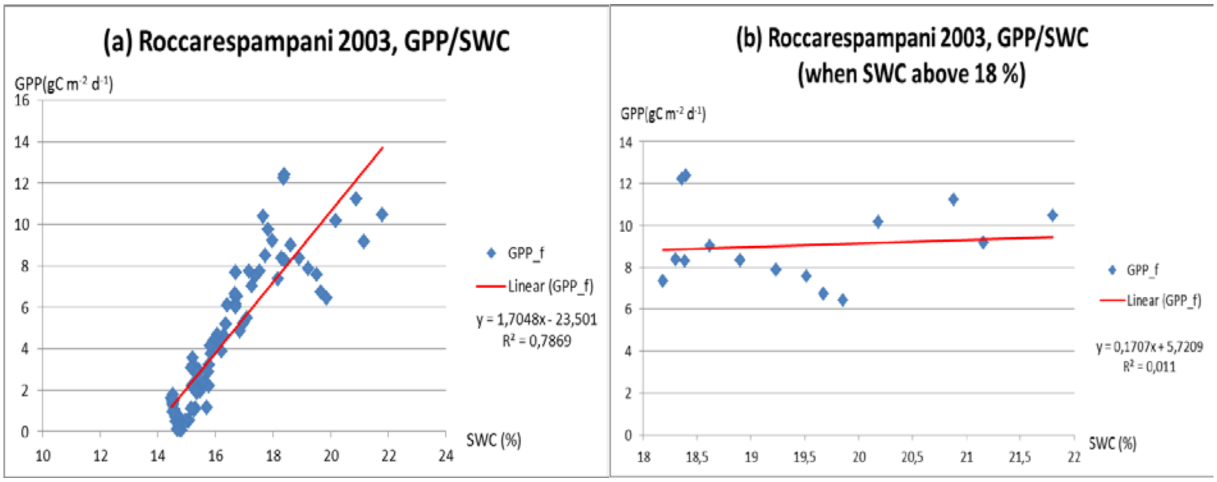


Figure 11: GPP related to SWC for every values (a) and when SWC is above 18% (b) during the summer 2003 in Roccarespampani.

Figure 11a shows that in this forest, GPP almost approaches zero when soil moisture is the lowest, and the R^2 is 0.79, which is extremely high, as well as the slope (1.70, that is to say 1.70 gC m^{-2} d^{-1} of GPP increase for an increase of 1% of the SWC). The effect of the drought is here well visible. Moreover, there seems to be a threshold around 18 % of water in the soil. Below 18% the response of GPP is clear, whereas after 18% the link between GPP and SWC is less clear. Figure 11b shows that when soil moisture is higher than 18 %, it is not anymore an important driver of GPP, as the R^2 is quite low (0.01).

To summarize, within a “normal summer”, GPP can either increase following the increase of temperatures (the three northern sites), or decrease following the increase of temperatures (the three southern sites). GPP is also strongly linked to light availability. Within an abnormally warm summer, GPP increases following the increase of temperature only in Norunda, the northernmost site. In the five other sites, GPP decreases following the increase of temperatures. In almost all the sites, the mean GPP during the abnormally warm years is lower than during normal years (Figure 5a). When data is available, it can be seen that this decrease is strongly linked to the decrease of soil moisture and water availability. It is even more marked in the southernmost sites, where it can be attributed to droughts.

4.2.3- Normal summer temperature effects on respiration

In most of the sites (all of them except Hesse-Sarrebourg, where the respiration does not especially increase or decrease following the increase of the temperatures), forests' respiration is directly affected by the summer temperature, as it can be seen in Tharandt-Anchor during the summer 2005. It is also the case of Norunda and Le Bray.

Figure 12 shows that, in Tharandt-Anchor in 2005, respiration is increasing almost linearly, following the increase of the temperatures, and ranging from 4.15 gC m^{-2} d^{-1} to 11.11 gC m^{-2} d^{-1}. The R^2, 0.72, is particularly high. It shows that here, temperature is the major parameter to control the evolution of the respiration throughout the summer. No SWC data is available to see whether the role of water in the respiration trend is major or not (but this subject will be treated in section 4.2.4).

This trend shows that, during a normal summer, the higher temperatures are, the higher respiration will be. But although this can be seen for most sites and years, this positive trend does not always occur, and the data showed other respiration patterns during normal summers as well.

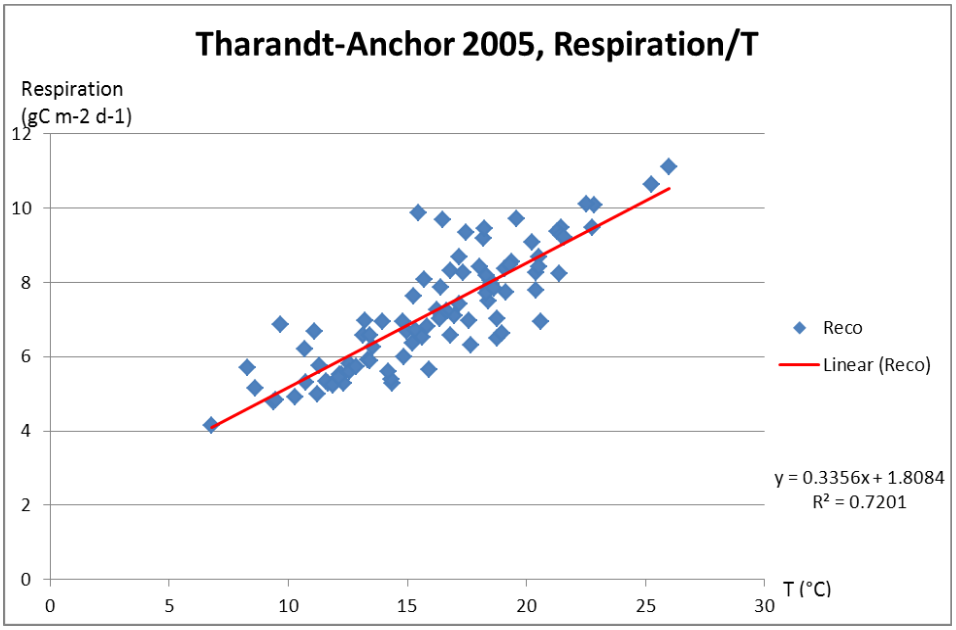


Figure 12: Respiration related to temperature during the summer 2005in Tharandt-Anchor.

It was found in some sites that respiration appears to be lacking a trend during the summer, which means that it does not seem to increase or decrease with temperature changes, and that the standard deviation is, in most cases, quite high. This case was for example found in Castelporziano during the summer 2000, in Hesse-Sarrebourg during the summer 1999, or in Tharandt-Anchor during the summer 1997.

In contrast to this, some sites also present an inverse respiratory trend and behavior. For example, in Roccarespampani, during a normal summer, respiration decreases when temperature increases, as seen on Figure 13a.

Here respiration ranges from 7.44 gC m^{-2} d^{-1} for low temperatures (between 17 and 20 °C) to 1.65 gC m^{-2} d^{-1} for some of the highest temperatures (almost 29 °C). This trend can be explained by the fact that soil moisture has a very strong impact on soil microbial activity, and consequently on respiration (Stark & Firestone, 1994; Ciais et al., 2005). When temperatures are high, soil moisture is likely to be reduced, which has an effect on cell dehydration and diffusional limitations of the substrate (the material that can be decomposed as CO_2). SWC decreases, soil pores drain and the water films that cover the soil surface become thinner, which make diffusion paths for the substrate more meandering. Moreover, the decrease of cell hydration reduces the activity of the enzymes responsible for respiration. As a consequence, the microbial activity is likely to be inhibited, and respiration might thus decrease (Stark & Firestone, 1994). This explains why in Roccarespampani in 2001, the link between respiration and Soil Water Content is so strong (Figure 13b).

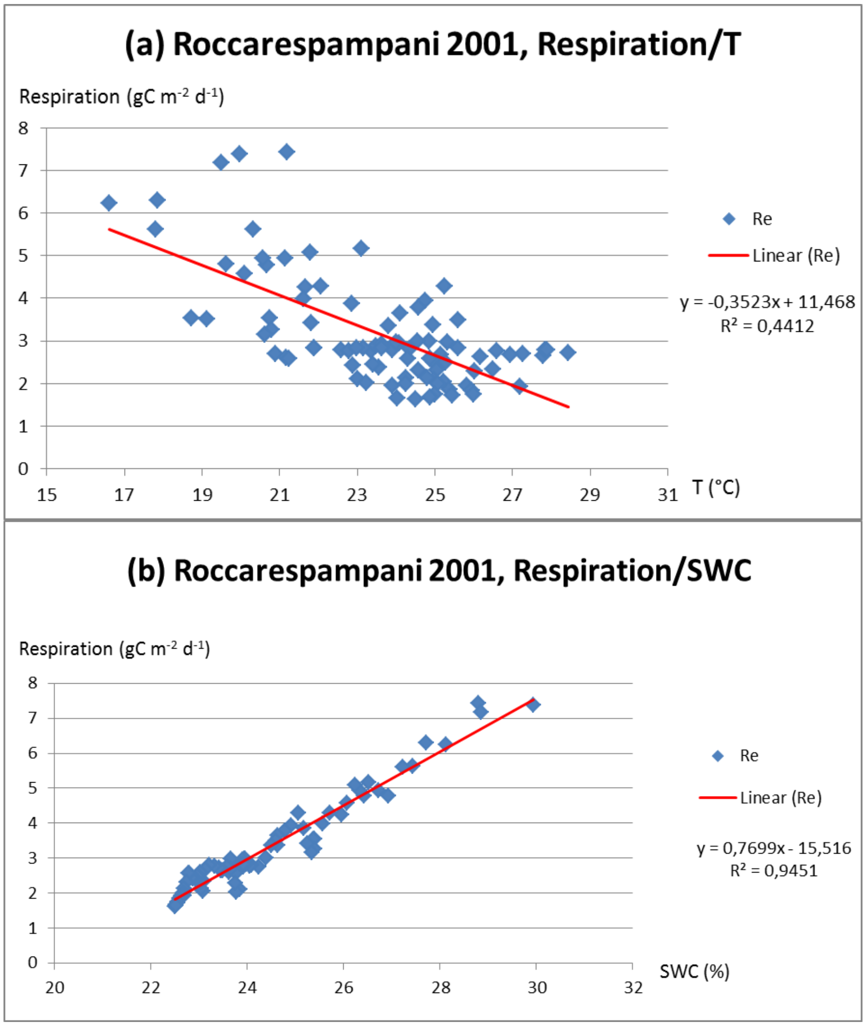


Figure 13: Respiration related to temperature (a) and SWC (b) in Roccarespampani during the summer 2001.

The marked decrease of respiration with the increase of temperatures can be found for every summer in Roccarespampani, except in 2002 (see Figure 14a).

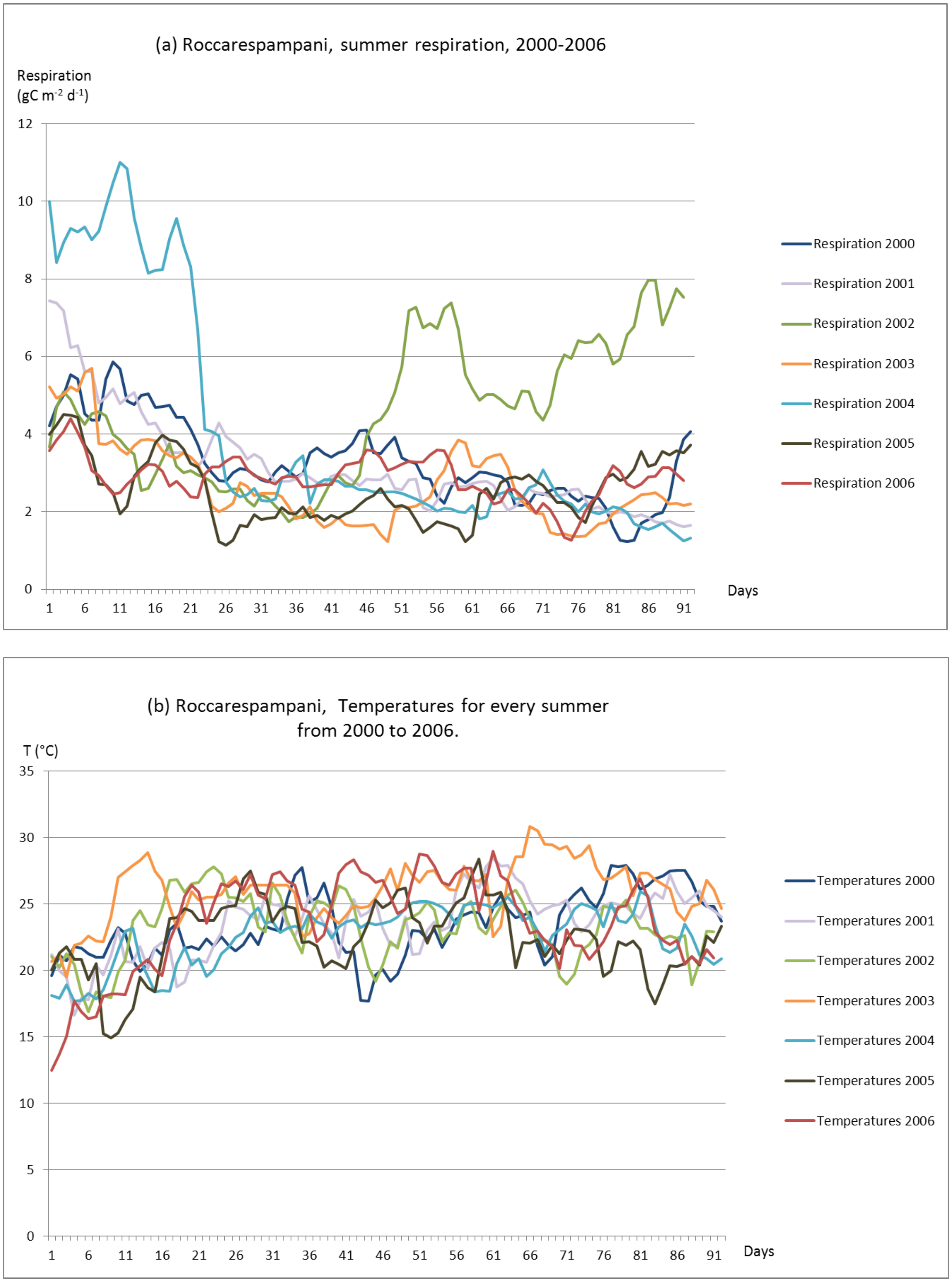


Figure 14: Respiration (a) and Temperature (b) for all the available years in Roccarespampani.

We can see here that, except for in 2002, respiration decreases throughout the summer, and, for the summers 2000, 2003, 2004 and 2006, starts to increase again at the very end of august, which corresponds to a slight decrease of the summer temperatures (figure 14b). The same trend can be found in Castelporziano.

An explanation for the behavior of the respiration in 2002 can be found in the precipitation pattern. Hence, throughout this summer, temperatures are quite constant and do not vary a lot (the standard deviation is 2.3 °C, below the mean standard deviation of all the summers in Roccarespampani, which is 2.5 °C), and there is no obvious increase or decrease that can explain the marked increase of respiration starting around the end of June. The answer might come from precipitation and soil moisture.

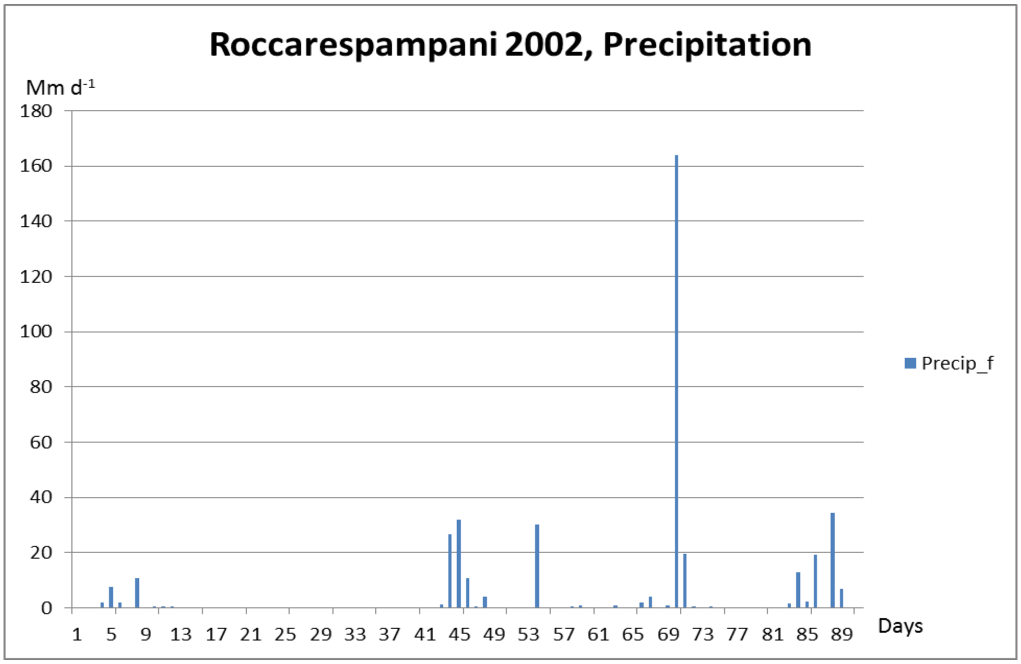


Figure 15: Precipitation in Roccarespampani for the summer 2002

In parallel with a slight decrease in temperature in august, precipitation at the same moment increases (see figure 15), which makes soil moisture increasing. As explained previously, it directly impacts the process of respiration.

4.2.4- Abnormally high summer temperatures effects on respiration

In two sites, Norunda and Hesse-Sarrebourg, during a heat wave and/or a drought year, respiration increases with abnormally high temperatures.

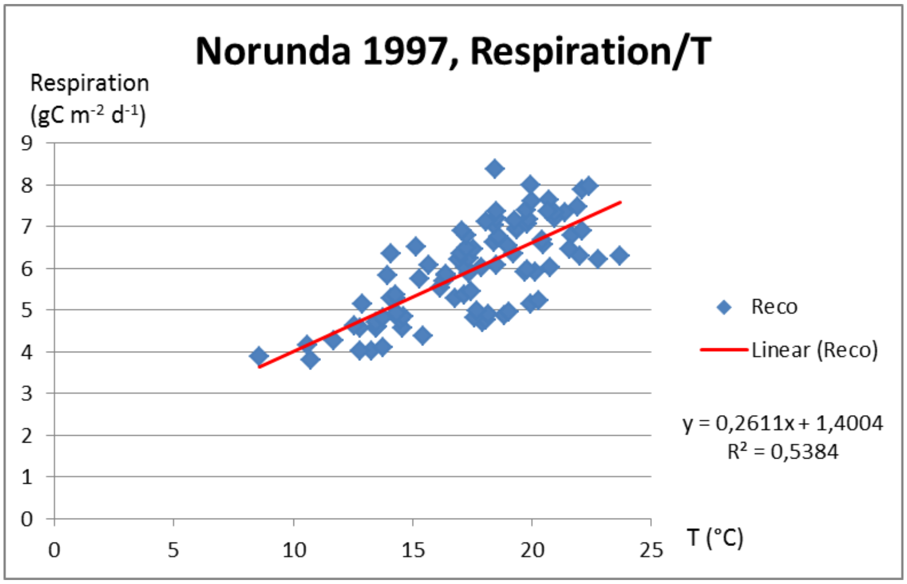


Figure 16: Respiration for the hottest year in Norunda.

Figure 16 shows that in Norunda, respiration follows a linear trend, and ranges from 3.82 gC m^{-2} d^{-1} to 8.39 gC m^{-2} d^{-1}. Standard deviation is not very high (1.1 gC $^{m-2}$ d^{-1}), which contributes to explain the high R^2 value, 0.5. It means that for this year, temperature is the main parameter to drive respiration. Moreover, the slope is 0.26, which means than for every increase of 1 °C, respiration increases of 0.26 gC m^{-2} d^{-1}. The R^2, 0.5, shows that the relationship between respiration and temperature is quite important here. In Norunda in 1997, the mean summer temperature is 17.5 °C, which is 1.7 °C more than the mean of the mean summer temperatures (15.8 °C). This trend in Norunda does not differ from those during normal years, whereas the increase of respiration following the increase of temperatures is typical from abnormally warm year in Hesse-Sarrebourg (see section 4.2.3).

The four other sites (Tharandt-Anchor, Le Bray, Roccarespampani and Castelporziano) show different trends. Figures 17c and 17d, which refer to the two southernmost sites, show a marked decrease of respiration, while this trend is more moderated for figures 17a and 17b. For these two sites, the R^2 is also higher, because, as Mediterranean sites, temperatures are extremely high, and are thus more likely to impact respiration, even if these forests are used to it.

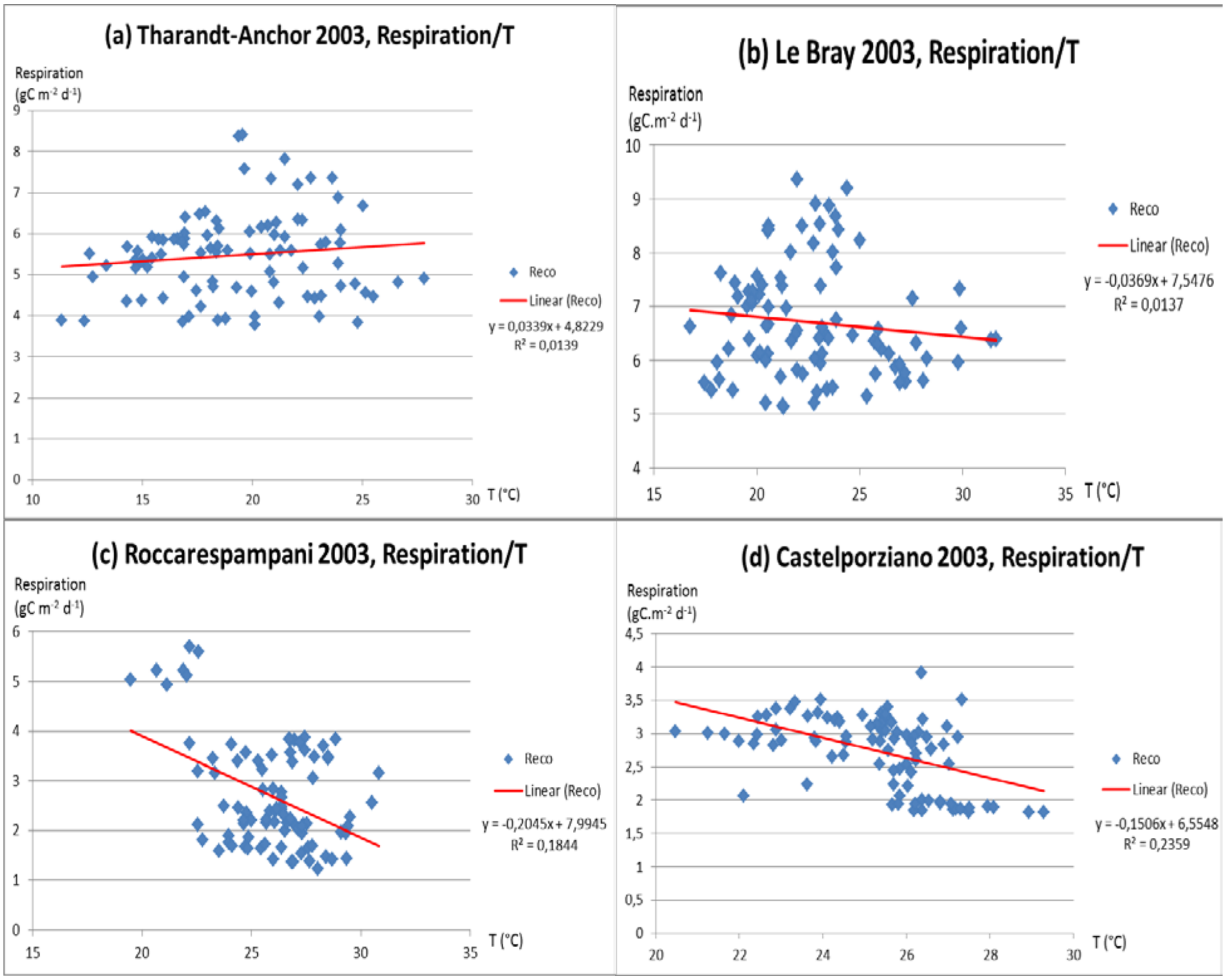


Figure 17: Respiration for the hottest years in Tharandt-Anchor (a), Le Bray (b), Roccarespampani (c) and Castelporziano (d)

Soil moisture is also an important driver of respiration, especially in three sites in 2003, even if they are not Mediterranean. It is the case for Tharandt-Anchor, where SWC data are available (see Figure 18). Here, the R^2, 0.3, is high, as well as the slope (0.52). The comparison between Figure 17a and Figure 18 shows that in Tharandt-Anchor in 2003, SWC is a more significant driver of respiration than temperature (even if both drivers are tightly linked).

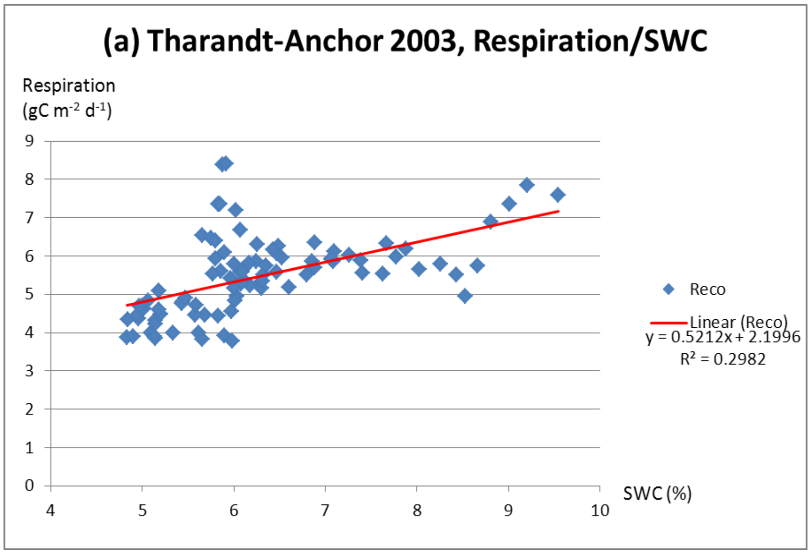


Figure 18: Respiration related to SWC in during the summer 2003 in Tharandt-Anchor .

To summarize, within a normal summer, respiration can either increase (Norunda, Tharandt-Anchor, Le Bray), lack any special trend (Hesse-Sarrebourg, but also for some years Tharandt-Anchor and Castelporziano) or decrease (Roccarespampani, Castelporziano) when following the increase of temperature. Within an abnormally warm summer, respiration increases following the increase of temperatures in Norunda and Hesse-Sarrebourg; no clear trend can be found in Tharandt-Anchor, and it decreases in Le Bray (slightly though), Roccarespampani and Castelporziano. In both situations, ecosystem respiration is very dependent water availability (seen through SWC, VPD, and precipitation).

4.3- Common features

The results found previously show that the six forests react differently to normal and abnormally warm summer temperatures. It will now be tried to classify these behavior according to the special characteristics and location of these forests.

4.3.1- Vegetation type effect - evergreen and deciduous forests

The results above tend to show some common features between vegetation types. Two sites are deciduous and four sites are evergreen, three of them are broadleaved and three of them are needleleaved, and they are spread over Europe, from the northernmost to the southernmost latitudes (table 1). The first division that can be found is between evergreen forests (Norunda, Tharandt-Anchor, Le Bray, Castelporziano) and deciduous forests (Hesse-Sarrebourg, Roccarespampani).

It was seen in the results (Figures 6, 8 and 12) that only two forests which are evergreen and needleleaved, Norunda and Tharandt-Anchor, never show a decrease of GPP following the increase of temperatures during abnormally warm summers. It is even more obvious that both sites are well-followed by scientists, which means that there was plenty of years to check if these responses were common or not. (six years for Norunda and eleven years for Tharandt-Anchor). The two other evergreen sites, Le Bray and Castelporziano, show a decrease of GPP with the increase of temperatures, but it is not possible to determine whether it is due to the evergreen parameter or to a latitude factor coupled with them (Norunda and Tharandt-Anchor are the two northernmost sites). As phenology and location are tightly linked (for example evergreen broadleaved forests like Castelporziano are mostly found in the southern latitudes), one can say they are interdependent. The fact that both Norunda and Tharandt-Anchor include one same species, *Picea Abies*, might also explain why they react the same way.

It has also been found that in 2003 in three of the four evergreen sites (Tharandt-Anchor, Le Bray and Castelporziano), respiration does not increase when temperatures increase, but rather stay constant, or decrease (as seen on Figures 17a, 17b and 17d). This could be explained by the fact that with the increase of temperature to high levels, the metabolism of the leaves slows down in these forests, with makes the respiration decreasing (see section 2.1.4). Nevertheless, depending on the time of the year a larger part of respiration comes from heterotrophic respiration, which is why those results could also be explained by the fact that microbes and roots cannot work any more with the decrease in SWC (see section 4.2.3). This behavior was also found in Roccarespampani for the same year.

Concerning GPP, the most marked changes were found in the deciduous forest. It could be explained by the fact that deciduous trees, on the contrary to evergreen trees (which most of the time are needleleaved), have broad leaves, which store more heat than the needle leaves. Indeed, the leaves of the evergreen (mostly needles) trees are smaller. Thus, their surface area is large, compared to their mass. Consequently, according to Oke (1978), this leaf geometry enables these trees to send the heat accumulated to the environment, using convection and long-wave radiation.

Here the link between evergreen/deciduous and needleleaved/broadleaved forest cannot be unraveled, as the only site that could help to distinguish these, Castelporziano, is also strongly influenced by its location (as will be shown below).

4.3.2- Broadleaved and needleleaved forests

The main difference between broadleaved and needleleaved forests lies in the NEE values. During normal years various parameters as temperature and soil moisture control these processes. When respiration is higher than GPP, the values of NEE are positive and there is a release of CO_2; and when GPP is higher than respiration, the values of NEE are negative and there is an uptake of CO_2. It is difficult to say precisely which one of the GPP or of the respiration controls NEE variability within a summer, as NEE varies considerably between years and between sites.

Nevertheless, it was found in this study that during normal summers, the uptake of CO_2 is dominant in nearly all the sites, and GPP is higher than respiration. A difference was found between broadleaved and needleleaved forests. Indeed, even during normal summers, the respiration of the three needleleaved forests, Le Bray, Tharandt-Anchor and Norunda, which is a well-known CO_2-source (Halldin et al., 1999; Feigenwinter et al., 2008), is often higher than the

GPP, compared to the broadleaved sites (Hesse-Sarrebourg, Roccarespampani and Castelporziano), where it only happens when temperatures are abnormally high. This situation might be caused by the relatively high values of SWC in these sites, which positively affects respiration (see section 4.2.3).

4.3.3- Climatic zone/latitude gradient

The latitude gradient is important to understand the different ways that forests react during normal and hot summers. It is an important driving variable, as a range of factors depend on it, such as precipitation, temperature, radiation balance, length of the growing season (Valentini et al., 2000). In their study, Valentini et al. (2000) showed that the smallest GPP are found in the northernmost sites.

Table 3: GPP (gC m^{-2} d^{-1}) for a normal year, 1997, in five sites where data are available (1996 for Norunda).

Site	Number of days	Minimum GPP	Maximum GPP	Mean GPP	Std. Deviation
Norunda	92	4.17	17.90	10.8345	3.07956
Tharandt-Anchor	92	3.44	15.73	10.5766	2.44181
Hesse-Sarrebourg	92	1.34	15.48	10.2956	2.81233
Le Bray	92	2.39	13.64	8.5640	2.18491
Castelporziano	92	2.67	8.80	5.9504	1.48099

Table 3 shows that the mean GPP for a normal summer decreases with decreasing latitude. Moreover, the latitude gradient explains why Roccarespampani and Castelporziano, the two Mediterranean and southernmost forests, show common features, such as the way respiration decreases with temperature increase for some summers (particularly 1997, 2003 and 2004). In addition, respiration values are particularly low during abnormally warm summers in these two sites, as can be seen in table 4.

Table 4 shows that during a very hot summer, both Roccarespampani and Castelporziano have the lowest mean respiration, as well as the lowest minimum and maximum respiration.
Valentini et al., (2000) explain that the low rates of respiration (when compared to the other sites in Europe) might be caused by the drought factor, which directly limit the possibility for soil to respire (Valentini et al., 2000). Indeed, when temperatures become very high and water supply scarce, both photosynthesis and respiration decrease, as the entire metabolism of the trees is affected (Jones, 1992).
These results show that for some sites, the location, for example in the north or in the south of Europe, and its particular characteristics (temperatures, humidity, weather…), does influence GPP and respiration during the summer.

Table 4: Respiration (gC m^{-2} d^{-1}) for the hottest years in every sites – 1997 for Norunda and 2003 for the other sites.

Site	Number of days	Minimum Respiration	Maximum Respiration	Mean Respiration	Std. Deviation
Norunda	92	3.82	8.39	5.9668	1.11197
Tharandt-Anchor	92	3.78	8.41	5.4771	1.03334
Hesse-Sarrebourg	92	1.95	7.62	4.4686	1.42354
Le Bray	92	5.13	9.37	6.7068	1.04792
Roccarespampani	92	1.23	5.69	2.6830	1.05578
Castelporziano	92	1.82	3.91	2.7420	.53268

5- Discussion

5.1- Missing data

One problem when analyzing the data has been the lack of some years or important variables. Because of this, it was not always possible to compare every site, which constrained to go further in the analysis of the results.

For example, in some sites several years between 1996 and 2006 are missing. For example in Norunda, 2006 is not available. It let a gap when analyzing sites by common features (evergreen/deciduous, needleleaved/broadleaved, climatic zone), as some sites did not show a lot of information.

Moreover, it was often found that some key parameters, such as SWC (missing in almost half of the available years in every site), GPP, ecosystem respiration, precipitation or the incoming and outgoing radiations are also lacking. For example, there are only two years of SWC data for Hesse-Sarrebourg or Le Bray (out of ten and eight years available for temperatures, respectively). These gaps in the data made it difficult to explain every trend and every behavior noticed in the sites.

Some other important parameters were also lacking, like for example the litter availability, which could have been useful when analyzing the ecosystem respiration.

5.2- The heterogeneity of the sites

When analyzing the results, it should be kept in mind that all the sites are different, because of their species and location, but also because of their age, and the way humans have impacted them (and still do). For example, the stand age of the Roccarespampani's forest is between 0 and 20 years old, while that of the Tharandt-Anchor's forest is one hundred and eight years old. It has been found in some studies that maximum uptakes of CO_2 occur when forests are between 50 and 100 years old (boreal conifer forests), or 50 and 200 years old (other forests) (Baldocchi, 2008). In this way, one could expect to see NEE differences between sites only by looking at their stand age. One of the two sites which have the highest NEE during the available years (Fig. 5c) is indeed a deciduous forest aged 108 (Tharandt-Anchor). But the forest of Hesse-Sarrebourg, which also shows a high uptake of CO_2 compared with the seven other sites, is only 35 years old. In this way, the stand age factor might play a role in the CO_2 balance, even if it is not always a decisive factor.

Figures 19a and 19b are an example of the difference of forests' stem density between two sites, Norunda and Roccarespampani. These differences might impact the way they react during the summer, that is why one must be careful when analyzing the data. Indeed, the different layers of vegetation and the stem density are some parameters that impact the exchange of carbon in a forest.

Figure 19: Photos of the forest of Norunda (a) (Sarah Loudin) and Roccarespampani (b) (Fluxnet)

Moreover, the canopy height controls the storage volume (Aubinet et al., 2005) and is different in every site, which increases the heterogeneity.

5.3- Interpretation of the data

5.3.1- GPP

The results confirm the findings of Baldocchi et al. (2000): deciduous forests have a higher rate of CO_2 uptake than evergreen forests. Indeed, Figure 5a let us show that the highest fluxes of CO_2 uptake are found in a temperate deciduous forests (Hesse-Sarrebourg).

But some results that were found in articles and books did not match those found above. For example, Falge et al. (2002) found that coniferous forests (or evergreen forests) show lower maximum values for GPP than deciduous forests, which is not the case with the studied data. Indeed, table 4 shows that it is actually the contrary, the higher maximum uptake was found in an evergreen forest (Tharandt-Anchor, 15.73 gC m^{-2} d^{-1}).

Moreover, no strong latitude gradient for GPP (or NEE) were found in the results for every site (on the contrary to what was said by Valentini et al., 2000), as it was seen on Figure 5a. The highest values of CO_2 uptake are found in Hesse-Sarrebourg and Tharandt-Anchor, two sites that are situated in the temperate parts of Europe. The lowest values were found for the northernmost and the southernmost sites (Norunda, Le Bray, Roccarespampani and Castelporziano). This could be related to the climate of the south of Europe (very dry during summer) and to the low temperatures of the north of Europe.

5.3.2- Respiration

Contrary to the GPP and to the NEE, the ecosystem respiration is influenced by the latitude gradient (see Figure 5b), which confirms the results of Falge et al. (2002). Among the six sites that were studied, the boreal forest does have the highest respiration (see Figure 5b), as it was said by Valentini et al (2000). The importance of the location appears as a more important driver of respiration, compared to the life-form (even if, as said by Oke (1978), needleleaved trees are supposed to respire more).

Nevertheless, life-form also plays an important role in respiration. Indeed, it explains why, in 2003, the only three sites where respiration following temperature increase does not increase, but rather stay constant or decrease are three evergreen sites (Tharandt-Anchor, Le Bray and Castelporziano).

Also, contrary to what was said by Ciais et al. (2005), in 2003 respiration does decrease, but not in every site. Thus, as seen previously, in Norunda and Hesse-Sarrebourg respiration increases with very high temperatures.

It is also true that, as said by Valentini et al. (2000), that the ratio Respiration versus Temperature is less significant than the ratio GPP versus Temperature. If we have a look at the R^2s of the six sites, it is not often as high as the GPP versus temperature R^2s (even if for some years, it can be very high, for example in Norunda in 1997, as seen on Figure 16a).

Moreover, it was said by Baldocchi et al. (2000) that Norunda, as a boreal conifer forest, might show small uptake and small release of CO_2 during the summer (chapter 2). But the data here analyzed showed that the release of CO_2 in Norunda is actually high, compared to the other site (Fig. 5b). The GPP, compared to the other site, was also found not to follow the expected behavior, as it is not especially low, and very variable depending on which summer is analyzed (Fig. 5a).

5.3.3- What remains unknown

It is important to remind that two main parameters were studied in this thesis, temperature and water availability (mostly through the use of soil moisture values), but that there are not the only one to influence GPP and respiration. When they are not related to one of these two parameters, one should have a look to light availability and precipitation, which also influence greatly photosynthesis and carbon release. It was here done some times, but in a future work highlight could also be put on them. Furthermore, as all the parameters that affect the carbon cycle vary a lot depending on years, GPP and respiration results have to be analyzed carefully.

Furthermore, respiration is dependent on the sources of carbon produced by photosynthesis, which means that there is a strong link between GPP and respiration (Lagergren et al., 2008) and that GPP explains a part of the respiration response. This link was not studied here, as no data about litter or leaf area index were available.

5.4- General comments

When putting in order the results according to common features, it was seen that it is often hard to say which result can be attributed to the evergreen or to the needleleaved characteristics (or for deciduous and broadleaved forests). The only site which could have helped to make the difference, Castelporziano, is strongly influenced by its location, in the south of Europe where temperatures already are very high in the summer and where the water factor is more important than the temperature one.

In order to understand better these results, it would have been helpful to, first of all, have all years between 1996 and 2006 for all sites, as well as all the parameters available, especially soil moisture, which plays a major role in the response of the forests to high temperatures and can give key-indications. Having more years for Norunda or Hesse-Sarrebourg would have been helpful in order to see some common trends between the six sites.

It would also have been helpful to have some other parameters to clarify the response of forests, such as, for example, the leaf area index and the way it changes throughout the year, and especially during the summer, which is not available through the Fluxnet network. These data would have helped to confirm (or possibly invalidate) what was said previously about photosynthesis and the growth or dying of trees during normal and hot summers.

The use of formulas, like the use of multiple regression, to find curves fitting the results would also have been substantial. These curves would be based on the theoretical response found in the data, rather than on linear regression, as it was used in the thesis and which sometimes simplified too much the trends. Working on formulas might be useful and provide new information about the studied sites. The site of Hesse-Sarrebourg would probably be the most interesting to study, as it is clearly visible on some charts that changes in carbon uptake and release follow certain threshold and trends.

Moreover, it would be interesting to focus on other factors induced by abnormally high summer temperatures and which have strong effects on forests behavior and the long-term carbon balance, such as tree damages, changes in the CO_2 pool size or in litterfall rate (Ciais et al., 2005). These disturbances were not studied in this thesis, but they are strongly linked to the carbon balance functioning. As they have consequences beyond the duration of extreme climate events, such as heat waves or drought (Ciais et al., 2005), they might be in some forests an explanation for the behavior of GPP, respiration and NEE. The study of the growing season, a complementary variable to the study of CO_2 fluxes in the summer, would also have helped to see more effects of the increase of temperature over the six sites. Besides, Falge et al. (2002) pointed out that the interrannual variability in the growing season length might help a lot to know whether boreal forests are a net CO_2-sink or a CO_2-source.

Finally, with the same data set that was used here, it would be interesting to focus on heat waves and drought specifically, and on very precise period of the summer, rather than on the entire summer, as it was done here. In this thesis, the attention was drawn on a comparison between normal and warm summers, rather than within one summer. Looking at more precise periods might help to clarify the picture that has been presented here, and bring more details.

6- Conclusions

As previously said in the Results and Discussion part, various responses were found in the sites for each summer and each variable. GPP is both decreasing and increasing with temperature during normal summer, as well as during abnormally warm summers (except in Norunda and Tharandt-Anchor). In the same way, respiration is increasing, decreasing or staying constant with temperature during normal summer, as well as during abnormally warm summers. The trend for respiration is very variable according to the site, and there is no dominant trend for all forests. As a result of these two parameters, NEE is very variable according to which sites we look at. Most of NEE values are negative, which means that CO2 uptake is more important that CO2 release, except in all the needleleaved forests during very warm years, and Norunda. When all these pieces of information were put together, several trends were then found between sites, dividing them according to the influence of common features.

[1] To which extent the increase of temperatures in summer is going to affect the uptake and the release of CO2 of forests in Europe?

The most marked changes of GPP appeared in the deciduous forests (with the R2 and the slope representing the sensitivity), which make us think that they are more sensitive to temperature variability, and more likely to experience possible dieback during other hot summers coming in the future.

Concerning the respiration, the study showed that it never decreases following the temperature increase in three of the four evergreen sites, which let think that, again in a perspective of climate change, the respiration in the evergreen sites which belong to temperate or Mediterranean climate would continue to increase, until maybe reaching a certain threshold and then starting to decrease. From this one can deduce that, as the respiration in deciduous forests decreases more easily with high temperatures, again these trees might be the most affected by very high temperatures, as the decrease of respiration often mean that tree metabolism is shutting down to avoid damages.

[2] Do forests react differently to normal and abnormally warm summer temperatures depending on their characteristics?

Yes, especially depending on their phenotype, as well as their foliage and location.

For example, the foliage parameter (needleleaved/broadleaved) plays an important role in the NEE changes of forests. Indeed, needleleaved forests often show positive values of NEE, which means that they are releasing more CO2, and more often, than broadleaved forests. The

respiration fluxes are more important there than the CO2 uptake fluxes. As this trend is getting more and more important as temperature increases, it might be that in the future, forests are likely to act more and more as CO2-sources during hot summers, instead of CO2-sinks. This statement is also valid for broadleaved forests, as during hot summers their NEE got closer and closer to zero and to positive values.
Moreover, it was shown that two of the three northernmost sites never show any decrease of GPP with temperature, which might be related either to their location or to their phenology.

[3] Will a GPP and respiration gradient be seen depending on the location of the sites?

It does for some sites, for example in the north or in the south of Europe and its particular characteristics (temperatures, humidity, weather…). Respiration values showed common trends according to the location of the sites, following a north-south gradient. For example, during summers with heat waves, the more north sites are situated, the higher their respiration is (except for Le Bray, which has the highest values for 2003).

In parallel of these possible changes in the coming decades, some studies also pointed out that the length of the growing season is expected to change in Europe (Falge et al., 2002), as temperatures will be hot enough earlier. Consequently, the use of the fluxnet data might be more and more required to help to define the parameters of new soil-vegetation-atmosphere models, as well as to valid them (Falge et al., 2002). Thanks to this, the scientific community will be more able to understand and anticipate the changes in the ecosystem processes due to climate change, and forecast their impact on human societies (Falge et al., 2002). And as both carbon sequestration by forests, but also water cycle are two key challenges for humans in the coming decades (Zierl et al., 2007), gaining knowledge about it will be more and more at stake in the coming years.

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