Impact of tree canopy on thermal and radiative microclimates in a mixed temperate forest: A new statistical method to analyse hourly temporal dynamics

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ABSTRACT

Forest shelter buffers microclimate, decreasing daily ranges of solar radiation and temperature, yielding higher minimum and lower maximum temperatures than those of open field. The most common way to analyse sets of these data is to compare mean, maximum and minimum values of climate parameters of open field and understorey conditions at daily, monthly or seasonal scales; however, this approach loses information about temporal dynamics. This study developed a statistical method to analyse hourly dynamics of temperature (T) and radiation (Rad) together and quantify effects of canopy openness and seasonality on these dynamics. Eight experimental sites were chosen in small gaps located in a temperate oak-pine forest (France), and five plots were established in each along a light gradient (i.e. a total of 40 plots), which delimited a transect along which T and Rad were measured hourly at a height of 200 cm from May 2009 to March 2010. T and Rad were also measured in open field. A specific Principal Component Analysis (PCA) with an innovative graphical representation was performed on this dataset. This statistical method allowed hourly temporal dynamics of all data recorded to be analysed and included a chart to interpret the distribution of the data in the principal plane defined by the PCA. Except in winter, results demonstrate the well-documented buffering effect of the tree canopy on T, with higher minimum and lower maximum values in the forest understorey. This effect was especially pronounced for minimum T and increased as canopy grew denser. In summer, T remained higher than expected in the understorey and was lower than expected in the open field, indicating thermal inertia in the understorey and an a priori cooling effect linked to wind or radiative losses during the night in the open field. The newly developed statistical method offers an innovative approach to better understand the tree canopy's buffering effect on temporal dynamics.

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1. Introduction

In the current context of climate change, many concerns about the sustainability of ecosystems and crop production exist (Lobell and Gourdji, 2012), especially because temperatures are predicted to steadily increase in the near future and have a strong impact on many plant processes (Atkin et al., 2015; Blessing et al., 2015; Duursma et al., 2014; Kolari et al., 2014; Sendall et al., 2015). In forest ecosystems, understorey microclimate is controlled by characteristics (age, species, etc.) and the spatial structure of overstorey trees (Aussenac, 2000; Malcolm et al., 2001). Most microclimate variables are buffered by the shelter which trees provide (e.g. Karki and Goodman, 2015; Siegert and Levia, 2011; von Arx et al., 2012). Consequently, forest shelter creates cooler and wetter conditions for plant species sensitive to high temperatures or drought and thus thermophilisation of plant communities via macroclimate warming – i.e. favouring species adapted to warm conditions – could be limited (De Frenne et al., 2013). Therefore, both the macro- and microclimate should be considered to adequately predict the

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future of ecosystems. Many researchers have demonstrated that mean climate change, especially average temperature, is probably not the best way to predict adverse consequences of climate change on ecosystems (Thornton et al., 2014) and Henttonen et al. (2014) emphasised the need to use high-resolution climate data when analysing tree growth.

Forest temperatures are often estimated from open field weather stations, sometimes located far from study sites, even though tree canopies modulate their own microclimate, and systematic differences between temperatures measured in forests and at open field weather stations have been identified (Kollas et al., 2014). As Körner (2016) emphasised, plants experience temperatures that are rarely reflected by average data and "to advance vegetation ecologists need to collect bioclimatic data, rather than rely on weather station data". Most ecological or physiological studies have used climate data at a resolution of several kilometres or more, whereas organisms experience microclimate at a finer scale, from millimetres to metres (Suggitt et al., 2011). While the general buffering effect of the tree canopy is known, i.e. a decrease in maximum temperatures and an increase in minimum temperatures, further investigation is needed into daily variations in temperature, and their relations to solar radiation below the canopy.

The buffered thermal range is influenced partly by reduced radiation in the understorey, as radiation and temperature are highly correlated (Bristow and Campbell, 1984; Jegede, 1997). Daily temperature and radiation dynamics are rarely considered together in studies linking understorey plant behaviour to microclimate characteristics, even though temperature alone is often not enough to explain plant processes. For example, phenology of leaf senescence is mainly under thermal control at low and middle latitudes, while photoperiod becomes the primary factor at high latitudes (Gill et al., 2015). Many studies address only radiation or temperature (often added to moisture). They mainly focus on i) impacts of these climate parameters on understorey plant behaviour (see e.g. Ammer (2003), Balandier et al. (2007) and Gaudio et al. (2011a,b) for light, and Butt et al. (2014) and De Frenne et al. (2013) for temperature) or ii) the microclimate itself, as modified by forest shelter (see e.g. Balandier et al. (2006b) for light and Morecroft et al. (1998) for temperature).

This study's aim was to accurately characterise microclimate in the forest understorey by considering both temperature and radiation, as they strongly influence plant processes. The dual challenge was to consider i) temperature and radiation together because the relation between the two could differ in the forest compared to the open field and ii) hourly dynamics of these two variables, to extend analysis beyond daily mean, minimum and maximum values. To this end, we used an exploratory method based on Principal Component Analysis (PCA) with an innovative graphical representation. This article focuses on describing the statistical method and its ability to describe forest microclimate defined by hourly dynamic behaviour of two or more climate parameters. In particular, it describes the buffering effect associated with forest shelter: conditions under which buffering occurs (i.e. the influence of canopy density or cover) and how seasonality influences it.

2. Materials and methods

2.1. Study site and experimental design

The study was conducted from May 2009 to March 2010 in the Orleans plain forest in France (47°51′–47°77′N, 2°25′–2°36′E, mean elevation: 140 m). This region has a semi-oceanic climate, with mean annual precipitation of 740 mm evenly distributed throughout the year and mean annual temperature of 11.3 °C (data from 1981 to 2010). In winter 2008, a network of eight experimental
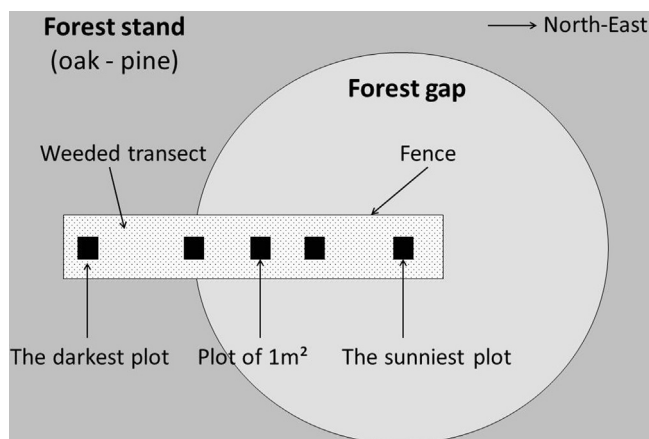

Fig. 1. Diagram of an experimental site (located in Orleans forest, France). Each experimental site consisted of one transect made up of five 1 m^2 plots organised to catch the light gradient at the stand – gap interface, i.e. the first plot was inside the forest stand (the darkest plot) and the fifth plot was in the middle of the gap (the lightest plot).

sites was established in mixed oak (*Quercus petraea* Lieblein) – Scots pine (*Pinus sylvestris* L.) stands (Table 1). Mean, minimum and maximum distances between the experimental sites were respectively 5.2, 1.2 and 11.2 km; therefore, they were considered independent. An open field site was also identified near the selected experimental sites to provide a reference measurement of the microclimate for all measurements described hereafter.

At each experimental site, we took advantage of small gaps (779 m^2 ± 352 m^2) within the stand to increase the number of radiation situations explored. Each experimental site contained a transect with five 1 m^2 plots organised to capture the natural light gradient which occurs between a darker plot in the stand and a lighter plot in the middle of the gap (Fig. 1). As plot location was adapted to each stand's gap characteristics to capture the light gradient, the total length of transects ranged from 19 to 39 m, and the distance between two plots within a transect ranged from 3 to 25 m. The category "understorey conditions" grouped plots that were influenced by all degrees of tree canopy openness. All plots were kept free of understorey vegetation during the entire experiment. The experimental sites were fenced to protect them from wildlife.

2.2. Measurements

2.2.1. Temperature

In early spring 2009, experimental sites were equipped with temperature sensors, i.e. thermocouples (T type class 1, CETIB Dexis, Clermont-Ferrand, France), which measured temperature T with 0.01 °C precision. To measure air T instead of sensor T, each thermocouple was protected in a well-ventilated white shelter of 950 cm^3 to allow airflow. Data were recorded every minute, averaged at an hourly time step, and stored using a datalogger (CR800, Campbell Scientific Ltd, Loughborough, UK) powered by a 12 V battery. One thermocouple was placed at a height of 200 cm in each of the 40 plots (i.e. 8 sites × 5 plots). Another thermocouple was placed at a height of 200 cm in the open field to provide the reference T. Data were collected for eleven months, from May 2009 to March 2010.

2.2.2. Radiation

Incident quantum of Photosynthetic Active Radiation (PAR, 400–700 nm, μmol m^{-2} s^{-1}) was measured throughout the experiment (from May 2009 to March 2010) with a light sensor (DLT/BF3, Delta-T, Cambridge, UK) placed at a height of 200 cm in the open