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Carbon and water vapor fluxes over four forests in two contrasting climatic zones

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ABSTRACT

The inter- and seasonal patterns of water vapor and canopy carbon fluxes were compared for four forest ecosystems in two contrasting climatic zones in Europe. The eddy covariance and ancillary data were taken from the Carboeurope and FLUXNET databases and a linear modeling statistical analysis was made. The four sites were a high-density poplar (*Populus* spp.) short rotation coppice plantation (in Lochristi, Belgium) and a mature Scots pine (*Pinus sylvestris*) forest (in Brasschaat, Belgium) in the Temperate climate versus a fast-growing Eucalypt (*Eucalyptus*) plantation (in Espirra, Portugal) and a Holm oak (*Quercus ilex*) forest (in Puechabon, France) in the Mediterranean climate.

- The Eucalypt stand showed an efficient stomatal control in response to changes in vapor pressure deficit (VPD), suggesting an ideal adaptation of this species to the severe Mediterranean climate.
- The fast-growing poplar stand did not show a similar stomatal control under conditions of moderate water stress. But during an intensive dry period a decrease in the development of the leaf area index (LAI) was observed.
- The Holm oak stand showed a low GPP, which is typical for a low productive species with a long rotation cycle. The GPP showed low diurnal variability, even under high solar radiation. This behavior suggested a strong stomatal control caused by the severe water stress, a mechanism that allowed this stand to cope with diurnal and seasonal water deficits.
- The mature Scots pine forest in the Temperate climate showed no variation in the GPP – radiation relationship. In this forest no water stress was observed, probably because the trees always had access to the water table. Irrespective of the climate the evapotranspiration of the Scots pine forest presented a tight coupling with the atmosphere, i.e. a low decoupling factor, Ω, comparable with the Holm oak and the Eucalypt forests.

The high Ω values of the young poplar plantation were not typical for forest canopies. These values confirmed the strong influence of solar radiation and available energy on evapotranspiration and on the dynamics of this fast-developing canopy. At all four sites the forests showed their capacity to react to the environmental drivers, characteristic from their respective climatic types. However, drastic climatic changes – such as heat waves or long drought spells – may compromise the productivity of fast-growing plantations such as the Eucalypt and poplar stands. The response of the poplars to these events is mainly achieved through LAI control in contrast to the stomatal control in the Eucalypts.

1. Introduction

Since the mid 1990s many studies have tried to quantify the exchanges of mass and energy between forest stands and the atmosphere. Direct measurements of the atmospheric flux of several forests with the eddy covariance methodology

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(Baldocchi, 2003; Aubinet et al., 2000; Lebaube et al., 2004; Granier et al., 2008; Migliavacca et al., 2009) were incorporated in research networks as CARBOEUROPE (http://www.bgc-jena.mpg.de/public/carboeur/) on European Scale or FLUXNET (http://fluxnet.ornl.gov/) on a global scale. All this information is based on the eddy covariance methodology, widely applied since the mid-nineties. The results from these integrated large-scale networks improved our knowledge of the environmental control of the seasonal and inter-annual variability of the energy, the carbon and the water fluxes between different types of ecosystems and the atmosphere. They have also led to a better understanding of the spatial (Valentini et al., 2000) and the temporal variability (Falge et al., 2002) of the carbon uptake by forests.

The carbon assimilation by forest ecosystems is determined by the biology of the trees (e.g. leaf area index (LAI), tree physiological activity, length of the growing season) as well as by the physical environment (e.g. atmospheric and meteorological conditions, soil temperature and moisture content) (Schmid et al., 2000). In general gross primary productivity (GPP) is mainly dependent on the global solar radiation, or more specifically the photosynthetically active radiation (PAR), in combination with LAI. Total ecosystem respiration (TER) primarily responds to air and soil temperature (Carrara et al., 2004; Baldocchi, 1997; Reichstein et al., 2002).

Carbon sequestration by forest ecosystems is affected by climate change and the magnitude of this sequestration may be significantly reduced by climate extreme anomalies (e.g. heat waves, drought, outbreaks of diseases, natural disturbances, fires) and management activities (Ciais et al., 2005; Zhao and Running, 2010). The frequency and intensity of these events are expected to increase under climate change projections (Trenberth, 1991; Seneviratne et al., 2012). Moreover, recent evidence indicates that the impact of the increased frequency of heat waves, droughts and flooding events may be stronger for fast-growing forests (e.g. Eucalypt and poplar plantations), which are commonly used in agro-forestry (Easterling et al., 2007). Under a globally changing climate more frequent and severe droughts are expected in some regions of the globe, mainly in the Northern hemisphere (Meehl and Tebaldi, 2004; Schär et al., 2004; IPCC, 2007). Furthermore, one of the characteristics of the changing climate is an increase in the weather variability (Allan and Soden, 2008; Karl et al., 2009). Since the 1970s the frequency and the severity of droughts in the Western Mediterranean region increased due to higher air temperatures and reduced winter–spring precipitation (Miranda et al., 2002). As water shortage generally decreases both GPP and TER in forests (Ciais et al., 2005; Granier et al., 2007; Pereira et al., 2007), drought strongly influences the inter-annual and seasonal variation in the ecosystem carbon exchange with the atmosphere. Other natural or anthropogenic disturbances, such as defoliation or tree felling, also determine the magnitude and the temporal patterns of carbon sequestration by forests (Rodrigues et al., 2011; Xiao et al., 2003). In mediterranean areas several mechanisms for drought response were already observed with Eucalypt such as the reduction in LAI, the erectophile arrangement of the leaves, the high stomatal sensitivity to VPD, the deep rooting and an osmotic manipulation to maintain leaf turgor (Whitehead and Beadle, 2004).

For many Mediterranean species a midday stomatal closure has been reported (Tenhunen et al., 1987). This significant drop in stomatal conductance has been interpreted as a feature which allows Mediterranean species to limit their water loss when the atmospheric demand is at its maximum. Tenhunen et al. (1987) suggested that the midday stomatal closure is determined by the leaf-to-air vapor pressure deficit, whereas others believe that it depends on the interactions among several factors, in particular the instantaneous water potential of the plant (Hinckley et al., 1983). The influence of water stress on leaf and canopy gas exchange was intensively studied in Portuguese *Quercus coccifera* and *Eucalyptus globulus* stands (Tenhunen et al., 1985; Pereira et al., 1986) and for *Quercus ilex* L. (Sala and Tenhunen, 1996; Rambal et al., 2003). This last mentioned optimization pattern has already been validated for a few Mediterranean species (William, 1983; Xu and Baldocchi, 2003). Notwithstanding all these insights we must consider that a 20-year period is short compared to the long rotation cycles that are used for most tree species. During a rotation cycle, forest management practices like, planting or coppicing regimes, thinning, fertilization, pest and weed control or prunings are also likely to impact carbon sequestration. In addition, the European continent has contrasting climate pattern between the Temperate North and the Mediterranean South leading to totally distinct soil–plant–atmosphere relations. In the Mediterranean area the problems of drought and carbon sequestration are interlinked drought is reported to strongly affect carbon sequestration in forested ecosystem. Thereby, much effort is still needed to improve the quantitative and qualitative knowledge of the dynamics of forest soil–plant–atmosphere. In this entire context, the continuation of the ongoing field measurement campaigns and eddy covariance measurements is of utmost importance.

The aim of this study was the comparison of the inter- and intra-annual patterns of water vapor and carbon fluxes of four forest sites – with a contrasting vegetation, strand structure, phenology and management – in two different climatic zones in Europe. Our main objectives were: (i) to evaluate the main factors driving the carbon and water vapor fluxes in each site (ii) to analyze the main evapotranspiration patterns at each site by quantifying the decoupling factor and (iii) to evaluate the role of stomatal control analysing the hysteresis of GPP and evapotranspiration versus gobal solar radiation. For this study we used eddy covariance data in combination with ancillary data which were gathered at each site.

The four sites were a high-density poplar (*Populus* spp.) short rotation coppice plantation (in Lochristi, Belgium) and a mature Scots pine (*P. sylvestris)* forest (in Brasschaat, Belgium) in the temperate climate versus a fast-growing Eucalypt (*Eucalyptus*) plantation coppiced for pulp production (in Espirra, Portugal) and a Holm oak (*Q. ilex*) forest (in Puechabon, France) in the Mediterranean climate.

The time periods analyzed for each site were constrained by available data serie, which were 2010–2011for the poplar site, 1999–2010 for the Scots pine site, 2001–2006 for the Holm oak site and 2002–2006 for the Eucalypt site. The latter period concerned the last six years of a 12-year rotation cycle with a clear cut in November 2006. The data taken thereafter (2007–2010) were not considered for analysis. A statistical analysis, based on linear models with ANOVA (SS3 Sum Type) and multiple linear regression and correlation coefficients was performed, allowing to conclude that a detailed analysis of GPP and LE responses in the years with higher and lower precipitation were representative for a throughout comparative analysis. The monthly inter-annual differences in precipitation in the 2 years with higher and lower precipitation were particularly contrasting when comparing the two Temperate with the two Mediterranean sites. Rainfall in the former was evenly distributed along the year. In the latter two sites, under more solar radiation and higher atmospheric water vapor deficits, rainfall was mostly concentrated in spring and autumn and almost nil in summer periods.

2. Materials and methods

2.1. Experimental sites

Four experimental forest sites were selected for this comparative study. Two sites with a temperate maritime climate – “Lochristi

Table 1
Main characteristics of the four forest research sites of this study, including location (latitude and longitude in decimal units); forest vegetation type; climate type; mean (long-term) annual temperature; mean (long-term) annual precipitation; available data set; and principal bibliographic reference for each site. The sites are presented from the most northern (top) to the most southern site (bottom).

Site	Coordinates (Lat, Long)	Forest vegetation	Climate type	Mean annual temperature (°C)	Mean annual precipitation (mm)	Available data set	Bibliographic reference
Lochristi, Belgium	51.11 N 3.85 E	SRC poplar plantation (*Populus* spp.)	Temperate maritime	9.5	726	2010–2011	Broeckx et al. (2012) and Zona et al. (2012, 2013)
Brasschaat, Belgium	51.30 N 4.52 E	Scots pine (*Pinus sylvestris*) & oak (*Quercus robur*)	Temperate maritime	9.8	767	1999–2010	Carrara et al. (2003)
Puechabon, France	43.74 N 3.60 E	Holm oak (*Quercus ilex*)	Mediterranean	13.5	908	2001–2006	Allard et al. (2008)
Espirra, Portugal	38.63 N 8.60 E	Eucalypt (*Eucalyptus globulus*)	Mediterranean	15.9	709	2002–2010	Rodrigues et al. (2011)

SRC, short-rotation culture.

“and “Brasschaat”, both in northern Belgium – and two with a Mediterranean type climate, i.e. “Puechabon”, in southern France, and “Espirra”, near Lisbon in Portugal. The coordinates and the main characteristics of each of these sites are summarized in Table 1.

The four forest stands had a very different vegetation type, stand structure, phenology and management. A statistical analysis with weekly data based on linear models with analysis of variance, multiple linear regressions and correlation analysis, was performed on the entire data series of the four sites and separately on the years with higher and lower precipitation. These 2 years (Table 2) were selected with the aim to study the role of water availability related factors as drivers for GPP at each site. As the inter-annual pattern of rainfall presented a very high variability at the Mediterranean sites we selected the year with the least precipitation in combination with a clear summer drought. The statistical analysis allowed verifying that the main drivers of GPP and water vapor fluxes with the two time sampling criteria were essentially the same, and that a detailed analysis of GPP and water vapor responses in the two-year periods was thereby representative.

As the field site in Lochristi was established in 2010, only 2 years of data (2010 and 2011) were available for the analysis, however it included a three-month period with very low precipitation in 2011. A detailed description and an in-depth analysis of the meteorological conditions are presented in Section 3.1. The two-year periods with lower and higher precipitation were 2006 and 2008 for Brasschaat, 2005 e 2004 for Puechabon and 2005 and 2006 for Espirra.

The Lochristi research site is a fast-growing short rotation coppice (SRC) of poplar clones for bioenergy production. It is located 11 km from the city of Ghent – province East-Flanders, Belgium – at an altitude of 6 m above sea level. It is currently used to study the full greenhouse gas budget within the POPFULL research project (http://webh01.ua.ac.be/popfull). The soil has a sandy texture with a clay-enriched deeper soil layer. A total of 18.4 ha was planted on April 7th–10th 2010, with different poplar clones (belonging to the species *Populus deltoides*, *Populus maximowiczii*, *Populus nigra* and *Populus trichocarpa*, and interspecific hybrids) in a double-row planting scheme (with 0.75 m and 1.5 m between the rows; 1.1 m within the rows) at a planting density of 8000 plants ha^{-1}. The canopy height of the plantation – measured in front of the eddy covariance mast – increased from 1.3 m on August 2nd 2010 (i.e. four months after planting) to 2.1 m on September 29th 2010 during the first growing season. Near the end of the second growing season – in September 2011 – the average canopy height was 4.5 m. Ditches of 80 cm drained water into deeper canals (1.5 m depth) at the outer edges of the field site. As a consequence the soil surface was mostly dry and drainage of standing water was fairly rapid. The site is surrounded by intensively managed croplands (mostly monoculture corn and potatoes). A detailed description of the field site, the plantation and the experimental set-up can be found in Broeckx et al. (2012) and Zona et al. (2012, 2013).

The forest site “De Inslag” is located in Brasschaat in the Belgian Campine region. The experimental area consists mainly of Scots pine (*P. sylvestris* L.) (Nagy et al., 2006). The forest surrounding the experimental area consists of several broadleaf species, some native as *Betula pendula* Roth., *Quercus robur* L. and *Sorbus aucuparia* L., and some introduced species as *Quercus rubra* L. and *Castanea sativa* Mill. The site has a temperate maritime climate, with a long-term mean annual temperature of 11 °C. The long-term mean temperatures of the coldest and warmest months are 3 and 19 °C, respectively, and mean annual precipitation is 830 mm. The site has a flat topography (slope of 0.3%) with an elevation of 16 m above sea level. The soil is covered with an organic surface layer of 7.5 cm depth. A deep aeolian cover sand layer (Dryas III) rests on a substratum of clay of the Campine (40% of clay) (Tiglian) at a variable depth, between 1.2 and 2.5 m and more. The upper soil is rarely saturated, because of rapid hydraulic conductivity in the upper horizons. During wet periods in winter a perched water table is often present above the clay layer. According to the World Reference Base for Soil Resources version 2006 (WRB, 2006), the soil is classified as an albic hypoluvic arenosol. In 1995 tree density was 538 trees ha^{-1}. In the winter of 1999, 163 trees ha^{-1} were harvested thereby decreasing the density to 375 stems ha^{-1} (Xiao et al., 2003). Stand inventories in 2001, 2003 and 2008 indicated that no further reduction in tree density occurred during the study period (1997–2006) (Carrara et al., 2003; Gielen et al., 2010, 2013).

The Puechabon experimental forest is located on a flat plateau, 35 km North-west of Montpellier in southern France. The forest has been managed as a coppice for centuries and was last clear-cut in 1942. The vegetation is dominated by a dense overstorey of the evergreen Holm oak (*Q. ilex* L.). Understorey coverage is low (<25%) and consists mainly of *Buxus sempervirens, Phyllirea latifolia*, *Pistacia terebinthus* and *Juniperus oxycedrus*. In 2005 the canopy height was about 5.5 m, the density of the resprouted stems was 8170 stems ha^{-1}, the mean stem diameter at breast height was 7 cm and the LAI was 2.8 ± 0.4 m^2 m^{-2}. The area has a Mediterranean-type climate, with 80% of rainfall occurring between September and April. The mean annual precipitation is 908 mm, with a range of 556–1549 mm recorded during the past 22 years. The mean annual temperature over the same period was 13.5 °C. The parent material at the site is Jurassic limestone bedrock, which is overlaid by a very shallow and homogeneous silty clay loam soil (35% silt and 39% clay). The mean volumetric fractional content of stones is about 0.75 for the top 0–50 cm of the soil and 0.90 further below. About 90% of the root mass can be found in the first 50 cm, but some roots have been found up to 4.5 m deep (Rambal et al., 2003, 2004; Allard et al., 2008). A more detailed description of the field site can be found in Allard et al. (2008).

Table 2
Years with less *respectively* more precipitation selected from the available data set for each forest research site. In Lochristi only 2 years of data were available for the analysis (2010 and 2011) as the short-rotation poplar plantation was established in 2010 only.

Site	Year with less precipitation	Precipitation (mm) Annual	Precipitation (mm) August	Year with more precipitation	Precipitation (mm) Annual	Precipitation (mm) August
Lochristi						
Brasschaat	2006	677.4	186.6	2008	852.5	112.7
Puechabon	2005	705.2	14.4	2004	834.6	69.2
Espirra	2005	395.8	1.6	2006	805.6	24.8

The Espirra experimental site is situated in the municipality of Palmela, 60 km south of Lisbon (Portugal) and is located in a 300 ha Eucalypt (*E. globulus* Labill.) plantation. It was originally planted in 1986 following a 3 m by 3 m spacing, resulting in ca. 1100 trees ha^{-1}. It is managed in productive rotation cycles as a coppiced culture for pulp production. It was cut in 1996 and is currently in the second coppice rotation. The site is located on a flat terrain 90 m above sea level, and the soil is a Dystric Cambisol with a mean depth of 1.3 m. Long-term annual (1961–1990 average) precipitation and temperature are 709 mm and 15.9 °C, respectively. In 2002 the 7-year-aged stand had a 20 m mean canopy height. A more detailed description, including the history of the experimental site can be found in Rodrigues et al. (2011).

2.2. Flux measurements and data processing

All four-study sites adhered to the protocols of the CarboEurope network (Aubinet et al., 2000; www.carboeurope.org) and the data processing schemes of Fluxnet (Papale et al., 2006; Reichstein et al., 2005; Moffat et al., 2007). The EC setup includes a meteorological tower equipped with an EC system to measure the net exchanges of CO_2, H_2O and energy between the ecosystem and the atmosphere (Aubinet et al., 2000). Atmospheric fluxes of water vapor (latent heat, LE, further this is called actual evapotranspiration and abbreviated as E) and net ecosystem exchange of CO_2 (NEE) were measured using the eddy covariance (EC) technique. The Lochristi experimental site was installed in 2010, and EC measurements were made according to the same methodology.

Water vapor and CO_2 fluxes were determined as the covariance between the vertical wind speed and the water vapor and CO_2 mixing ratio's, respectively, using 30-min block averaging (Webb et al., 1980). Further details about the EC instrumentation and meteorological measurements for the four particular sites can be found in the specific publications for each site as listed in Table 1. At all sites a sonic anemometer was used for the measurement of the three-dimensional wind components. CO_2 and H_2O concentrations were measured at Espirra with an open-path infrared analyzer. On the three other sites a fast-responding closed-path infrared gas analyzer was used. Fluxes were computed every half hour. Flux calculations involved axis coordinate rotation, linear detrending and the Webb–Leuning correction (Webb et al., 1980) for density fluctuations of the open-path CO_2 analyzer data and the Schotanus correction for the sonic temperature, (Schotanus et al., 1983).

Meteorological data were continuously recorded with automatic weather stations. Gap filling and NEE partitioning in gross primary production (GPP) and total ecosystem respiration (TER) were made using the online software Eddyproc (2010) (http://gaia.agraria.unitus.it/.database/eddyproc/EddyInputForm.html) according to the methodology proposed by Reichstein et al. (2005). The same gap filling procedure was applied to the data from all four sites. The footprint analyses for the three CarboEurope sites were described in Göckede et al. (2008). The analysis of Göckede et al. (2008) addressed the spatial representativeness of the flux measurements, the instrumental effects on data quality, spatial patterns in the data quality, and the performance of the coordinate rotation method. This footprint analysis had shown that Puechabon and Espirra represent their specified target land cover type very well. The EC measurements at these two sites could be used without additional footprint filters, as the influence of disturbing heterogeneities is very low. For Brasschaat the percentage of measurements exceeding the 80% threshold of flux contribution from the target land cover (i.e. forest) is only 42.5%. Application of a footprint filter based on Rebmann et al. (2005) increased the contribution of the target land cover at this site to >90% (Nagy et al., 2006). Because a stable stratification is predominantly a nighttime phenomenon at the Brasschaat site, the footprint filter strongly affected the nighttime fluxes (on average more than 10% reduction), while it had virtually no effect on the daytime fluxes. At Lochristi only data with wind direction between 50° and 250° – when the poplar plantation contributed for ≥80% to the overall fluxes – were used. This filter has been defined using the footprint model of Rannik et al. (2003) in a simplified version for surface layer conditions above a low vegetation and by applying a site characterization approach using a specific routine described earlier (Göckede et al., 2004, 2006).

A statistical analysis of data for all sites was implemented. Firstly we performed a correlation analysis between GPP, evapotranspiration, global solar radiation, precipitation and canopy resistance (SAS 9.1, PROC CORR) providing the Pearson correlation coefficients (hereafter Rp). The variables explaining most variability were submitted thereafter to a linear analysis with ANOVA (SS3 Type Sum) (SAS 9.1, PROC GLM) and multiple linear regression (SAS 9.1, PROC REG), taking GPP and evapotranspiration as dependent variables, and global solar radiation, VPD, canopy resistance and precipitation as independent variables. The linear models were selected based on *P* values, variance inflation factors for collinearity analysis and R^2 (coefficient of determination).

2.3. Evapotranspiration regime

The evapotranspiration regime was analyzed based on the Penman–Monteith equation as modified by McNaughton and Jarvis (1983) to study the relative contribution of radiative and aerodynamic terms:

$$LE = \Omega \frac{\Delta}{\Delta+\gamma}(Rn-G-Q)+(1-\Omega)\left(\frac{\rho Cp}{\gamma}\right)\frac{VPD}{r_c} = \Omega LE_{eq}+(1-\Omega)LE_1 \qquad (1)$$

with *LE* being the latent heat flux (W m^{-2}), Δ the rate of change of saturation vapor pressure with air temperature (Pa K^{-1}), Rn the net radiation, G the soil heat flux, *Q* the rate of change of heat storage per unit ground area (W m^{-2}), (Rn–G–Q) the available energy taken as $LE+H$, γ the psychrometer constant (Pa K^{-1}), Ω the dimensionless decoupling factor, *L* the latent heat of evaporation considered as 2465 × 103 J kg^{-1}, VPD the water vapor deficit (Pa), r_a the aerodynamic resistance (s m^{-1}), r_c the canopy resistance (s m^{-1}), LE_{eq} and LE_i, respectively, the equilibrium and the imposed evapotranspiration. Latent heat flux (*LE*; expressed in W m^{-2}) was recalculated into evapotranspiration (*E*) and expressed in mm day^{-1}. Soil heat flux (*G*) plus heat storage (*Q*) was assumed as being equal to the difference between net radiation and the sum of latent and sensible heat fluxes (H). Aerodynamic resistance r_a was calculated from the sonic anemometer output as:

$$r_a = \frac{u}{u_*^2} + 6.2u_*^{-2/3} \quad (2)$$

where u is the mean horizontal wind velocity and u_* is the friction velocity (Thom, 1975; Migliavacca et al., 2009). Canopy resistance r_c was obtained by inversion of the Penman–Monteith equation (Monteith and Unsworth, 1991) using the latent heat flux obtained by eddy covariance:

$$r_c = \frac{\rho c_p VPD}{\gamma LE} + r_a \left[\frac{\Delta}{\gamma} \left(\frac{Rn - G - Q}{LE} - 1 \right) - 1 \right] \quad (3)$$

with ρ being the air density (kg m^{-3}), c_p the specific heat of air (J kg^{-1} K^{-1}).

The decoupling coefficient Ω was calculated as:

$$\Omega = \frac{\frac{\Delta}{\gamma} + 1}{\frac{\Delta}{\gamma} + 1 + \frac{r_c}{r_a}} \quad (4)$$

The Ω coefficient is thus associated with canopy resistance and thereby with the dynamics of the stomata controlling water vapor and carbon dioxide fluxes. For rough forest canopies typical values for the decoupling factor are in the order of 0.1–0.2, indicating a strong coupling of the canopy to the prevailing aerodynamic conditions. Ω-values of 0.8–0.9 are generally observed for low and even (i.e. smooth) canopies, closely coupled to the available solar radiation (Monteith and Unsworth, 1991).

3. Results and discussion

3.1. Site differences in meteorological parameters

A detailed analysis of the microclimate at the four sites is available in the referenced publications for each site (listed in Table 1). The meteorological data of air moisture and global solar radiation (Table 1) clearly reflected the contrasting climate types. Mean monthly values of global solar radiation (Fig. 1) were highest in Espirra and Puechabon with a slightly higher radiative energy at the former site peaking to a maximum monthly average of 834 MJ month^{-1} in July. In Puechabon global solar radiation peaked in June and was in the order of 800 MJ month^{-1}. In Lochristi and Brasschaat global solar radiation was significantly lower with monthly averaged peaks of 600 MJ month^{-1} in May and June, respectively (Fig. 1).

The mean monthly values of rainfall in Brasschaat were fairly well distributed throughout the year peaking slightly during summertime, but also showed a higher standard deviation in this period (Fig. 2). On the other hand, in Puechabon and Espirra, monthly precipitation was more concentrated in October–March with a very dry July–September period (Fig. 2). A significant variability in the monthly rainfall in autumn and spring periods was also noticed in Puechabon and Espirra (Fig. 2) mainly due to the occurrence of storm events. In Lochristi rainfall was fairly well distributed throughout the year, but in 2011, second growing season, there was a three-month dry period (March, April and May 2011; Fig. 2). Indeed in Lochristi total precipitation in April–May 2011 was 26 mm, much lower than the (longer-term) correspondent average over the period of 2000–2010, i.e. 74 mm (data from the Royal Meteorological Institute; http://www.kmi-irm.be). The consequent water stress was reflected in a significant decrease in the LAI increment, mainly during the April–June period. Indeed the LAI remained almost constant from the middle of May (1.2 m^2 m^{-2}) until the end of July (1.8 m^2 m^{-2}). From June 2011 precipitation increased – to 62 mm per month – and doubled the (longer-term) mean values of the month.

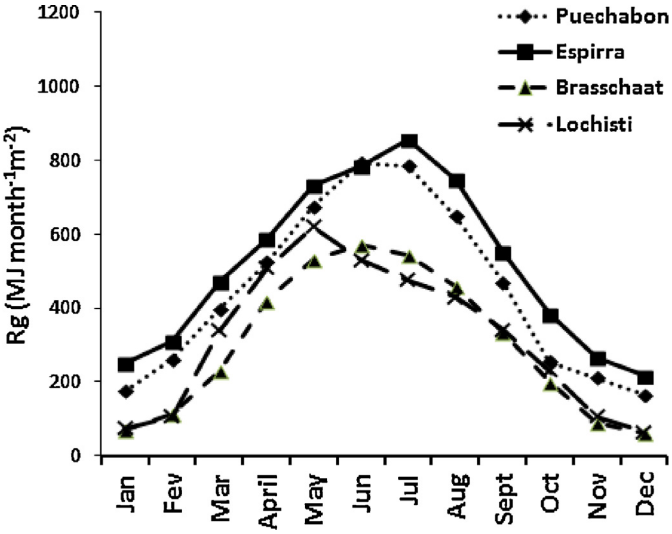

Fig. 1. Monthly average of incoming solar radiation (R_g) for the four forest sites, presented for the entire period of the available data set. For Brasschaat: 11 years of data, 1999–2010; for Puechabon: 6 years of data, 2001–2006; for Espirra: 9 years of data, 2002–2010. For Lochristi: only data from the year 2011.

As expected, evaporative atmospheric demand, measured by VPD during sun light hours, was higher in Espirra with an average monthly peak of 23 hPa in August and in Puechabon with an average monthly peak of 20 hPa in July (Fig. 2). The two Mediterranean sites exhibited very high VPD values – i.e. higher than 20 hPa – in summer and low values of ca. 5 hPa in winter. These values contrasted sharply with the two Belgian sites, where the VPD varied between 2 hPa and 10 hPa. At these latter sites the mean monthly VPD was almost constant during the growing season. However, during the 2011 growing season monthly VPD decreased in Lochristi from 10 hPa in May to 5 hPa in August.

In Puechabon the years with the highest and the lowest precipitation were 2004 (834 mm) and 2005 (705 mm), respectively. The abnormal rainfall in 2005 was much lower than in 2004, but it was also concentrated in September and October due to a storm in this period. This resulted in an uneven monthly distribution at the Puechabon site in 2005 with precipitation values of only 67 mm in April–May and of 22 mm in the July–August period (Fig. 2). In contrast, rainfall was much more evenly distributed over the year in 2004, with two-month period values of 162 mm (April–May), 115 mm (July–August) and 194 mm (September–October).

In 2004 and 2005 the Espirra site experienced an exceptionally low rainfall, with reductions of more than 50% compared to the long-term mean. Both years 2004 and 2005 also showed uncommon monthly patterns of rain distribution over the year. Rainfall in the first quarter of 2004 (210 mm) corresponded to 55% of the total annual precipitation. In 2005, about 38% of the scarce rainfall occurred in March and 40% in the last quarter of the year.

3.2. Statistical analysis

Correlation analysis (not shown) showed that in general for all sites global solar radiation, VPD, canopy resistance r_c, Ω and precipitation showed the highest significant correlation with GPP. Linear modeling of GPP and evapotranspiration (Table 3) was performed for each site for the entire data set and for the years with higher and lower precipitation. Results showed that global solar radiation is a significant variable for all models, for both GPP and evapotranspiration. At the Mediterranean and Temperate sites in addition to solar radiation, canopy resistance and Ω are, respectively, the most important independent variables influencing both

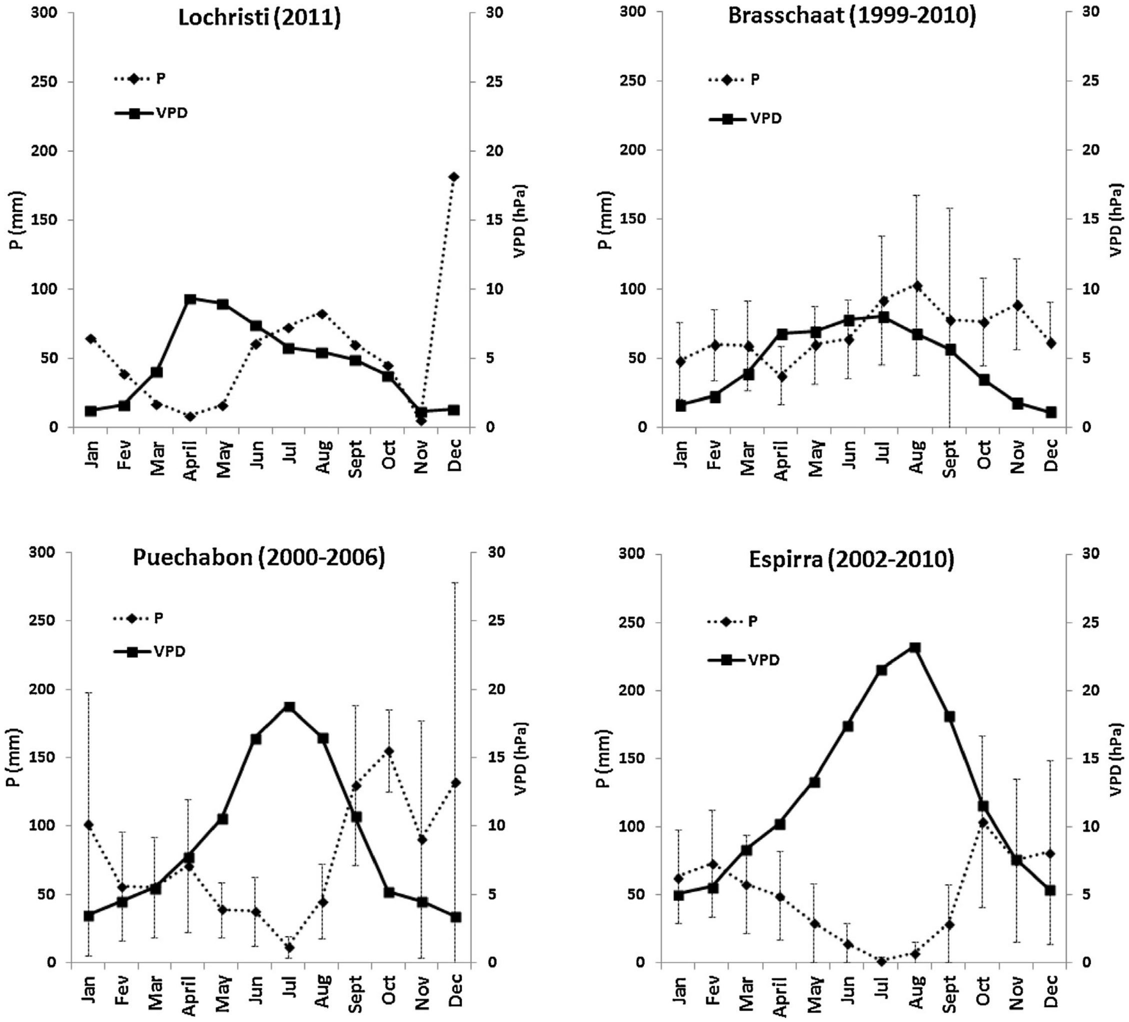

Fig. 2. Monthly average precipitation (P) – with standard deviation – and vapor pressure deficit (VPD) during the measurement period for each forest site. VPD was measured during sun hours.

Table 3
Linear modeling of GPP and evapotranspiration in each site for the available data set and for the years with higher and lower precipitation for each forest research site. The columns report the site, the dependent variables, the datasets, the significant independent variables, the linear model, the model's coefficients of determination and *p* values, and variance inflation factor representative of the independent variables collinearity (VIF).

Site	Dep. variable	Year	Indep. variables	Linear equation	R^2	*p* value	VIF
Lochristi	GPP	2010	Rg, rc	$GPP = 11.22 + 0.272Rg - 0.045rc$	0.73	<0.0001	<1.9
		2011	Rg, rc	$GPP = 30.94 + 0.41Rg - 0.15rc$	0.72	<0.0001	<1.4
	LE	2010	Rg, Ω	$LE = -9.94 + 0.28Rg + 34.46\,\Omega$	0.79	<0.0005	<1.01
		2011	Rg, Ω	$LE = -11.07 + 0.22Rg + 42.24\,\Omega$	0.84	<0.0001	<1.0
Brasschaat	GPP	2006	Rg, rc	$GPP = 3.79 + 0.37Rg - 0.014rc$	0.87	<0.044	<1.28
		2008	Rg, Ω	$GPP = -10.14 + 0.24Rg + 147.23\ \Omega$	0.80	<0.0001	<1.127
		1999–2010	Rg, P, Ω	$GPP = -6.2 + 0.36Rg + 0.12P + 24.86\ \Omega$	0.82	<0.0001	<1.07
	LE	2006	Rg, Ω	$LE = -6.59 + 0.22Rg + 5.69\Omega$	0.93	<0.0003	<1.4
		2008	Rg, Ω	$LE = -7.38 + 0.14Rg + 89.75\ \Omega$	0.78	<0.0001	<1.13
		1999–2010	Rg, P,Ω	$LE = -5.6 + 0.21Rg + 0.052P + 22.41\ \Omega$	0.77	<0.0024	<1.07
Puechabon	GPP	2004	Rg, rc	$GPP = 12 + 0.255Rg - 0.026rc$	0.89	<0.0001	<1.55
		2005	Rg, rc	$GPP = 10.86 + 0.18Rg - 0.02rc$	0.76	<0.0001	<1.41
		2001–2006	Rg, rc	$GPP = 13.59 + 0.20Rg - 0.02rc$	0.65	<0.0001	<1.41
	LE	2004	Rg, rc	$LE = 5.88 + 0.19Rg - 0.02rc$	0.80	<0.0001	<1.55
		2005	Rg, rc	$LE = 3.59 + 0.17Rg - 0.01rc$	0.85	<0.0001	<1.42
		2001–2006	Rg, rc	$LE = 5.56 + 0.18Rg - 0.016rc$	0.75	<0.0001	<1.41
Espirra	GPP	2005	Rg, VPD, rc	$GPP = 29.01 + 0.1Rg - 1.03VPD - 0.005rc$	0.57	0.009–0.024	<3
		2006	Rg, VPD	$GPP = 14.84 + 0.3Rg - 1.03VPD$	0.69	<0.0001	<2.87
		2002–2006	Rg, rc	$GPP = 25.6 + 0.122Rg - 0.051rc$	0.41	<0.0001	<1.19
	LE	2005	Rg, P, rc	$LE = 7.12 + 0.49P + 0.12Rg - 0.007rc$	0.62	0.0001–0.028	<1.34
		2006	Rg, rc	$LE = 10.56 + 0.27Rg - 0.02rc$	0.79	<0.0001	<1.16
		2002–2006	Rg, rc	$LE = 12.66 + 0.18Rg - 0.016rc$	050	<0.0001	<1.19

Table 4
Mean values of the monthly typical day of total solar radiation (Rg; MJ m^{-2} day^{-1}), gross primary productivity, (GPP; gC m^{-2} day^{-1}), Evapotranspiration (*E*; mm day^{-1}), and precipitation (*P*; mm day^{-1}) from the 2 selected years for each site.

	Lochristi					Brasschaat					Puechabon					Espirra				
Month	Year	Rg	GPP	*E*	*P*	Year	Rg	GPP	*E*	*P*	Year	Rg	Gpp	*E*	*P*	Year	Rg	Gpp	*E*	*P*
January	2010					2006	3.1	0.6	0.0	0.5	2004	5.3	2.2	0.6	2.2	2005	10.1	4.2	0.8	0.0
February							3.6	0.5	0.1	2.3		8.9	2.7	0.7	2.4		13.3	4.1	0.7	0.2
March							8.6	1.1	0.3	1.3		12.7	4.0	0.8	3.4		15.1	4.1	1.2	1.4
April							13.4	2.9	0.8	1.2		15.5	5.0	1.2	4.5		20.7	6.1	1.7	0.6
May							15.4	4.3	0.9	2.4		22.6	6.5	1.5	0.9		24.2	5.1	1.8	1.1
June		19.2	2.0	1.5	0.1		19.6	7.5	1.9	1.5		27.7	7.4	2.0	1.3		25.6	3.2	1.2	0.0
July		17.7	4.6	2.3	1.7		21.1	7.4	2.3	0.4		26.9	4.6	1.1	0.1		27.5	2.2	1.1	0.3
August		12.7	4.4	1.6	6.0		11.4	6.1	1.3	6.0		18.3	5.2	1.7	2.2		24.1	1.9	0.9	0.1
September		10.1	3.4	1.2	3.2		11.6	4.7	1.3	0.3		16.9	5.0	1.6	2.9		19.9	1.5	0.8	0.2
October		6.7	2.2	0.7	2.2		6.4	3.2	0.6	2.4		7.2	3.5	0.6	3.5		11.6	3.3	0.9	5.0
November		2.4	0.6	0.3	3.5		3.3	1.1	0.2	1.9		7.8	2.7	0.8	0.8		9.5	2.6	0.7	3.0
December		1.8	0.2	0.1	0.9		1.5	0.5	0.1	2.0		5.7	2.1	0.5	3.3		7.8	3.1	0.7	1.1
January	2011	2.4	0.3	0.2	2.1	2008	2.1	0.4	0.0	2.4	2005	7.5	2.1	0.5	0.3	2006	9.0	4.5	0.8	1.8
February		3.8	0.6	0.2	1.4		6.2	1.2	0.3	1.9		10.9	2.2	0.5	1.1		11.6	4.0	1.4	2.0
March		10.9	1.7	0.6	0.6		7.6	1.5	0.3	4.1		15.0	2.7	0.7	0.7		12.8	4.7	2.1	3.0
April		17.0	5.5	1.6	0.3		14.6	3.5	0.6	2.0		18.7	5.0	1.5	1.4		19.1	6.3	2.5	1.4
May		20.0	7.9	1.5	0.5		19.1	5.1	0.9	1.6		24.9	5.5	1.6	0.8		25.3	8.1	3.1	0.0
June		17.7	6.9	1.5	2.1		17.9	7.5	1.6	2.0		28.2	5.0	1.8	2.2		24.1	7.6	3.4	1.1
July		15.4	5.7	1.3	2.4		16.7	7.5	1.8	3.3		27.5	3.2	1.2	0.2		26.2	6.3	3.0	0.1
August		13.9	7.8	1.5	2.7		13.5	6.1	1.5	3.6		23.7	1.4	0.7	0.5		25.0	4.2	2.1	0.8
September		11.4	7.7	1.5	2.0		11.2	3.4	0.7	1.7		16.8	2.9	1.0	7.2		17.8	4.0	1.6	1.7
October		7.5	3.7	0.6	1.5		6.6	2.7	0.6	2.5		6.9	2.5	0.5	6.4		11.1	4.1	1.7	6.9
November		3.5	1.2	0.1	0.2		2.7	0.9	0.1	1.7		7.5	2.2	0.6	2.2		8.2	4.1	1.8	6.3
December		2.1	0.4	0.1	5.9		2.3	0.2	0.0	1.1		6.1	1.0	0.3	0.2		8.3	0.0	0.9	1.5

GPP and evapotranspiration. Variation inflation factors showed small collinearity between the independent variables. Results from the linear models showed that for both GPP and LE, coefficients of determination were higher for the selected drought and wet years compared to the entire time series. Especially for Espirra and Puechabon, where R^2 values are 0.41 and 0.50 for the entire time series of GPP and LE in Espirra, and 0.65 and 0.75, respectively in Puechabon. In Espirra, the correspondent R^2 values for the two-year periods are 0.57 and 0.69 for GPP and 0.62 and 0.79 for LE and in Puechabon R^2 values to the two-year periods are 0.89 and 0.76 for GPP and 0.80 and 0.85 for LE. In the Brasschaat and Lochristi sites, the R^2 values to GPP and LE are higher than in the Mediterranean sites. In Brasschaat, R^2 values are 0.82 and 0.77 for full periods of GPP and LE. In the same site, the correspondent R^2 values for the two-year periods are 0.87 and 0.80 for GPP and 0.93 and 0.78 for LE. The lower values of R^2 correspondent to the full period, compared with the respective R^2 values for each year in analysis at the Mediterranean sites, are due to the higher inter annual variability of the climatic parameters in these sites. Considering the sets of models, concerning full periods and two-year periods to GPP and LE, it can be seen that, generally, the same independent variables showed significant. Model results showed that in general, for both the entire time series and the selected years, the same variables explained most variability in GPP and LE.

3.3. Gross primary productivity (GPP)

Mean daily values of the monthly typical day of total solar radiation, Rg; gross primary production GPP; evapotranspiration, E; and precipitation, P; from the 2 years chosen for each site are shown in Table 4. The two intensively managed coppice sites of Eucalypt (at Espirra) and poplar (at Lochristi) showed the highest mean daily GPP. The Eucalypt stand (at Espirra) assimilated 8.1 gC m^{-2} day^{-1} in May 2006, closely followed by the poplar plantation (at Lochristi) with a mean daily GPP of 7.9 gC m^{-2} day^{-1} in May 2011. But in 2006, the dry summer at Espirra with high water stress (typical for the Mediterranean climate characterized by almost nil rainfall, high VPD, air temperature peaking above 32 °C and of high solar radiation) limited the capacity of the canopy to maintain the high carbon uptake rate (Table 4). Indeed at Espirra, the mean daily GPP fell to 4.2 gC m^{-2} day^{-1} in August 2006 while at Lochristi this uptake rate was 7.8 gC m^{-2} day^{-1} during August 2011, similar to the values of May 2011.

At Lochristi the carbon uptake by the poplar plantation was higher in the second year of the rotation (2011). This strong increase in GPP during the second year was caused by a significant increase in LAI, from 1.2 ± 0.5 to 2.6 ± 1, respectively (Broeckx et al., 2012). The denser canopy, and resulting higher GPP, were probably also caused by the strong development of the root system. This larger root system allowed access to a larger soil volume with an increased amount of water and nutrients, thereby improving the resource availability. Although the peak in typical day GPP during the second growing season was in May 2011, GPP was of similar magnitude as the values observed in August of that year. This was due to a decrease of global solar radiation (Table 4) from 20 MJ m^{-2} day^{-1} in May 2011, to 13.9 MJ m^{-2} day^{-1} in August 2011. Despite the high value of solar radiation in May 2011, in this month GPP was limited by the lower LAI of 1.2 as compared to 2.2 in August 2011. The mean diurnal pattern of GPP was always in phase with the solar radiation, i.e. GPP tightly followed solar radiation (Fig. 3); no stomatal control of GPP was observed along the typical day curves of the months shown in Fig. 3.

At Lochristi the GPP versus solar radiation curves (Fig. 3) showed also no hysteresis in 2010 and 2011. In 2011 GPP values were higher, under a similar solar radiation, compared to 2010. The carbon uptake rate was higher due to the more developed canopy (demonstrated by the higher LAI) and possibly also because of the more developed root system in the second growth year. In May 2011, at the beginning of the growing season, leaves were not yet fully developed and GPP saturated at about 16 gC m^{-2} s^{-1} under a global solar radiation exceeding 500 W m^{-2}. However, due to the simultaneous reduction in solar radiation (i.e. bad weather conditions during the summer season) the effect of the increasing LAI, from May to August 2011, on GPP was hardly detectable.

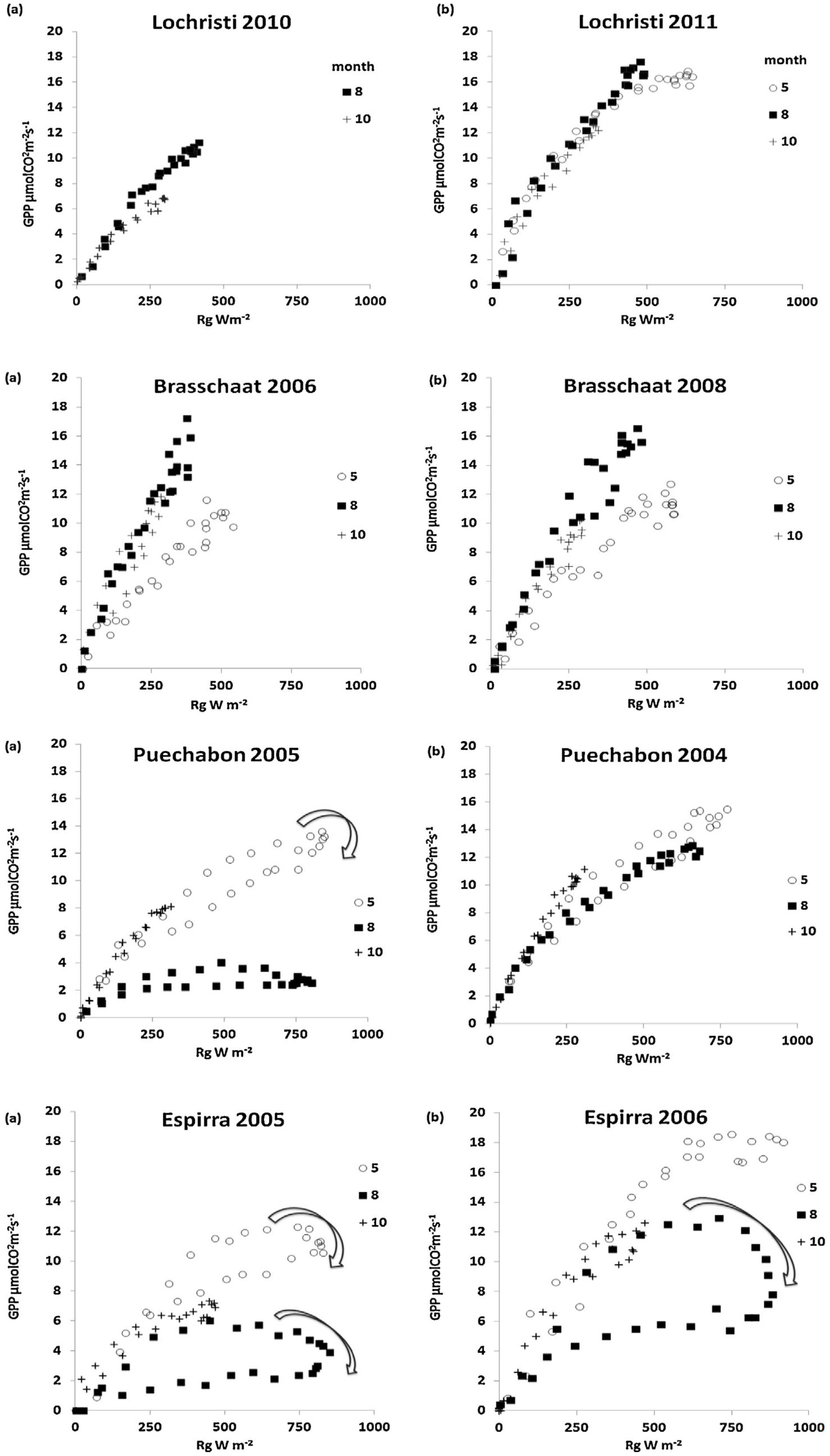

Fig. 3. Gross primary productivity (GPP; µmol CO_2 m^{-2} s^{-1}) versus incoming solar radiation (Rg; W m^{-2}) along a typical day. Mean daily patterns for May (month 5), August (month 8) and October (month 10) from the 2 selected years for each site are shown. Left panels (a) represent the years with less precipitation: Brasschaat 2006, Puechabon 2005 and Espirra 2005. Right-hand panels (b) represent the years with more precipitation: Brasschaat 2008, Puechabon 2004 and Espirra 2006. For Lochristi the 2 years with available data are shown: 2010 (a) and 2011 (b). The arrows indicate the evolution along the day.

The linear models showed a significant contribution of global solar radiation and canopy resistance, to GPP in 2010 and 2011 with an R^2 of 0.73 and 0.72, respectively (Table 3). Weekly solar radiation explained most variability of GPP (Rp = 0.66 and 0.81, in 2010 and 2011, respectively). This shows, as expected and despite the role of canopy resistance the importance of radiation to carbon uptake in this Temperate site.

For Brasschaat, the driest and the wettest years from 1999 to 2010 data series were 2006 and 2008, respectively. For these years the mean daily GPP values from June, July and August did not differ significantly (Table 4). The analysis of the diurnal relation between GPP and global solar radiation for three selected months along the growing season (Fig. 3) showed that the Scots pine site was the only one without meaningful differences between the driest and the wettest years. The corresponding curves showed no hysteresis meaning that response to solar radiation was similar during the morning and afternoon. In both years (2006 and 2008) the rate of carbon uptake versus global solar radiation was lower in May as compared to August and October (Fig. 3). In May, mean GPP was 9 μmol CO_2 m^{-2} s^{-1} for a global solar radiation of 400 Wm^{-2}, while in August it was 14 μmol CO_2 m^{-2} s^{-1}, at the same radiation intensity (Fig. 3). The LAI of the Scots pine forest increased in the beginning of the growing season with the emergence of the new needles and decreased in September when the two-year-old needles were shed (Op de Beeck et al., 2010). The photosynthetic capacity of the young needles reached their maximum when they were fully developed in their first year, resulting in a higher GPP in August than in May of that year.

The linear models for this site showed a significant contribution of global solar radiation and canopy resistance, to GPP in 2006 and 2008 with R^2 of 0.87 and 0.80, respectively (Table 3). Weekly solar radiation explained the most variability of GPP (Rp = 0.93 and 0.74, in 2006 and 2008, respectively). These results showed, like in Lochristi, the importance of radiation to carbon uptake at this Temperate site.

At Puechabon, GPP was lower than at the three other sites and the driest and the wettest years were 2005 and 2004, respectively. At this site daily values of GPP in 2005 were lower compared to 2004 due to the reduced water availability (Allard et al., 2008). The daily values of GPP in 2004 (Table 4) were different from the one observed in 2005, and showed a more progressive decrease during the year. The rainfall pattern in 2005 was associated with a strongly seasonal course of Water Stress Integral (WSI), a cumulative index of drought severity, including soil moisture, and duration (Allard et al., 2008). At this site the relation between GPP and global solar radiation showed almost no hysteresis in 2004 and 2005 (Fig. 3). This fact should be enhanced in 2004, the wettest year, when despite the higher summer VPD in summer the available soil water (Allard et al., 2008) was enough to minimize water stress and thereby canceling the hysteresis (Fig. 3). In August 2005, when soil moisture content was very low (Allard et al., 2008), GPP remained practically constant at 3 μmol CO_2 m^{-2} s^{-1}, under solar radiation varying between 200 W m^{-2} and 800 W m^{-2}. This behavior suggested a strong stomatal control due to the severe water stress reflecting a small hysteresis in Fig. 3. As in other Mediterranean species, the stomatal closure allows the Holm oak to cope with diurnal and seasonal water deficits.

The linear models at this site showed a significant contribution of global solar radiation and canopy resistance, to GPP in both 2004 and 2005 with an R^2 of 0.89 and 0.76, respectively (Table 3). The Rp values for GPP and solar radiation at weekly timescale in 2004 and 2005 were 0.57 and 0.84, respectively, showing a smaller contribution of radiation to GPP, probably due to a determinant influence of canopy resistance.

At Espirra the driest and the wettest years were 2005 and 2006, respectively. The highest carbon uptake rate, 18 μmol CO_2 m^{-2} s^{-1} (Fig. 3), occurred between 10 h and 14 h in May 2006. This value was of the same order of magnitude of carbon assimilation rate in May and August 2011 at the poplar bio-energy site in Lochristi. At Espirra the rate of carbon uptake, GPP, in May 2006 was closely coupled to solar radiation (Fig. 3). At Espirra a severe drought occurred in 2004 and 2005, as already mentioned. In 2005, GPP was lower than in 2006 during the three months that were analyzed (Fig. 3). In 2005 the Eucalypt trees controlled their transpiration by decreasing LAI from 5 (2004) to almost 2 (Rodrigues et al., 2011) and by closing their stomata as well.

At the Espirra site, October of 2005 and 2006 and May 2006 were the months during which the curves from Fig. 3 showed no hysteresis. In May 2006 GPP saturated with solar radiation above 600 W m^{-2} (Fig. 3). In August 2006 a very pronounced hysteresis, due to stomatal closure in the afternoon, prevented the recovery of GPP to the initial morning values (Fig. 3). In August 2005 this temporal hysteresis in GPP was not so prominent. This is probably due to the fact that the stomata were already partially closed in the morning due to the accumulated effect in water stress of a two-year-long drought period (García-Herrera et al., 2007). This drought most likely caused an increase of the predawn leaf water potentials. In August 2005, VPD varied between 5 hPa at sunrise and 32 hPa at 15 h, explaining the drastic decrease in typical day GPP to 4 gC m^{-2} day^{-1}. Indeed in the Eucalypt forest, the effect of the increasing VPD on stomatal conductance was larger at high than at moderate predawn leaf water potentials (Pereira et al., 1987).

The linear models in this site showed a significant contribution of global solar radiation, canopy resistance and VPD, to GPP in 2005 and 2006 with R^2 of 0.57 and 0.69, respectively. Indeed, despite the significance of linear models (Table 3) during the driest year, the weekly canopy resistance and VPD explained the most variability in GPP (Rp = 0.64 and 0.61, respectively). In 2006, global solar radiation was the independent variable with more significant Rp with GPP (Rp = 0.67). This is due to the importance of canopy resistance and VPD under high water stress conditions during the severe drought in 2005.

3.4. Evapotranspiration and decoupling factor

The daily means of evapotranspiration (E in mm day^{-1}) are shown in Table 4. The Portuguese Eucalypt forest showed the highest evapotranspiration rate (E in mm day^{-1}) of the four sites: E was 3 mm day^{-1} in May 2006 and 2 mm day^{-1} in August 2006. The second highest E was observed in the Holm oak forest of Puechabon with values of 1.5 mm day^{-1} and 1.7 mm day^{-1} in May and August 2004, respectively. The lowest monthly E was observed in Puechabon in August 2005, i.e. 0.7 mm day^{-1}, simultaneously with the lowest monthly GPP of 1.46 gC m^{-2} day^{-1}.

The poplar plantation at Lochristi had similar peak values of monthly E in August 2010 and August 2011, of 1.6 mm day^{-1} (Table 4) under similar solar radiation values. Most probably the evaporation from the wet soil surface contributed significantly to the total LE during the first growing season in 2010. Although the solar radiation in May 2011 was much higher than the one in August 2011 (Table 4), both months had an identical E and an identical GPP as well. The lack of evapotranspiration from the poplar canopy to the incoming solar radiation in May 2011 could be explained by the lower values of soil water content after a period of low precipitation. Indeed as mentioned above, the total precipitation in April and May 2011 was 27 mm, much lower than the long-term average of 74 mm for the site for the same months.

Also in the Scots pine forest in Brasschaat, no significant monthly inter-anual differences in E were observed between the 2 years in the analysis, with a aximum E of 1.3 mm day^{-1} in August 2006 (Table 3). These results were similar to the correspondent results of GPP.

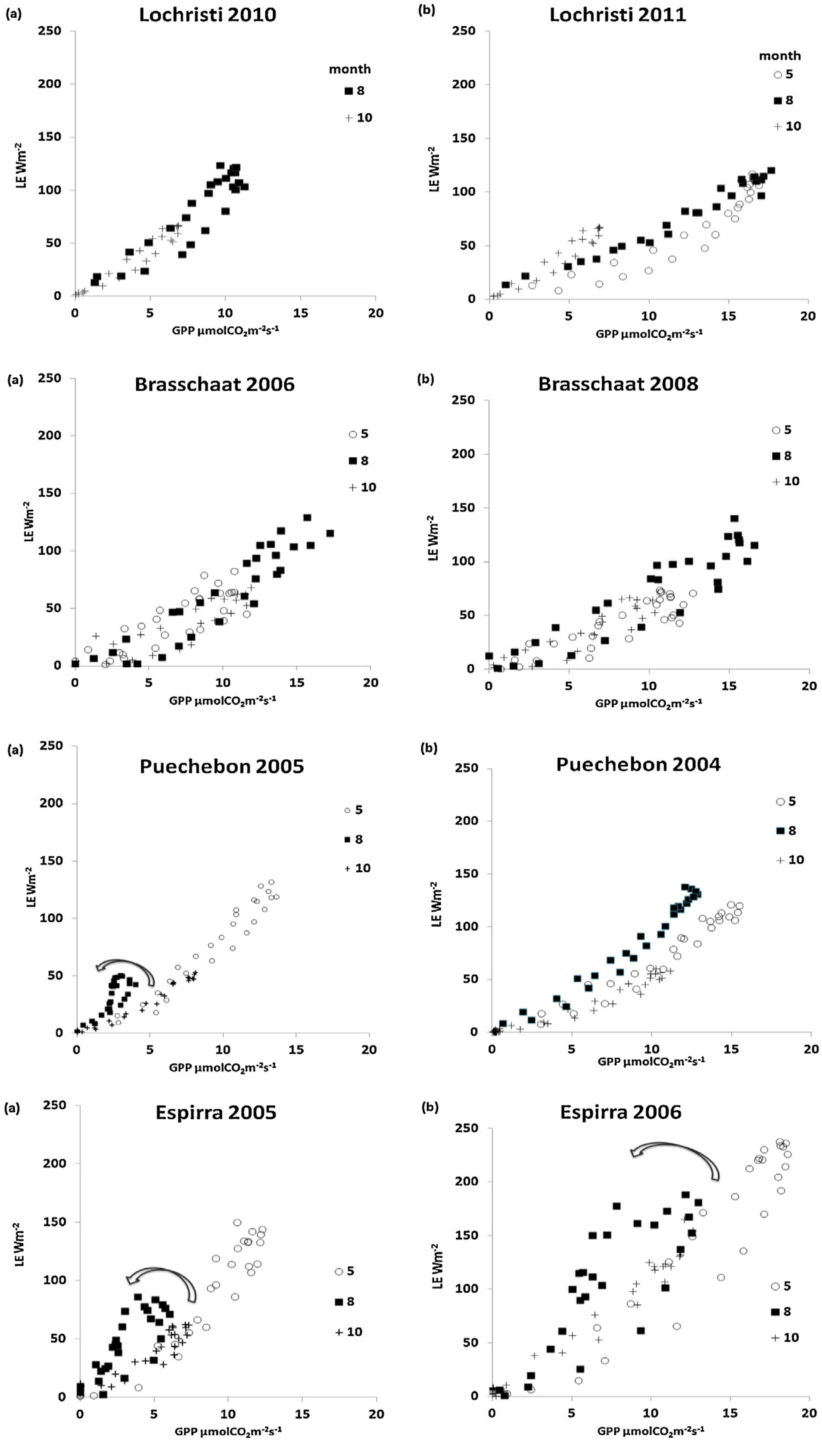

Fig. 4. atent heat flux (LE; W m^{-2}) versus gross primary productivity (GPP; µmol CO$_2$ m^{-2} s^{-1}) along a typical day. Mean daily patterns for May (month 5), August (month 8) and October (month 10) from the 2 selected years for each site are shown. Left panels (a) represent the years with less precipitation: Brasschaat 2006, Puechabon 2005 and Espirra 2005. Right-hand panels (b) represent the years with more precipitation: Brasschaat 2008, Puechabon 2004 and Espirra 2006. For Lochristi the 2 years with available data are shown: 2010 (a) and 2011 (b). The arrows indicate the evolution along the day.

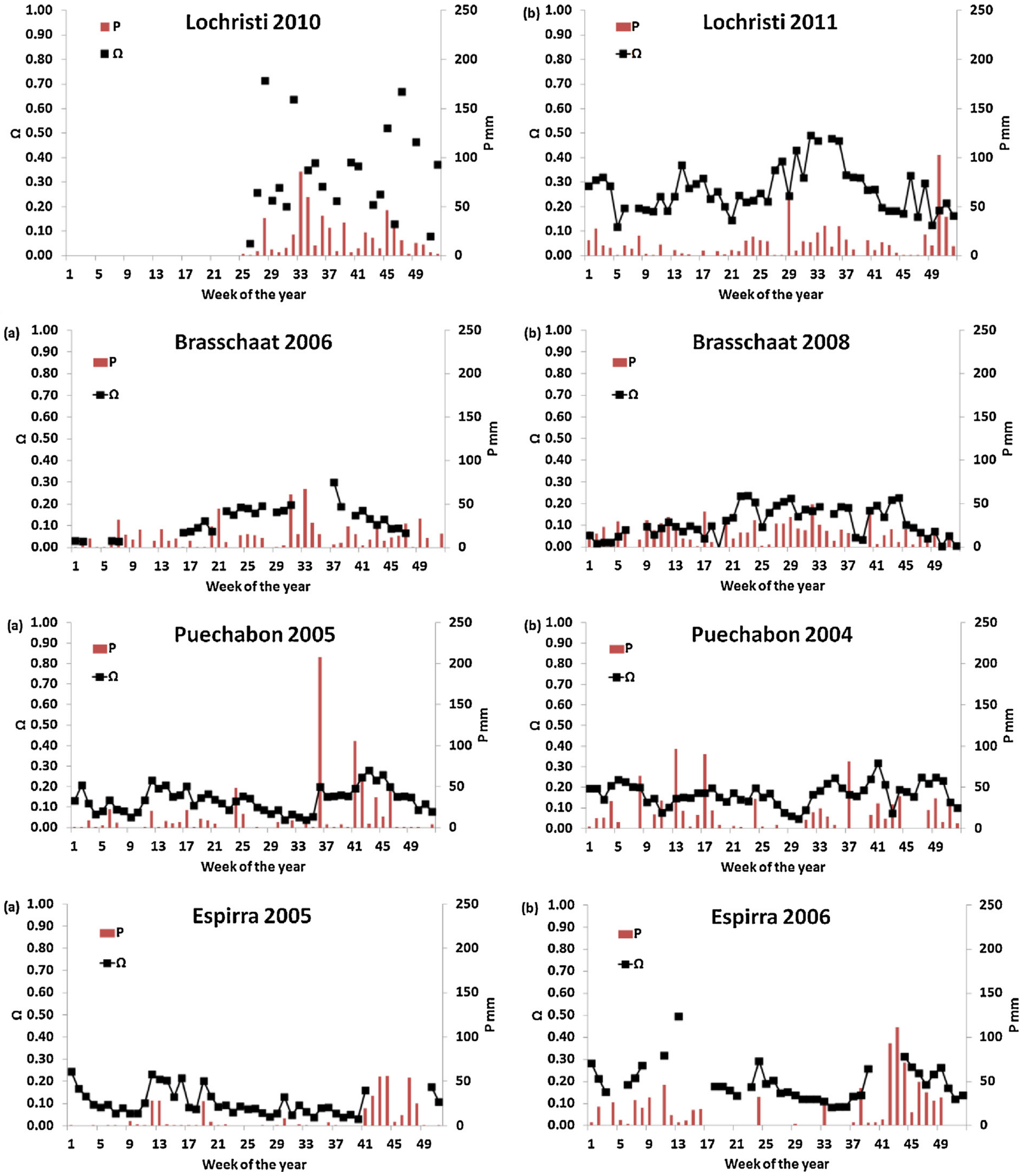

Fig. 5. Weekly values of precipitation (P; mm) and of the decoupling factor (Ω) during the 2 selected years for each site. Left panels represent the years with less precipitation: Brasschaat 2006, Puechabon 2005 and Espirra 2005. Right-hand panels represent the years with more precipitation: Brasschaat 2008, Puechabon 2004 and Espirra 2006. For Lochristi the 2 years with available data (2010 and 2011) are shown.

The results from the linear models for these two Temperate sites showed a significant contribution of global solar radiation and the decoupling factor, explaining the variability in evapotranspiration (Table 3). In Lochristi, R^2 coefficients of linear models were 0.79 and 0.84 in 2010 and 2011, respectively. In Brasschaat, R^2 coefficients were 0.93 and 0.78 in 2006 and 2008, respectively. At these sites, global solar radiation was the independent variable with most significant values of Rp with evapotranspiration. In Lochristi Rp between solar radiation and evapotranspiration was 0.73 and 0.90 in 2010 and 2011, respectively. The correspondent values of Rp in Brasschaat were 0.94 and 0.72 in 2006 and 2008. In Lochristi and Brasschaat diurnal relation between LE and GPP showed reasonable agreement with minor hysteresis (Fig. 4). The Pearson correlation coefficients between these two variables were highly significant for these sites. For Brasschaat the Rp values were 0.95 in 2006 and 2008 and the correspondent values in Lochristi were 0.68 and 0.90 in 2010 and 2011.

The prominent role of global solar radiation as driver of evapotranspiration and GPP in these Temperate sites, justified the minor hysteresis in the LE diurnal relationship between LE and GPP.

The two Mediterranean sites showed higher interannual monthly differences in evapotranspiration (Table 4) between the 2 years analyzed than the two Temperate sites., this can be mainly attributed to the different interannual patterns of precipitation (Table 2).

At Puechabon the typical diurnal curves of the relation between LE and GPP showed reasonable agreement with minor hysteresis (Fig. 4) with the peculiarity that in August 2005 (the driest year) a strong reduction in GPP (maximum 4 μmol CO_2 m^2 s^{-1}) was accompanied by a similar reduction of LE (maximum 50 W m^{-2}). This is a consequence of stomatal closure, reducing foliar gas exchanges. At this site, the only relevant difference in LE between the 2 years happened in August. Indeed, in August 2004 the maximum average typical day LE was 138 W m^{-2}, while it decreased to 50 W m^{-2} in August 2005 (Fig. 4). This difference in latent heat flux was associated with the difference in precipitation between the 2 years, i.e. a total precipitation of 115 mm in July and August 2004 versus only 22 mm in the same period in 2005.

The linear models in Puechabon showed a significant contribution of global solar radiation and canopy resistance, to evapotranspiration in 2006 and 2008 with R^2 of 0.80 and 0.85, respectively (Table 3). Weekly solar radiation was the independent variable explaining most variability in LE (Rp = 0.80 and 0.76, in 2004 and 2005, respectively). The Rp coefficient between GPP and LE was 0.90 in Puechabon, in both years, due to a common pattern of factors controlling gaseous fluxes.

The evapotranspiration and like GPP, in Espirra was lower in 2005 than in 2006, in all three months of the analysis (Table 4 and Fig. 4). The diurnal relation between LE and GPP showed higher hysteresis in 2006 (wettest year) than in 2005 (driest year) (Fig. 4). This was due to the higher contribution of evaporation in the total measured evapotranspiration and probably to the decrease of the ratio of carbon uptake to water loss as trees experienced higher evaporative demands. This in line with similar observations on a Eucalypt forest stand in Australia (Drake et al., 2012).

The linear models in Espirra showed a significant contribution of global solar radiation, canopy resistance an precipitation, to GPP in 2005 and global solar radiation and canopy resistance in 2006 with R^2 of 0.62 and 0.79, respectively. Indeed, despite the significance of linear models (Table 3) in the driest year, 2005, the weekly rainfall showed the highest Rp in relation with evapotranspiration (Rp = 0.64). In 2006, global solar radiation showed the highest Rp in relation with evapotranspiration (Rp = 0.78). The Rp correlations between LE and GPP were respectively 0.6 in 2005 and 0.90 in 2006. All these statistical results reflect the fact that due to high water stress small rain events have a large effect. The results also show the determinant role of solar radiation in carbon and water vapor leaf exchanges.

The main drivers of canopy evapotranspiration can be evaluated via the decoupling factor (Eqs. (1) and (4)). Fig. 5 presents the weekly values of precipitation and of the decoupling factor during the two selected years for each of the four sites. At all four sites there was a seasonal pattern in Ω; this pattern differed between the Temperate climate sites and the Mediterranean climate sites. The Lochristi poplar site showed the highest values during the growing season, with highly variable values increasing from zero to circa 0.5 during the weeks 34 to 36 (August). Similar values of 0.6–0.7 were reported by for high-density poplar plantations (Hinckley et al., 1994). These high values are not typical for forest canopies (Jarvis and McNaughton, 1986; Pereira, 2004); they confirmed the strong influence of incoming solar radiation and available energy on the evapotranspiration of this dynamically growing poplar canopy. Only from mid-April until the end of May 2011 – i.e. weeks 16–23 Ω decreased from 0.35 to 0.16 in the poplar stand. The coupling between the canopy and the atmospheric drivers was primarily altered by a slowing-down of the LAI increase during a moderately dry period, as mentioned above.

In contrast with the Lochristi site, all other sites presented Ω values of about 0.2–0.3, typical values for forest canopies (Jarvis and McNaughton, 1986; Pereira, 2004). The Scots pine forest stand at Brasschaat showed slowly increasing Ω values in summer, but they did never exceed 0.2 (Fig. 5). This suggested that evapotranspiration was mainly controlled by atmospheric conditions and by canopy resistance. The two Mediterranean forests showed a good agreement between Ω and the precipitation values. Very low Ω values occurred during the dry season when the Eucalypt and Holm oak canopies controlled their transpiration through their stomata, completely in line with the above analysis of the daily patterns of GPP and LE. The highest Ω values at the Mediterranean sites occurred during the rainy season and matched with the rain events. The higher Ω values after precipitation were due to the evaporation from the wet canopy, driven by solar radiation, and also possibly to the higher soil moisture content.

4. Conclusions

Concerning the three main objectives defined (i) in general the main factors driving the carbon and water fluxes were global solar radiation and canopy resistance. Although this was the prevalent rule, the most important exception was the situation in Espirra in 2005 where precipitation was identified as the most important driver of the carbon and water fluxes; (ii) the evapotranspiration followed the typical patterns of forest canopies with average observed values for the decoupling coefficient of about 0.2. These values are typical for forests where the atmospheric vapor deficit and canopy resistance determine the coupling between the canopy and the atmosphere. The exception to this rule was the poplar site with average observed values for the decoupling coefficient of 0.5, which are typical for more homogeneous smooth canopies; and (iii) the stomatal control was the most important control of carbon and water vapor exchanges for the Mediterranean sites due to the higher atmospheric evaporative demand at these sites.

Overall, the present analysis showed that the SRC poplar plantation might be the most sensitive to increasing drought because of its lower stomatal control. Long periods of drought – as predicted by climate change scenarios for the Mediterranean region – may cause significant reductions in the carbon assimilation of e.g. fast-growing Eucalypt plantations, and thus compromise their economic viability.

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