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Inter-annual variability of Net Ecosystem Productivity for a temperate mixed forest: A predominance of carry-over effects?

Marc Aubinet[a,*], Quentin Hurdebise[a], Henri Chopin[a], Alain Debacq[a], Anne De Ligne[a], Bernard Heinesch[a], Tanguy Manise[a,b], Caroline Vincke[b]

[a] *TERRA Teaching and Research Centre, University of Liège – Gembloux Agro-BioTech, 2 Passage des Déportés, B-5030 Gembloux, Belgium*
[b] *Earth and Life Institute, Université catholique de Louvain, Louvain-la-Neuve, Belgium*

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ABSTRACT

This study presents twenty years of Net Ecosystem Productivity estimations obtained using eddy covariance in a mixed forest, dominated by beech with sparse conifers, at the Vielsalm station, in the Belgian Ardennes.

First the quality and reliability of the data set is discussed. An uncertainty analysis showed that if, on one hand, the site heterogeneity and set-up changes may strongly affect yearly NEP estimates, questioning thus the total carbon budget relevance, on the other hand, robust inter-annual anomalies may be obtained as long as a site dedicated data treatment is carefully applied. A validation of the anomalies by comparison with a growth index derived from tree ring measurements is given. The resulting anomalies (range: $[-206; +123]$ g C m^{-2} yr^{-1}, standard deviation: 93 g C m^{-2} yr^{-1}) being larger than their own uncertainty ($\sim$30 g C m^{-2} yr^{-1}), an inter-annual variability analysis is possible.

This analysis shows that the sources of NEP inter-annual variability at the Vielsalm station are multiple but the most prominent causes are biotic processes driven by carry-over effects of preceding meteorological events. The lowest observed NEP, in 2000, resulted from a bark beetle attack probably prompted by an early frost event in 1998. Besides, the robust lagged correlation between NEP anomalies and mean vapor pressure deficit during the preceding vegetation season also suggests a carry-over effect of water limitation during the previous year on the beech NEP. Mechanisms driving this carry-over effect are supposedly linked to tree physiology, which is confirmed by a dependency of canopy photosynthetic capacity to previous year water limitation. Some hypotheses, involving biomass allocation and bud formation, are proposed to explain its lagged impact on canopy photosynthetic capacity.

Other causes of NEP inter-annual variability are the radiation during the current vegetation season and the temperature at the end of the winter but the latter variable rather indicates an effect on the conifers interspersed in the plot. Overall, the photosynthetic capacity combined with these two factors explained about 75% of NEP inter-annual variability.

1. Introduction

Terrestrial ecosystems play an important role in climate change mitigation as they reabsorb about one third of the carbon emitted by anthropogenic activity (Le Quéré et al., 2018). However, the captured quantity varies greatly from year to year and the mechanisms underlying this reabsorption remain poorly understood. It is thus difficult to predict how this component of the global carbon budget will evolve in the future. A better understanding of the mechanisms controlling the inter-annual variability of carbon sequestration by ecosystems is needed and long-term carbon exchange follow-ups could help to comprehend them. Since the end of the 1990s, several networks have been established around the world with this objective, e.g., Euroflux (Valentini et al., 2000); Asiaflux (Yamamoto et al., 2005); CarboEurope (Schulze et al., 2010); Ameriflux (Ameriflux, 2018); Ozflux (van Gorsel et al., 2018), Fluxnet (Baldocchi et al., 2001), ICOS (ICOS, 2018) and all of these used the eddy covariance method (Aubinet et al., 2012).

Measuring and analyzing long-term CO_2 exchanges between ecosystems and the atmosphere with the eddy covariance method is challenging, not only because of the difficulties in performing measurements and maintaining apparatus over a long-term perspective, but also in view of the long-term evolution that both the ecosystem and the

* Corresponding author.
E-mail address: marc.aubinet@uliege.be (M. Aubinet).

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measurement system undergo during the experiment (Hurdebise et al., 2017). In addition, further difficulties occur at sites characterized by heterogeneous canopies, as is the case for many forested sites. These evolutions may blur the inter-annual variability signal and need careful data treatment to unravel real source/sink variability and artificial variations. One of the aims of this paper is to establish a data treatment that, as far as possible, disentangles the artificial from the natural causes of carbon sequestration inter-annual variability.

At present several long-term studies (over ten years) are available and allow analysis of inter-annual variation of Net Ecosystem Productivity (NEP) by ecosystems to be deepened. In particular, several studies focused on temperate deciduous forests (Saigusa et al., 2005; Urbanski et al., 2007; Granier et al., 2008; Pilegaard et al., 2011; Froelich et al., 2015; Wilkinson et al., 2012) and a synthesis for all ecosystem types has been proposed recently by Baldocchi et al. (2018). The causes of inter-annual NEP variability in forests have been found to be multiple and to vary according to the climate and forest type but also, for given climate and forest type, from site to site. Most often identified causes include the variability of meteorological conditions (spring temperature, intensity or length of drought season, radiation), of the biotic response to the environmental forcing (Richardson et al., 2007); long-term trends (Pilegaard et al., 2011) and natural or anthropic disturbances (logging, fires, thinning, insect infestations). However, it is recognized that, even for a given site, it is generally not possible to explain NEP inter-annual variability with a single factor (Pilegaard et al., 2011). Until recently, only a few studies (Granier et al., 2008; Zielis et al., 2014) considered the impact on NEP variability of lagged or carry-over effects. The importance of these effects is however more and more often recognized by ecologists who highlight impacts on wood increment (Rohner et al., 2016), masting (Vacchiano et al., 2017), net primary productivity (Campioli et al., 2011; Babst et al., 2014) or carbon dynamics (Starr et al., 2016). Carry-over effects of drought stress in the prior season on growth have also been highlighted by Bréda et al. (2006) and Granier et al. (2008) while Desai (2014) also reported that moisture stresses in the preceding season may inhibit photosynthesis.

The present study is based on twenty years of measurements performed at the Vielsalm station (VS) in the Ardennes, Belgium. The site is a mixed forest composed of deciduous and coniferous species and the set-up has been modified after twelve years of measurements, therefore a long-term analysis required a specific methodology that took site heterogeneity and data harmonization into account. This paper thus aims to answer two main questions:

- Is it possible to obtain robust long-term budgets and inter-annual variability estimates in a heterogeneous forest and, if yes, which methodology can be followed in order to avoid biases due to heterogeneity and set-up changes?
- What are the main causes of inter-annual variability at VS? This question will be addressed by specifically focusing on direct but also on carry-over effects of antecedent weather conditions on canopy photosynthetic capacity and NEP.

2. Materials and methods

2.1. Site description

The Vielsalm station is located in a mature mixed forest in the Ardennes region in eastern Belgium (50°18'18" N, 5°59'53"E) at an altitude of about 470 m a.s.l. The winds blow mainly from the South West (SW) and the North East (NE). The vegetation in the vicinity of the measurement tower is a mixture of coniferous species, mainly Douglas fir (*Pseudotsuga menziesii* [Mirb.] Franco), Norway spruce (*Picea abies* [L.] Karst.), silver fir (*Abies alba* Miller), western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) and deciduous species, mainly European beech (*Fagus sylvatica* L.). The species distribution around the tower is heterogeneous, the SW sector being covered mainly by beech (28–29 m height) with some conifers interspersed (30–35 m height), while the other sectors are mostly covered by conifers. Douglas firs (35–41 m height) are mainly concentrated in the NE sector. The Douglas firs were planted in 1935 and 1937 and the beeches in 1908. A more complete description of the vegetation has been given by Soubie et al. (2016). More complete descriptions of forest history have been given by Aubinet et al. (2001) for the period before 1996 and by Hurdebise et al. (2017) for the measurement period. Thinning was performed at the beginning of 2001, in mid-2003 and at the end of 2004. The soil at the site is 50–100 cm deep and is classified as a dystric cambisol. The soil surface is slightly sloping (3%) in the NW direction. The climate is temperate maritime with an annual mean temperature around 8.4 °C and an annual precipitation of 1000 mm without a dry season. The site provides a fetch of 1500 m in the SW direction and 500 m in the NE direction.

2.2. Site instrumentation

Eddy covariance measurements began at VS in August 1996 and are still running. Presently, VS is a candidate ICOS station. The present analysis focuses on the twenty years taken from 1 Jan 1997 to 31 Dec 2016. The eddy covariance set-up (infrared gas analyzer LI-6262, LI-COR Inc., Lincoln, NE, USA; 3D sonic anemometer SOLENT 1012R2, Gill Instruments, Lymington, UK) was installed at 36 m a.g.l. in August 1996 and moved to 40 m a.g.l. in March 1997. In May 2009, it was raised to 52 m a.g.l and, in 2014, it was updated in order to comply with ICOS recommendations (infrared gas analyzer LI-7200, LI-COR Inc., Lincoln, NE, USA; 3D sonic anemometer SOLENT HS50, Gill Instruments, Lymington, UK) and placed at 51 m a.g.l. The impact of measurement height on the flux estimates has been discussed in detail by Hurdebise et al. (2017).

Complementary measurements included above and within canopy air temperature and humidity, global, net and photosynthetically active radiation (PAR), soil temperature and moisture profiles, rainfall, mean atmospheric pressure, soil heat fluxes and CO_2 concentration profiles below the measurement point. All these measurements are taken bi-hourly. Sensor type, number and position varied during the 20 year period. More complete descriptions of the meteorological set-up are given by Aubinet et al. (2001) for the original system and by Vincke et al. (2016) for the current system.

2.3. Flux data treatment

The Eddysoft software package (Kolle and Rebmann, 2007) was used to perform data acquisition and flux computation for all the years. Computation and correction followed the recommended standard procedures (Rebmann et al., 2012). The double rotation method was used for coordinate rotation. The first steps of classical quality control were applied to the raw data (spike detection and stationarity test) and only those data meeting the quality criteria were retained (Aubinet et al., 2000). The spectral correction was based on the comparison between CO_2 and sensible heat cospectra (Foken et al., 2012), following a procedure described by De Ligne (2016): transfer functions and their cut off frequencies were obtained as the ratio of CO_2 and sensible heat cospectra, computed on each high quality half hour (stationarity criterion met; sensible heat > 20 Wm^{-2}). These functions were combined with a reference non attenuated local cospectrum (sensible heat cospectrum) in order to determine the correction factors. Look up tables grouping correction factors by wind velocity classes were built for 8 different periods (between each apparatus change), two wind sectors and two stability classes (stability threshold: z/L = 0.003).

Finally, data that did not meet the stationarity criteria (threshold 30%) were removed (Foken and Wichura, 1996). After these operations, 82% of the total data was available for analysis (Table SM I).