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ORIGINAL ARTICLE

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Predicting the onset of net carbon uptake by deciduous forests with soil temperature and climate data: a synthesis of FLUXNET data

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Abstract We tested the hypothesis that the date of the onset of net carbon uptake by temperate deciduous forest canopies corresponds with the time when the mean daily soil temperature equals the mean annual air temperature. The hypothesis was tested using over 30 site-years of data from 12 field sites where CO_2 exchange is being measured continuously with the eddy covariance method. The sites spanned the geographic range of Europe, North America and Asia and spanned a climate space of 16°C in mean annual temperature. The tested phenology rule was robust and worked well over a 75 day range of the initiation of carbon uptake, starting as early as day 88 near Ione, California to as late as day 147 near Takayama, Japan. Overall, we observed that 64% of variance in the timing when net carbon uptake started was explained by the date when soil temperature matched the mean annual air temperature. We also observed a strong correlation between mean annual air temperature and the day that a deciduous forest starts to be a carbon sink. Consequently we are able to provide a simple phenological rule that can be implemented in regional

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carbon balance models and be assessed with soil and temperature outputs produced by climate and weather models.

Keywords Phenology · Eddy covariance · CO_2 exchange · Canopy photosynthesis

Introduction

The timing of leaf out, across the temperate deciduous forest biome, has major implications on the seasonal variation of numerous ecosystem/atmosphere interactions. For example, the transition between dormant and vegetated states of deciduous forests causes an abrupt change in surface albedo, aerodynamic roughness and the surface conductance to water, carbon dioxide and pollutant transfer. Together, these variables alter the availability of energy and its partitioning into sensible and latent heat exchange (Blanken et al. 2001; Moore et al. 1996; Wilson and Baldocchi 2000). A perturbation in the partitioning of energy is consequential because it alters the growth rate and ultimate depth of the planetary boundary layer (McNaughton and Spriggs 1986). The modifications in boundary layer growth, in turn, affect the diurnal course and amplitude of temperature and humidity within the surface and planetary boundary layer (Schwartz and Karl 1990). Furthermore, the absence or presence of leaves can act as a switch for the formation of convective clouds through links with the properties of the planetary boundary layers (Fitzjarrald et al. 2001; Freedman et al. 2001; Schwartz and Crawford 2001).

The timing of leaf-out marks the beginning of the photosynthetic season for a deciduous forest and is a major determinant of its duration (White et al. 1999). With regards to terrestrial carbon cycling, the length of carbon uptake period has much predictive power about the spatial variation of the net annual carbon exchange of ecosystems (*NEE*) across a latitudinal and continental gradient of deciduous forests (Baldocchi et al. 2001)—the length of the carbon uptake period explained 80% of the spatial variance in annual *NEE*. It has also been reported—on both experimental (Black et al. 2000; Goulden et al. 1996b; Schmid et al. 2000; Schmid et al. 2003) and theoretical bases (White et al. 1999)—that the timing of leaf out provides partial explanation for the year-to-year variability in *NEE* at individual sites; additional controlling factors on *NEE* include presence and absence of snow, drought, and summer cloudiness.

Lately, phenology has received added attention because of its role as a surrogate in detecting global climate change (Jackson et al. 2001; Penuelas and Filella 2001; White et al. 2003). Phenological indices measured across Europe (Menzel and Fabian 1999) and North America (Cayan et al. 2001) and interannual measurements of biosphere greenness, as observed by satellites (Myneni et al. 1997; Tucker et al. 2001), are detecting a trend towards earlier springtime leaf-out, portending a potential signal of global warming. In order to simulate the implications of changing phenology on biosphere-atmosphere interactions, models that compute the biogeochemical cycling of water, carbon and nutrients, atmospheric chemistry, weather and climate need algorithms that can predict the timing of leaf expansion, the initiation of photosynthesis and the onset of net carbon uptake by deciduous forests (White et al. 1997).

Dates of bud break, leaf unfolding, and commencement of photosynthesis have been used to characterize aspects of forest phenology (Brugger et al. 2003; Gu et al. 2003). Physiological mechanisms for the timing of springtime phenological events involve a need for dormancy and are triggered by interactions between growth-promoting and inhibiting hormones (Schaber and Badeck 2003). The release of these hormones seems to be triggered by an accumulation of winter chilling, a critical photoperiod and springtime warming. Historically, phenological models have used photoperiod and cumulative heat and chilling units as independent variables (Chuine et al. 2003; Kramer et al. 2000; Nizinski and Saugier 1988; Raulier and Bernier 2000; Spano et al. 1999). While this class of models has many practical applications, it is highly empirical. Consequently, its generality is limited because the threshold sum of heat and chill units, that determines the date of a particular phenological event, needs to be calibrated at each site and for each mix of species (Kramer et al. 2000; Raulier and Bernier 2000; Taylor 1974). We also note that there can be considerable imprecision with identifying the specific date of a phenological event due to natural temporal and spatial variability and sampling errors. Phenological metrics like bud break, leaf unfolding and the onset of photosynthesis are not synchronous and can occur for an extended period (Brugger et al. 2003; Morecroft et al. 2003). For example, it takes 11 days for European oak leaves to transcend between budbreak and a physiological state that maintains a positive carbon balance (Morecroft et al. 2003). Considerable spatial variation in the timing of phenology will occur within a woodland, too, due to the presence of multiple species and because of microclimate variations. Sampling error is yet another source of variation. Detecting the precise date of a phenological event depends upon the sampling frequency and sampling area associated with manual observations or with the frequency of passage and pixel size associated with remote sensing instruments mounted on a satellite or tower.

Our goal is to assess a simple phenological rule that has a detection criterion that is based on biophysical principles and can be assessed with information that is commonly available at weather stations and from weather and climatological forecast models (e.g. air and soil temperature). We propose and test the hypothesis that: “the date of the onset of net carbon uptake by a temperate deciduous forest corresponds with the time when the mean soil temperature equals its mean annual air temperature”. This working hypothesis was generated from observing the timing of leaf-out near Oak Ridge, Tennessee. There, trees tended to leaf out when the soil temperature was near 13°C (Taylor 1974), a temperature that corresponds with the mean annual air temperature of the region. While this anecdotal observation requires further scrutiny with a larger database, we contend that there may be mechanistic justifications for this hypothesis. For example, soil temperature acts as a proxy

Table 1 List of the field sites used in this analysis, their location, mean annual air temperature and citations describing site characteristics and meteorological measurements

Site	Genera	Lat	Long	Mean annual temperature	citation
Prince Albert, Saskatchewan	Populus	53 N	106 W	0.6	Black et al. (2000)
Douglas Lake, Michigan	Populus/Quercus	45 N	84 W	6.2	Schmid et al. (2003)
Borden, Ontario	*Acer/Populus*	44 N	79 W	6.4	Lee et al. (1999)
Collelongo Italy	*Fagus*	41 N	13 E	6.5	Valentini et al. (1996)
Takayama, Japan	*Betula*	36 N	137 E	7.3	Yamamoto et al. (1999)
Harvard Forest, Massachusetts	*Quercus/Acer*	42 N	72 W	7.4	Goulden et al. (1996b)
Hainich, Germany	*Fagus*	51N	10 E	7.5	Knohl et al. (2003)
Soroe, Denmark	*Fagus*	55 N	11 E	7.6	Pilegaard et al. (2001)
Hesse, France	*Fagus*	48 N	7 E	9.2	Granier et al. (2002)
Morgan Monroe, Indiana	*Quercus*	39 N	86 W	11.8	Schmid et al. (2000)
Oak Ridge, Tennessee	*Quercus/Acer*	36 N	84 W	14.9	Wilson and Baldocchi (2001)
Ione, California	*Quercus*	38 N	120 W	16.5	Baldocchi et al. (2004)

for accumulated chill and heat units as it is an integrator of these measures due to the soil's thermal inertia and energy balance. Secondly, deciduous trees have evolved to be in synchrony with their climate to minimize the exposure of their young leaves to freezing and possibly lethal temperatures during the spring; the probability of frost becomes quite low once mean daily air temperature exceeds its annual mean temperature.

We test this hypothesis using continuous CO_2 flux measurements, an approach that has been adopted in other recent phenological studies (Gu et al. 2003; Suni et al. 2003). The analysis is based on over 30 site-years of meteorological and carbon flux data from 12 temperate deciduous forest sites that are associated with the FLUXNET project (Baldocchi et al. 2001). The datasets examined here were acquired from sites that are distributed across the geographic domains of Europe, North America and Asia and they span 16°C in mean annual temperature. An advantage of quantifying phenology with eddy covariance measurements includes its capacity to make nearly continuous measurements and to sample a large area, as characterized by its flux footprint (Schmid 2002).

Materials and methods

We restricted this phenological study to FLUXNET study sites whose trees have broad leaves and deciduous habits. The key genera at the sites used in this analysis include *Populus* (aspen), *Acer* (maple), *Quercus* (oak), *Betula* (birch) and *Fagus* (beech). Forests at the majority of sites inspected formed closed canopies; their leaf area indices ranged between 3 and 6 and their tree heights ranged between 8 and 30 m. With regards to age structure, most of the sites were second-growth forests and were less than 120 years old. Characteristics of the sites used in this analysis, and primary references describing additional site details, are summarized in Table 1.

A common set of meteorological and eddy flux measurements were acquired from each of the sites involved in the analysis. The datasets scrutinized here included long-term and simultaneous measurements of air and soil temperature and net ecosystem CO_2 exchange between the forest and the atmosphere. Air temperature was measured above the forest stands with aspirated and shielded sensors. Soil temperatures were measured with either thermistor or thermocouple sensors; most sites had soil temperature measurements at 2, 5, 8 or 10 cm depths. Daily means were computed from the original 30 min datasets using the mean diurnal course gap-filling method (Falge et al. 2001).

CO_2 flux densities were measured across the forest-atmosphere interface with the eddy covariance method (Baldocchi et al. 1988). In Europe, flux measurements systems were based on closed path CO_2 sensors (Aubinet et al. 2000), while in North America, both open and closed path CO_2 sensors were used; independent studies show that there is no bias by using either an open or closed path sensor system to measure CO_2 exchange (Billesbach et al. 2004; Suyker and Verma 1993).

Efforts have been made by the AmeriFlux and FLUXNET communities to inter-compare CO_2 flux measurements and meteorological measurements with a roving, calibration system (Baldocchi et al. 2001; Billesbach et al. 2004). In general, the absolute errors in eddy flux measurements of CO_2 exchange are less than 15%, with the application of proper corrections (Goulden et al. 1996a; Hollinger et al. 2004; Massman and Lee 2002).

The date of onset of net carbon uptake was identified as the day when daily integrated net CO_2 exchange (*NEE*) experienced a transition from its winter respiration phase to its spring/summer assimilation phase (Fig. 1). To deduce this date with objective and statistical rigor, we regressed measurements of daily *NEE* on day of year, using a subsets of data from this springtime source-sink transition period. The method has a clean and distinct signal with a quantifiable error. For the case shown in Fig. 1, the statistical variation in detecting the precise date of the zero crossing is ±2 days, based on the 95% confidence interval.

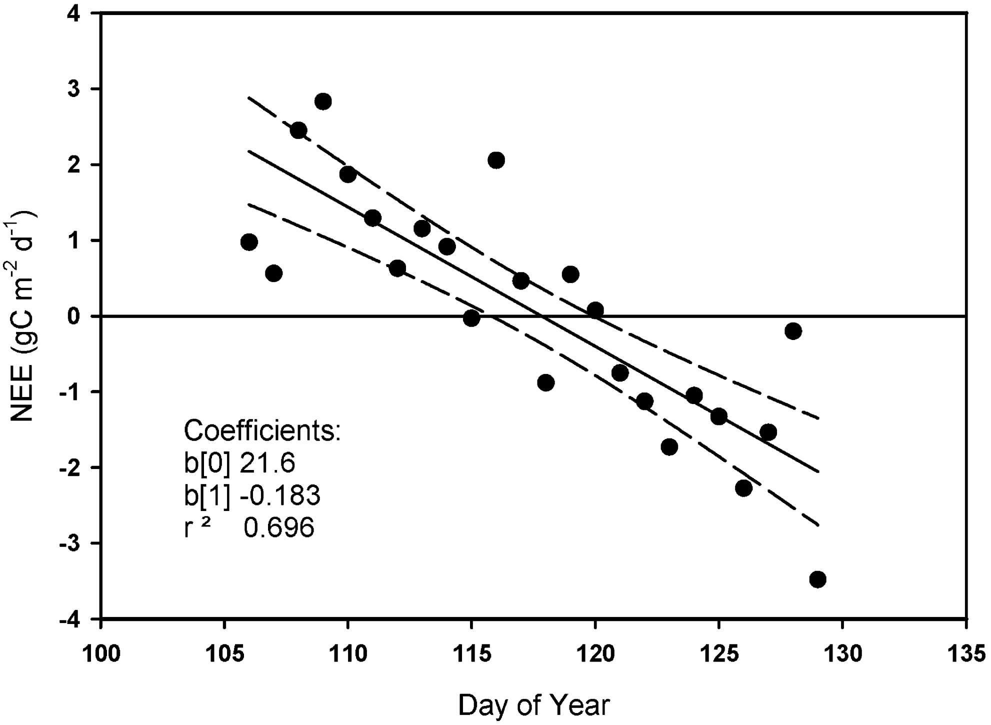


Fig. 1 An example of daily net ecosystem CO_2 exchange measurements (*NEE*) as a function of time. The *solid line* represents the linear regression and the *dashed lines* are the 95% confidence interval. During this transition period a linear regression was fit through the data and the 'leaf-out' date was computed by inverting that regression and solving for when *NEE* was zero

On a physiological and fundamental level, it may be preferable to detect the onset of canopy photosynthesis rather than rely on transitional observations of *NEE*. However, the use of canopy photosynthesis can introduce an additional source of error and imprecision because canopy photosynthesis is a derived quantity that is assessed by subtracting an indirect estimate of ecosystem respiration from direct measurements of *NEE* (Falge et al. 2002). Ecosystem respiration (R_{eco}), for example, is deduced from night measurements (which are uncertain due to turbulent mixing) and is calculated during the daytime with a temperature-dependent function (Falge et al. 2001). During the dynamic spring growth period, temperature response functions, that are commonly used to assess ecosystem respiration are apt to fail because growth respiration is accelerating during this transitional period and it enhances ecosystem respiration (Xu et al. 2004).

Our working hypothesis presumes that there is a correspondence between the date of the initiation of net carbon uptake and the day when mean daily-averaged soil temperature crosses a line corresponding with the mean annual air temperature. Since a tree is unable to sense the mean annual air temperature a priori, we decided to approximate mean annual air temperature ($\overline{T}$) using a low-pass, digital recursive filter (Hamming 1989). The low-pass character of this recursive filter provides us with a method that approximates the temporal mean by weighting the current air temperature with its history:

$$\overline{T_t} = (1-\alpha)\overline{T}_{t-1} + \alpha T_t \qquad (1)$$

The mean air temperature, at time t, is updated based on its previous mean value, at $t-1$, and the most recent daily-averaged air temperature, T_t. The weighting factor, α, is defined as:

$$\alpha = \exp\left(-\frac{\Delta t}{\tau}\right) \qquad (2)$$

We computed mean air temperature using a 730 day (2 year) time constant, τ, and a 1 day sampling interval, Δt.

Results and discussion

Before we attempt to test our working hypothesis across a network of field sites, it is crucial that we demonstrate whether or not this concept works across a representative sampling of study sites (Figs. 2, 3). Figure 2 shows a test of the hypothesis for a beech forest in Denmark; this site is near the most northerly and coolest end of the deciduous forest biome range in the FLUXNET network. We observe that there is very close correspondence between the date when net CO_2 exchange crossed the zero line and when mean soil temperature (computed with a 3 day running mean) crossed the isotherm representing the mean annual air temperature at that site. A second example is shown for a contrasting case, a site near Oak Ridge, Tenn. This site is near the most southern and warmest end of the deciduous forest biome (Fig. 3). Like the Danish forest, there is a close correspondence between the date of the zero crossing of canopy CO_2 exchange and when the soil temperature crosses the line representing the mean annual air temperature at that site. Despite the fact that the commencement of net CO_2 uptake near Oak Ridge, Tenn. occurs about 30 days earlier and the mean annual air temperature is about

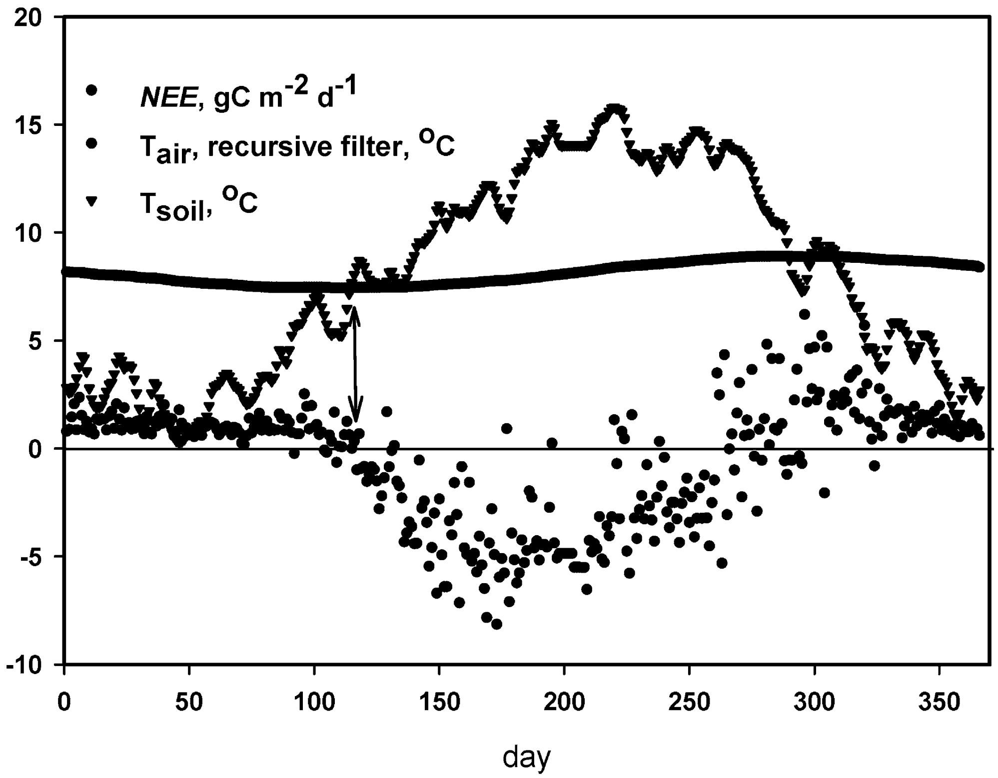


Fig. 2 Seasonal course in daily integrated net ecosystem CO_2 exchange (*NEE*), mean air temperature computed with a digital recursive filter, mean air temperature computed with a digital recursive filter and the mean daily soil temperature at 2 cm (based on a 3 day running mean). These data were acquired over a beech forest in Denmark during 1999. The *double-headed arrow* identifies when soil temperature matched mean annual air temperature and when *NEE* crossed zero (the *lower horizontal* line)

6°C warmer than in Denmark, the general relationship 'that a critical soil temperature identifies the onset of net carbon uptake by the ecosystem' holds.

How well the match between daily mean soil temperature and mean annual air temperature provides a precise gauge for predicting the onset of net CO_2 uptake for the entire database is quantified in Fig. 4. We report that a linear regression between the dependent (the day T_{soil} equaled mean annual air temperature) and independent (the day *NEE* equaled zero) variables accounts for 64% of the variance. Furthermore, the slope of the regression was close to, but significantly different from one (0.929±0.21) and the intercept was 17.1±25.3 days. Because the dependent and independent variables have sampling and measurement errors, we also computed the geometric mean regression. In this case, the slope was 1.15±0.344 and the intercept was −8.57±41.5.

Another question we can pose and address is: 'how well can climatological data describe when a deciduous forest transcends from being a carbon source to a sink?' Figure 5 shows that the start-date of net carbon uptake becomes earlier, in a linear fashion, as the local climate (mean annual air temperature) becomes warmer. Overall, perturbations in mean annual air temperature explain 69% of the variance in the start-date of net carbon uptake.

In sum, both phenology rules seem robust by working well over a 75 day range of the initiation of carbon uptake, starting as early as day 88 in near Ione, California to as late as day 147 near Takayama, Japan. However, the results shown here may not be universal for all functional plant types and climate zones. For example, Suni et al. (2003) reported that soil temperature was not a good indicator for signaling the onset of photosynthesis across the boreal forest biome. On the other hand, they found that air temperature was a good indicator of the onset of photosynthesis for conifers at high latitudes, but they found no unifying relationship that held across the boreal forest biome. Hence, we advise the reader to apply the functional relationship between soil temperature and the onset of carbon uptake only to deciduous broadleaved forests. Close inspection of Fig. 4 shows that the significant outliers were associated with measurements at Harvard Forest, in Massachusetts, where net carbon uptake starts later than one would expect based on soil temperature measurements. This site is near the eastern edge of the North American continent and is a locale subject to much climatic variability during the spring due to the passing of warm and cold air masses; examining over 40 years of mean air temperature we found that the daily mean temperature ranges between 0 and 20°C around the expected date of leaf out, approximately day 120. So soil temperature may not queue the phenology of net carbon uptake as well at this site as others. We also add that our phenology rule does not work well for a deciduous forest in the boreal zone, where the mean annual temperature is close to zero centigrade and snow cover keeps soil temperature close to zero during the winter and early spring (Griffis et al. 2003). Consequently, soil temperature in this region crosses the isotherm representing mean air temperature much sooner than when leaves emerge (Fig. 6).

Measurements of net CO_2 exchange have the potential for assessing the timing of leaf-out if we know the time

Fig. 3 Seasonal course in daily integrated net CO_2 exchange (*NEE*) and the mean daily soil temperature at 8 cm. These data were acquired over an oak/maple forest near Oak Ridge, Tenn. during 1996. The *double-headed arrow* identifies when soil temperature matched mean annual air temperature and when *NEE* crossed zero (the *lower horizontal line*)

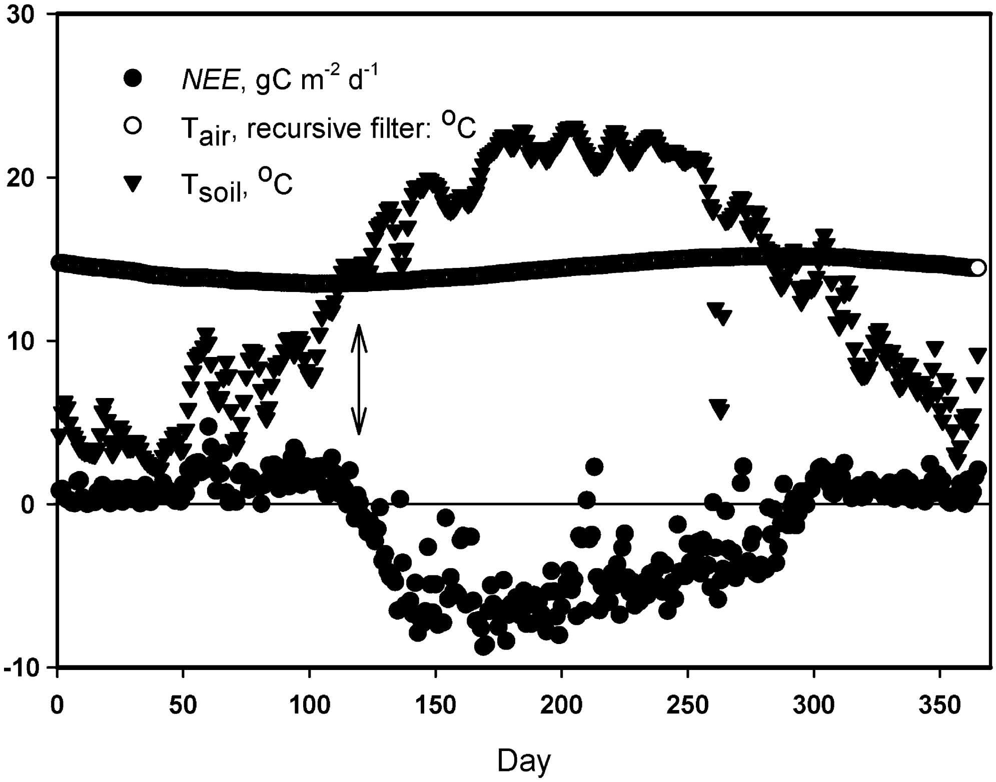
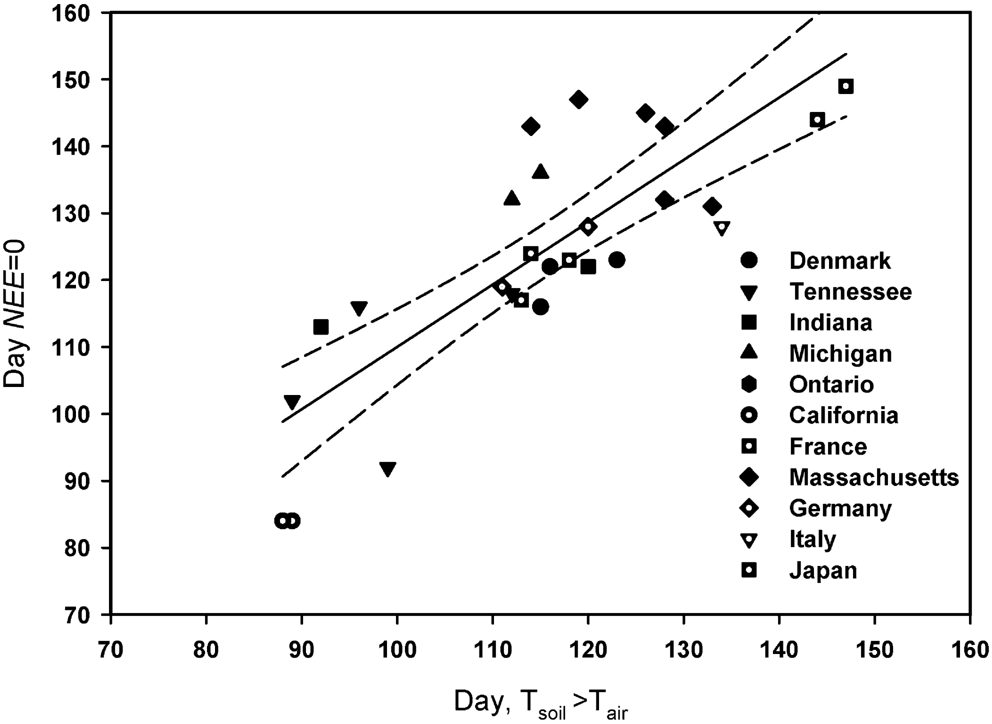


Fig. 4 The empirical relationship between the date when mean daily soil temperature equals mean annual air temperature and when daily net ecosystem carbon exchange (*NEE*) crosses zero. The *solid line* represents the linear regression through the data and the *dashed line* represents the 95% confidence interval



delay between when leaves unfold and when canopy photosynthesis matches soil respiration. We detected the date of leaf-out at a few selected sites using light transmission measurements through the canopy; leaf-out was identified when the fraction of beam penetration through the forest decreased, relative to its winter deciduous state. Our detection of the date of leaf out, with CO_2 flux measurements, accounted for over 94% of the variance in the timing of leaf-out observed with light measurements. The statistics associated with the linear regression possessed a non-zero intercept of 22.1±29.1 days and the regression slope that was less than one (0.744±0.243) (Fig. 7). We also observed

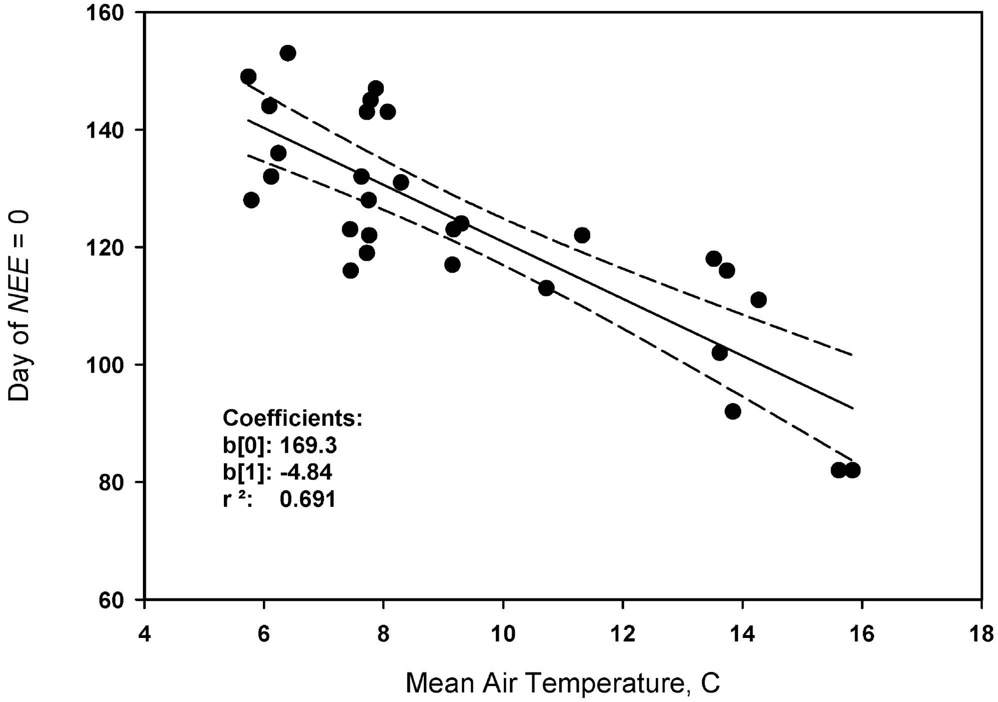


Fig. 5 The relationship between the mean annual air temperature and the day when net carbon of deciduous forests uptake commences. The *solid line* represents the linear regression through the data and the *dashed line* represents the 95% confidence interval

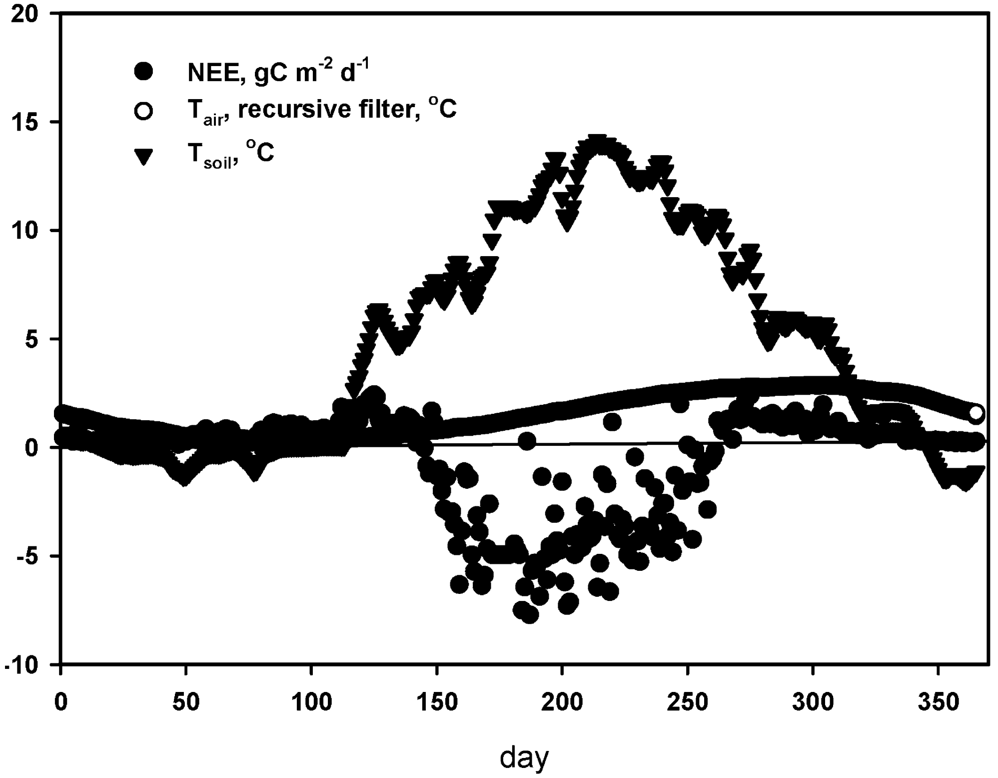


Fig. 6 Seasonal course in daily integrated net ecosystem CO_2 exchange (*NEE*), the mean daily soil temperature at 8 cm (computed with a 3 day running mean) and mean air temperature, computed with a digital recursive filter. These data were acquired over an aspen forest in the southern portion of the boreal zone of Canada during 2000

that the onset of net carbon uptake, relative to the date of leaf-out, becomes more delayed as the start of growing season becomes later.

To compensate for the bias between the date of observed leaf-out and the onset of net carbon uptake, we produced a transformed metric using the regression between the observed and inferred dates of leaf-out, discussed in Fig. 7. We next compared this transformed metric for identifying the date of leaf out against the date when mean daily soil temperature crosses mean annual air temperature (Fig. 8). For the dataset in hand, we found that the mean date of leaf out, detected using soil and air temperature, was ±114.9±14.9

Fig. 7 The relationship between the day net ecosystem CO_2 exchange crossed zero and the date that leaf out was observed. Data were from sites in Michigan, Tennessee, Saskatchewan and California

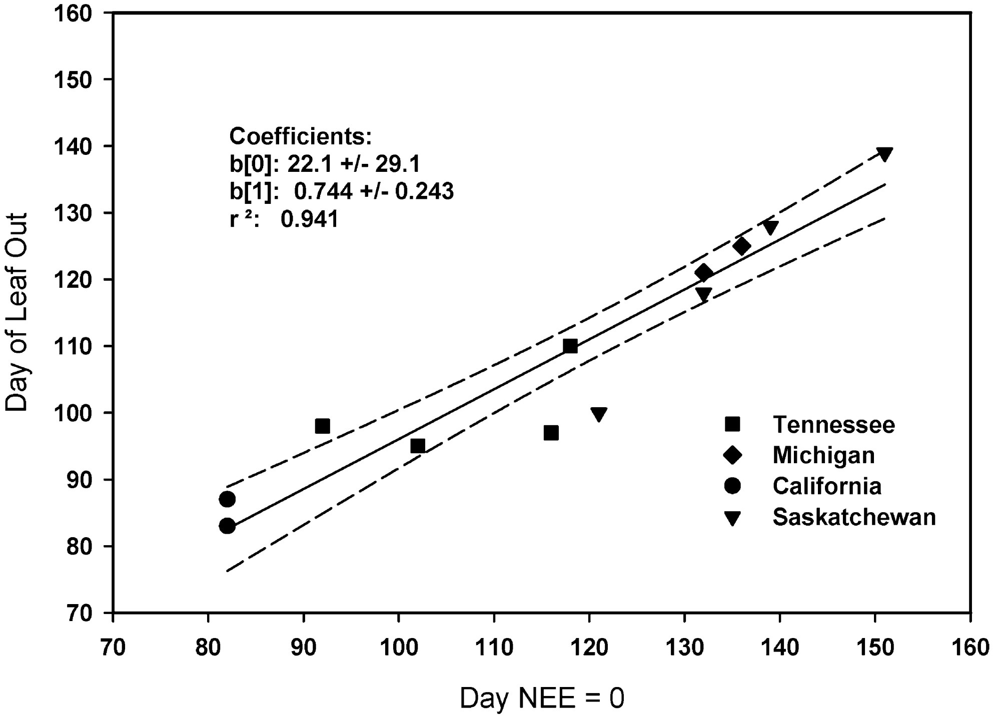
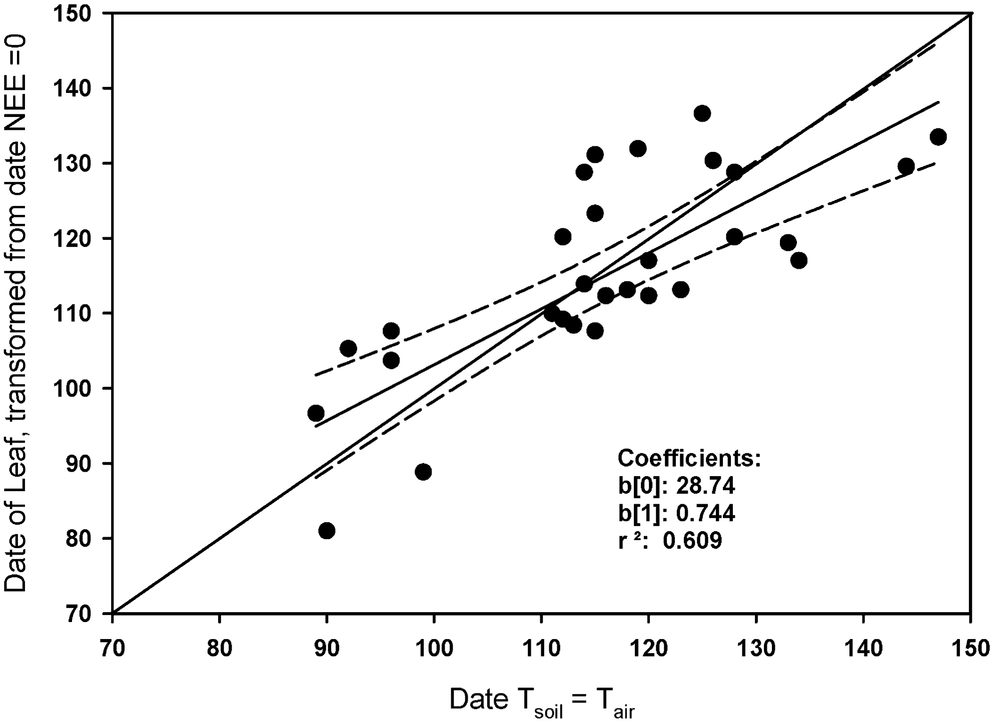


Fig. 8 A test of the timing of leaf out as detected by the date when soil temperature crosses the mean air temperature, as computed with a recursive digital filter. Data on the dependent axis were assessed by applying the empirical relation between the observed date of leaf out and that detected with CO_2 flux measurements. Statistical analysis (via a paired *t*-test) indicates there is no significant difference between the data on the dependent and independent axes



days and the mean date detected with the transformed CO_2 flux measurements was 116.6±14.3 days. Further analysis of the data, using Student's paired *t* statistic, indicates that there was no significant difference between the two means on the 5% probability level (t=0.413; P=0.60; 29 *df*). A linear regression between the independent and dependent variables explained 61% of the variance, had a slope of 0.744 and an intercept of 28.7.

There are several sources of variation associated with the results in Figs. 5 and 8 that merit further discussion. Soil temperature was not measured at uniform depths across the network, so this source of variation may contribute to some 'noise' introduced into the cross-site comparison. In general, we attempted to minimize this source of variation by: (1) using soil temperatures measured in the area of the main root activity, 5 to 16 cm; (2) by relying on daily

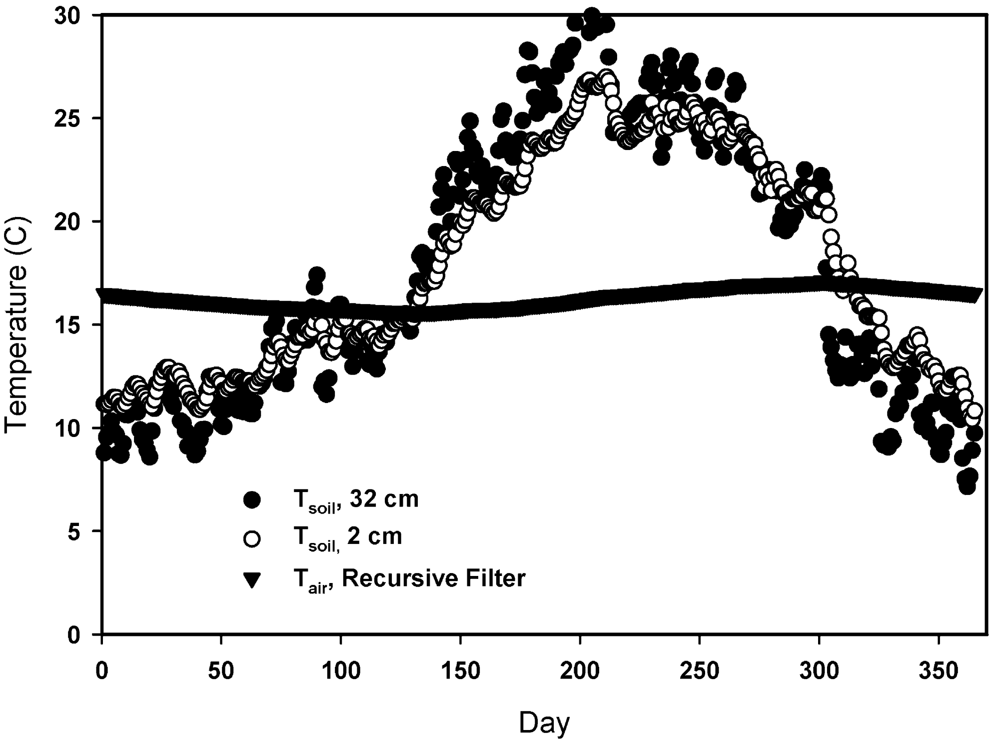


Fig. 9 Seasonal variation in mean daily soil at 2 and 32 cm and mean air temperature computed with a digital recursive filter. The data were collected at an oak woodland field site in California during 2003. Both measures of soil temperature crossed the mean air temperature at day 90

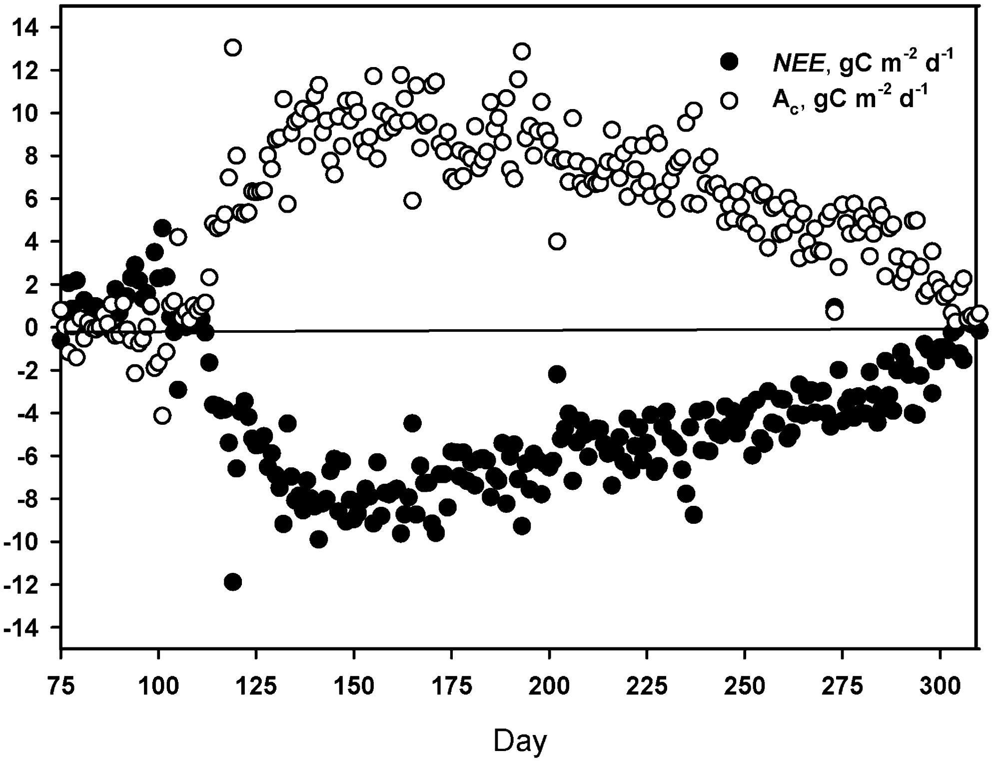


Fig. 10 Seasonal course of daily-integrated CO_2 flux and canopy photosynthesis at Oak Ridge, Tenn. during 1999. Canopy photosynthesis was computed by subtracting understory eddy flux measurements from the overstory measurements

mean temperatures, a more conservative metric; and (3) by applying a 3-day running mean to the soil temperatures. Overall, site-to-site differences in the depth of soil temperature measurements probably had a minor and secondary effect on the results shown in Figs. 5 and 8. This claim is supported with experimental data shown in Fig. 9. We observe that there was little difference when daily mean soil temperature, at 2 or 32 cm depths, first crossed the isotherm representing mean annual air temperature at an oak savanna field site in California and at other sites where soil temperatures was measured at multiple depths as in Oak Ridge, Tennessee and Soroe, Denmark (data not shown).

There may also be imprecision associated with using the CO_2 flux cross-over date as a measure of leaf out, rather than canopy photosynthesis. At most temperate deciduous forest sites there will be some photosynthesis prior to this date, which offsets soil respiration. But the temporal change in both *NEE* and A_c during spring is rapid and will only cause a few days lag in the detected leaf out date, as shown for a case near Oak Ridge, Tenn. (Fig. 10).

A strength of our approach, compared with traditional phenological models based on heat degree units, is that our method does not rely on an arbitrary heat unit threshold that must be calibrated on a site-by-site basis. It is also worth noting that the simple phenology scheme examined in this report says nothing about photoperiod, which may also be a source of variance and a weakness of the method we are advocating here (Nizinski and Saugier 1988; Raulier and Bernier 2000).

With regards to further work, we encourage a wider testing of this scheme with remote sensing data at continental scales. This exercise would involve predicting the seasonal course of soil temperature at each pixel in the deciduous forest biome and find the date when it matches the local mean annual air temperature. Then one would compare that product with remote sensing data of the green wave of spring. The phenology algorithm could also use additional validation against data from independent phenology networks (http://www.uwm.edu/∼mds/markph.html) and new measurements being produced by the Moderate Resolution Imaging Spectroradiometer (MODIS) on the TERRA satellite (Shabanov et al. 2003). Finally, we encourage colleagues to install video cameras at all FLUXNET sites and record the state of the canopy each day.

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