Management Effects on European Cropland Respiration

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Abstract

Increases in respiration rates following management activities in croplands is considered a relevant anthropogenic source of CO$_2$. In this paper, we quantify the impact of management events on cropland respiration fluxes of CO$_2$ as they occur under current climate and management conditions. Our findings are based on all available CarboEurope IP eddy covariance flux measurements during a 4-year period (2004–2007). Detailed management information was available for 15 out of the 22 sites that contributed flux data, from which we compiled 30 types of management for European-scale comparison. This allowed us to address the question of how management activities influence ecosystem respiration. This was done by comparing respiration fluxes during 7, 14, and 28 days after the management with those observed during the matching time period before management.

Median increases in respiration ranged from +83% (early season tillage) to −50% (rice paddy flooding and burning of rice residues) on the 28-days time scale, when only management types with a minimum of 7 replications are considered. Most management types showed a large variation among events and between sites, indicating that additional factors other than management alone are also important at a given site. Temperature is the climatic factor that showed best correlation with site-specific respiration fluxes. Therefore, the effect of temperature changes between the time periods before and after management were taken into account for a subset of 13 management types with adequate statistical coverage of at least 5 events during the years 2004–2007. In this comparison, late-season moldboard ploughing (30–45 cm) led to highest median increase in respiration on the 7-days timescale (+43%), which was still +15% in the 28-days comparison. On average, however, management-induced increases in respiration losses from croplands where quite moderate (typically <20% increase over 28 days).

An assessment of extreme values in daily respiration fluxes using the Gumbel distribution approach revealed that sites with larger average respiration fluxes also experience the larger extremes in respiration fluxes. This suggests that it is very unlikely that sites that generally have low respiration rates will have exceedingly high respiration rates as a result of certain specific management events.

Keywords: Ploughing; Tillage; Carbon Fluxes; Eddy Covariance; Cropland Management; Light response; Gumbel distribution; CarboEurope.
1. Introduction

Land use and land use changes directly and indirectly affect the surface energy budget of the Earth, and the greenhouse gas (GHG) budget, depending on management practice (Turner et al. 2007, Bavin et al. 2009). Drainage and ploughing changed the hydrology of landscapes during historical land transformations (e.g. Schneider and Eugster 2005), which feeds back to climate via the surface energy budget (typically termed the albedo effect) and via changes in GHG fluxes with respect to a reference land use type. In the context of climate change research, the Intergovernmental Panel on Climate Change (IPCC) uses the preindustrial period for reference (Rogner et al. 2007). During this period, deforestation and irrigation were the largest sources of human-released greenhouse gases to the atmosphere (Turner et al. 2007). However, very little is known about the specific influences of land management practices in arable cropland ecosystems on GHG fluxes except for tillage and ploughing, for which detailed experiments have tried to quantify these fluxes. Respiration – the sum of heterotrophic respiration of decomposing microbes in the soil and autotrophic respiration of active plants – is always a GHG loss term in an ecosystem, but the question to be addressed in croplands is whether management interventions enhance or reduce these losses.

Tillage has been shown to stimulate soil carbon losses by increasing aeration, changing temperature and moisture conditions, and thus favouring microbial decomposition (Reicosky et al. 2008). In addition, soil aggregate disruption by tillage exposes once protected organic matter to decomposition (La Scala et al. 2008). Many studies have investigated such short-term CO₂ losses from agricultural ecosystems in the first 24 hours after management such as tillage and ploughing (e.g. Gesch et al. 2007, Reicosky et al. 1997), the first few days (e.g. Reicosky et al. 2008) and up to 3–6 weeks (Reicosky and Lindstrom 1993, Rochette and Angers 1999, Morris et al. 2004, Chatskikh and Olesen 2007, Reicosky et al. 2007, Bono et al. 2008) after treatment. Ploughing and tillage were generally found to lead to significant CO₂ losses compared with a no-tillage treatment. The magnitude of these CO₂ losses generally correlates with the level of mechanical disturbance and depth of tillage (Reicosky and Archer 2007). Short-term responses, that is, the first hours after treatment, tend to be mostly related to mechanical outgassing of CO₂-rich air from the soil pores, but a rapid increase in microbial activity has also been postulated (Reicosky et al. 1995). Whereas the mechanical outgassing can only be measured directly after tillage, microbial decomposition of organic matter that is related to the management disturbance can last for days to weeks. In histosols for example, disturbance effects of tillage were found up to 20 days after management, and in mineral soils, the effects are reported to last up to 42 days (Morris et al. 2004). In histosols, but also...
in eutric-stagnic cambisols (see e.g. Alaoui and Goetz 2008) the high clay content tends to lead to large cracks when the soil dries (natural droughts or management-induced drying). This increases the active surface area for outgassing of CO₂ from such soils.

In contrast to this knowledge on cultivation and tillage, relatively little is known about the impact of other important management practices on CO₂ losses in croplands at the ecosystem scale. Practices such as fertilization and application of plant protection products are expected to change the carbon balance of the crop via (a) modification of the CO₂ fixation by crop and weed, and (b) changes in soil microbial metabolism. The quantification of these losses has become important for national greenhouse gas budget reporting under the Kyoto Protocol. Thus, one aim of the CarboEurope Integrated Project (IP) of the 6th European Framework Programme on Research and Development was to provide quantitative estimates of CO₂ budgets and respiration losses from representative croplands in Europe. In contrast to previous studies, which were typically based on manual chamber measurements under partially controlled experimental conditions, the approach taken by CarboEurope IP involved state-of-the-art eddy covariance flux measurements that provided continuous information on ecosystem-scale CO₂ exchange under mainly business-as-usual farming conditions. Hence, our data collection approach follows an ecological survey design, which differs from a manipulative experimental design (see Legendre & Legendre 1998).

In this paper we focus on the impact of management effects on cropland respiration fluxes as observed at the ecosystem or field scale under present-day climate and management conditions. Our analysis is based on all available CarboEurope IP cropland CO₂ flux data during a 4-year period that corresponds to the length of a typical crop rotation period in many European cropping systems. The aspect of full crop rotations is covered in a companion paper by Kutsch et al. (2010 [this issue]), and the full greenhouse gas budget of these sites is addressed by Ceschia et al. (2010 [this issue]).

2. Material and Methods

2.1 Sites and dataset

The carbon flux measured with the eddy covariance techniques (Baldocchi 2003) is the net ecosystem exchange (NEE). NEE is measured on a half-hourly basis together with meteorological variables including photosynthetic photon flux density (PPFD), global radiation, air and soil temperature, volumetric soil moisture content, relative humidity, and precipitation. We used original site data in standardized format as provided by the CarboEurope IP database.
(http://gaia.agraria.unitus.it/database, level 2 data set; see below) from all cropland sites that provided periodic or continuous flux measurements during the 2004–2007 period. These sites cover the geographical area of Central Europe (Figure 1) from south-eastern Spain to the Czech Republic and from Italy to Denmark and Scotland. The western-most parts of the EU, the Adriatic and Mediterranean south-east (Greece and former Yugoslavia), Poland, and the northern limits of agricultural croplands (Sweden, southern Norway) are not represented in this analysis.

Soil organic matter content from the sites providing this information was derived from best available measurements which then were converted to soil C (% by mass).

### 2.2 Data screening

Level 2 data are original data supplied by the principal investigators of each participating site. We used these data as we also required information on extremes in cropland ecosystem respiration \((R_e)\) for the analysis, which are often eliminated from processed data by screening procedures. Data were used without considering quality flags, since these aim to filter out fluxes that were obtained during extreme conditions. Thus, the data screening used for this analysis was carried out in a conservative way that aimed to obtain maximum benefit from the available measured (non-gap filled) data, whilst minimizing the potential of erroneous removal of large respiration flux values that may actually be real. However, it still remained necessary to distinguish between realistic extreme fluxes and aberrant values and the flux data were rigorously screened to remove obvious and likely artefacts, as detailed below.

### 2.3 Determination of \(R_e\)

The main interest of this study was the respiration occurring during daytime conditions \((PPFD > 2 \mu\text{mol m}^{-2} \text{s}^{-1})\). Since it is difficult (if not impossible) to obtain defensible respiration values (mean fluxes and extremes) from \(\text{NEE}\) measurements on the time resolution of individual 30-minute flux values, we used a daily resolution, and only days with at least 10 half-hourly daytime \(\text{NEE}\) estimates as measured by eddy covariance with an ultrasonic anemometer in combination with an infrared gas analyzer (IRGA, see Smith et al. 2010 [this issue], Kutsch et al. 2010 [this issue]).

For each day that met this criterion \(R_e\) was determined using a light response curve for daytime (Gilmanov et al. 2003a, Gilmanov et al. 2003b, Gilmanov et al. 2007). Since the rectangular hyperbola tends to overestimate the physiological parameters (Gilmanov et al. 2003b) due to its inappropriate approximation at the edges (Moffat 2010), we chose to use the logistic sigmoid curve
(Moffat 2010). The logistic sigmoid curve properly describes the different phases of the light response: the linear increase at the onset of light, the transition, and the saturation at high irradiance and is thus a robust model to estimate the daily daytime \( R_e \) even from sparse and noisy data (Moffat 2010). It has the following equation:

\[
\text{NEE (PPFD)} = \text{GPP}_{\text{opt}} \cdot \text{Tanh} \left( \frac{\alpha \cdot \text{PPFD}}{\text{GPP}_{\text{opt}}} \right) - R_{e,\text{dayt}},
\]

where \( \text{PPFD} \) is photon flux density, \( \alpha \) is apparent photon (quantum) yield at low irradiances, and \( \text{GPP}_{\text{opt}} \) is the asymptotic maximum assimilation rate or optimum gross primary production under high light level, and \( R_{e,\text{dayt}} \) is ecosystem respiration rate during daytime, abbreviated as \( R_e \) hereafter. The physiological parameters \( \alpha \), \( \text{GPP}_{\text{opt}} \) and \( R_e \) were obtained by iterative least-squares fitting.

In cases where the nonlinear fit procedure did not converge (Figure 2a, c, e), a linear fit was used (Eugster et al. 2005):

\[
\text{NEE (PPFD)} = \alpha \cdot \text{PPFD} - R_{e,\text{dayt}}.
\]

This function has been shown to provide reliable estimates of \( \alpha \) and \( R_e \) for the linear phase of the light response (Moffat 2010). Such conditions are typical outside the peak growing season, but can also occur with very productive crop varieties during days where the curvature of the light response curve was so small that the nonlinear fit did not converge (Figure 2a, c).

To minimize the potential influence of instrumental offsets producing inaccuracies in the \( \text{PPFD} \) measurements, we applied an offset correction before determining light response curves (16 sites). This was done on a daily basis using the arithmetic mean of the nocturnal data (22–4 hours local time for the same day) in order to determine the offset to be applied to the \( \text{PPFD} \) values for each day. Depending on site, this correction was in the range \(-0.8\) to \(50.9 \mu\text{mol m}^{-2} \text{s}^{-1}\) (overall average correction \(3.4 \pm 2.3 \mu\text{mol m}^{-2} \text{s}^{-1}\)).

The fit of \( \text{NEE vs. PPFD} \) was plotted for each day as shown in the examples in Figure 2 (17,122 days in total). Extreme cases at each site were then visually inspected, and if necessary one or more of the following actions were taken: (a) if random scatter of data points were indicative of instrument or environmental problems, then the day was excluded (118 days or 0.69%); (b) if the fit was dominated by one or very few unrealistically large outliers in the data set for that day, up to 3 such values were marked as unrealistic (250 days or 1.46%) and a new fit was attempted on the
remaining data set (if \( n \geq 5 \)); (c) if questionable variation was seen at high light levels, but a clear linear relationship at lower light levels was found, then the fit was restricted to lower light levels (typically below PPFD of 500 to 1000 \( \mu \text{mol m}^{-2} \text{s}^{-1} \), 28 days or 0.16%); (d) if the linear fit to the data points provided the better fit than the nonlinear fit, the linear model was used to extract \( R_e \) (346 days or 2.02%). This last criterion was typically necessary during the winter season or with bare soil conditions (Figure 2f). This left us with 17,004 days used in this analysis (Figure 3).

In order to obtain daily values of \( R_e \) we assumed that the intercept of each daily light-response curve fit is close enough to the true daily respiration for the present analysis. It is clear that during the night temperatures are lower than during day, such that respiration should be higher during daytime than nighttime. On the other hand, light response intercepts (at zero light level) are strongly determined by early morning and late afternoon conditions and thus in principle should be rather representative for 24-hour mean \( R_e \). The use of daytime data for estimating \( R_e \) has advantages compared to using nocturnal data. It was shown by van Gorsel et al. (2008) that nocturnal data can be highly uncertain. Our choice to exclude such data from our analysis should therefore improve the robustness of our findings presented in the following. In addition recall that \( R_e \) estimated from light response curves is a flux density measured in \( \mu \text{mol m}^{-2} \text{s}^{-1} \) and thus can be considered the best estimate for \( R_e \) at the daily (24-hour) timescale.

### 2.4 Probability of extreme values

To investigate the statistical distribution of extreme respiration values we used the Gumbel distribution (Gumbel 1958), which is also known as extreme value type I distribution, Fisher-Tippette type I distribution, or double exponential distribution (Haan 2002, p. 132). This is probably the most widely used distribution for analyzing extreme values in hydrology (Maniak et al. 2005). The question asked was: what is the greatest respiration flux density that is expected to occur at least once within a certain time period of measurements? The reasons for using extreme values statistics for addressing this question are (a) because standard ensemble averages do not address statistical extremes, and (b) extremes are always rare by definition, which requires a firm statistical distribution model to assess their probability of occurrence in a robust way.

In mathematical notation (closely following Gumbel 1958), this question is expressed as a probability of occurrence, \( \Pr\{R_e \leq R(T_m)\} \), where \( \Pr \) is the probability function, \( R_e \) is the respiration flux density (one value per day as derived from daily light response curves), and \( R(T_m) \) is the greatest respiration flux expected within a return interval of \( T_m \) years. This return interval is simply
derived from the measured values of daily ecosystem respiration $R_e$ and was determined as follows. All values of $R_e$ were sorted in decreasing order from rank 1 to $N$, such that $R_{m}$ is the $m$th largest value of $R_e$ ever observed within the time period covered by the flux measurements. As $R_1$ was recorded only once during the entire period covered (2004–2007), all $R_e$ values are thus $\leq R_1$.

Hence, $R(T_m) = R_1$ for the site-specific time period $T_m$ covered with data. If $T_1$ is the full time period with data of a specific site, then the return period $T_m$ is simply

$$T_m = (N+1) / (m \cdot d_{yr}),$$

where $d_{yr}$ is the number of days within one year (365.25 yr$^{-1}$), which needs to be introduced into the analysis to yield $T_m$ values in units of yr. The probability of occurrence of $R_m$ is then expressed as a simple function of $T_m$, using the

$$\Pr\{R_m \leq R(T_m)\} = 1 - 1/T_m = 1 - m \cdot d_{yr} / (N+1).$$

The assumption is that extreme values follow a double exponential distribution of the type

$$G(x) = \exp\{-\exp[-(x - a) / b]\},$$

where $x$ is $\Pr\{R_m \leq R(T_m)\}$, and $a$ and $b$ are the location and scale parameters of the Gumbel distribution $G(x)$, respectively (see e.g. Haan 2002, p. 132). If this is true, then the sorted values of $R_e$ as a function of $x$ should fall on a straight line if a logarithmic $x$-axis is chosen. In cases where the empirical distribution of extremes in $R_e$ follows a different form, this should be evident as a curvature in the graphical display of the data (see Results section). In practice, a linear regression is used:

$$R_{Tm} = \alpha_0 + \alpha_1 \ln T_m,$$

where $\alpha_0$ and $\alpha_1$ are the intercept and slope of this linear regression with the logarithmic return interval. Since the intercept $\alpha_0$ is in fact the value for $\ln T_m = 0$ (which is $T_m = 1$ yr$^{-1}$), we will use the term “yearly maximum $R_e$” instead of intercept to avoid unnecessary confusion with the interpretation. The slope $\alpha_1$ can be similarly confusing, as it expresses the expected increase in yearly maximum $R_e$ with increasing duration of measurement as a value for each $e$-folding of sampling time (which means 2.718 times the longer period). We thus converted $\alpha_1$ to increases for each doubling of measurement period, which is $\alpha_1 \ln 2$, and named it “two foldrate of maximum $R_e$.”
In simple words, a Gumbel plot is a scatter plot of daily values (respiration rates in our case, or river discharge in Gumbel's examples) as a function of probability of their occurrence. The variant of the graphical display of the Gumbel plots that was used here follows that used by the Geological Survey (Gumbel 1958, p. 177). That is, the probability values from Eq. (3) are not directly shown, but \( T_m \) is shown instead on a logarithmic \( x \)-axis, whereas \( R \) is plotted on a linear \( y \)-axis. In contrast to hydrological records, the CarboEurope IP cropland flux time series are far from ideal with respect to gaps in the data due to instrumental breakdowns as well as data rejected because of limitations that are inherent in the eddy covariance approach (e.g. low wind speeds, or rainy periods with open-path IRGAs; Osborne et al. 2010 [this issue]). Therefore, we had to decide how to determine \( T_m \) in case that there were data gaps. Since we have only used extreme value statistics to assess how large the largest \( R_e \) might be (for all other aspects we use standard statistics in this paper), we used the definition of \( T_m \) in the strict sense expressed in Eq. (2). This means that we did not correct for the fact that the available and accepted data from the flux measurements covered a longer period than \( T_1 \). This was done deliberately because it allows us to firmly state that all \( R_e \) values with a specific return period should, by definition, be below the upper boundary of the values determined \( \text{via} \) the Gumbel plot approach.

Our use of Gumbel plots for assessing extreme values in ecosystem-scale flux measurements extends this statistical approach beyond hydrology, where it is well established. As a typical application Gumbel (1958) used the distribution of yearly maximum of daily peak river flows, which is quite similar to the application here with daily estimates of \( R_e \). Haan et al. (2002) (page 132) summarizes the three assumptions made by Gumbel (1958), which are also appropriate for this study: (1) the distribution of daily \( R_e \) (the parent distribution) is of the exponential type, (2) \( n=365 \) is a sufficiently large sample for assessing the yearly maximum, and (3) the daily values are independent of each other. According to Haan et al. (2002) the first and second assumptions cannot be checked because the analytical form of the distribution of discharges (and in our application of daytime \( R_e \)) is unknown. Moreover, the third assumption is clearly not true, but experience from hydrology shows that the use of the Gumbel distribution for daily discharges has been reasonably good in practice (Haan et al. 2002, p. 132).

Before carrying out extreme value analysis a supervised iterative screening of spurious values and outliers was made. At each site days where the light response fit yielded \( R_e > 9.5 \ \mu \text{mol m}^{-2} \text{s}^{-1} \) all 30-minute flux values that were used for the light response curve fitting were carefully inspected (see examples in Figure 2). Obvious outliers were removed and the fit was repeated. Days where no
light-response pattern was found by visual inspection were eliminated from the analysis.

2.5 Management information

Management information was extracted from the data files described in Ceschia et al. (2010) [this issue] for the sites where detailed data are available, and from the general information files available from the CarboEurope IP data base for other sites. Because no information was available on the exact hour of these managements and whether or not flux measurements were correctly continued, we excluded the day of management in our analysis of management effects. In summary, 15 out of 21 cropland sites that measured CO$_2$ fluxes also provided such information (Table 1). The terminology used was harmonized, as far as possible, to yield the largest possible groupings with the same type of management. In particular, tillage and ploughing were grouped into four categories and used the words “tillage” for shallow mechanical disturbances that does not entirely invert the top-soil layer (depths of 10 cm and 15 cm), and “ploughing” for moldboard ploughing (depth of 15 cm and 30 cm or more). A special type of tillage of rice paddies in Spain is called “fangeo” (Figure 4). Fangeo is a Spanish term that refers to tillage that only aerates the water saturated soil without mixing it in the way that regular tillage practices do. The tool utilized consists of wheels with empty metal tubes that penetrate into the soil typically up to 40–50 cm, but only up to 20–30 cm at the studied site ESES2. This operation is performed during the colder fallow season, when the site is flooded, i.e. in the cold season from November to February. In addition to this very crop-specific management type there are several others that are not only specific to some types of crops, but also appear to be specific for certain regional or national traditions that are not further investigated here. Moreover, managements of a certain kind are not independent of each other. For example, moldboard ploughing is often followed by shallow-depth noninversion tillage/harrowing, which is followed by sowing. These were, in most cases, implemented within a few days, and typically within less than 1–2 weeks, so that any time-series analysis focusing on one specific type of event is automatically confounded by subsequent managements that are in turn related to the previous management.

The general understanding of ecological survey analysis is important: these managements considered in our analysis do not represent treatments which are compared against a control (“no treatment”) case as would be done in a manipulative experiment study (the other general class of statistical sampling designs, see Legendre & Legendre 1998).
2.6 Meteorological information

In order to characterize and compare the meteorological conditions at the various measurement sites, annual means of air temperature and the precipitation sums were used as available on the CarboEurope IP database (http://gaia.agraria.unitus.it/database). For the integrative climatic comparison of sites it became clear, however, that the information available did not cover at least one full year's time period and for sites that did not measure during the winter, no adequate annual means could be derived from the meteorological data available in the CarboEurope IP database. Thus, for sites CZcrop, DKFou, UKESa and UKHer, we retrieved long-term climatic information from the database provided by Müller (1996), and compared the monthly averages with the data available on the CarboEurope IP database. Then, we scaled the annual mean values provided by Müller (1996) accordingly. In this way, a wetter than average year during the few months covered by these sites is expressed by wetter annual means in the comparison. In the case of the Dutch sites, precipitation data from the nearest Dutch KNMI weather stations for the specific year were provided.

For comparison of daily $R$, with meteorological data, we computed the daily average for the same selection of hours of day with $PPFD > 2 \mu\text{mol m}^{-2} \text{s}^{-1}$ that was used for determining $R_e$.

3. Results

As mentioned in the Material and Methods section our analysis is based on daily respiration fluxes obtained from daytime light response curves. We used robust statistics (median values with interquartile range etc.) in our assessment of cropland respiration response to temperature and the influence of management events on respiration rates. Only as a special aspect will we focus on extremes in respiration at the end of the Results section. Thus, methodical knowledge about analyzing the probability of extremes is only needed for an understanding of the last subsection “Extremes in cropland ecosystem respiration”.

3.1 Cropland respiration response to temperature

All cropland sites show the typical exponential increase of $R_e$ with increasing air temperature (Lloyd and Taylor 1994; Figure 5). Relationships with soil temperature measured near the surface at sites where such values are available are very similar (data not shown). Since using soil temperature
in place of air temperature would reduce our data basis by another 8%, we used air temperature as a predictor for $R_e$. This relationship is valid at the lower range of temperatures experienced at each site. At higher temperatures, the trend differs among sites. Most sites exhibit a change from an exponential increase of $R_e$ with temperature towards an asymptotic upper limit (e.g. FRLam, FRGri, CHOe2). At other sites, a clear decline of $R_e$ at the highest temperatures was observed either in the top temperature class (e.g. ESES2, ITBCi, DEKli, NLDij, DKRis) or over more than one class of highest temperatures (e.g. CZcrop, FRAur, FRAvi, NLVre). These declines at the higher temperatures is indicative of either water deficits during the active phase of vegetation growth, or for croplands in particular, because of the coincidence of senescence and harvest with peak summer conditions where temperatures are highest. Some inconsistent behaviour was found with a few sites where there were more limited data (e.g. UKHer, DKFou). A noteworthy special case is the rice paddy field, ESES2, which shows quite a different temperature response than the other sites (Figure 5). However, this can be explained by the typical rice paddy management that includes flooding. Obviously, such a flooded paddy environment creates anoxic conditions that largely suppress $R_e$ at lower temperatures.

The highest respiration rates at a given temperature were not found at the sites that experience warmer climate, but at the northernmost site UKESa (Figures 5 and 6) with higher precipitation amounts than the average European cropland sites (Figure 1). From the five southernmost sites (ESES2, ITBCi, FRLam, FRAur, FRAvi; Figure 6) only three sites (ITBCi, FRAur, FRAvi) had more than ten days of respiration estimates in the highest temperature class during the full period (29–31°C). Of those, the two French sites exhibit a decreasing respiration rate at daily mean temperatures above 23°C, but with an increase again in the highest temperature class (Figure 6). In contrast, this early decrease of respiration with increasing temperatures is not found at the ITBCi site, but a very large increase between 21 and 27°C, followed by a consistent decrease at the highest temperatures (Figure 6). The main difference in these southern sites is in annual precipitation (Figure 1). ITBCi receives well above 1000 mm, mainly in the winter, with a clear summer minimum during which time temperatures are highest. The French sites receive well below 1000 mm, with smaller differences in monthly precipitation, and thus a longer, but typically less severe, water deficit during the summer. The Lamasquère site is located in an alluvial valley and is bordered by two rivers. Therefore the soil moisture content is never as low as on the Auradé site located in a hilly area only 12 km away. This difference in soil moisture probably causes differences in soil respiration (i.e. higher respiration rates at Lamasquère). Another possible cause for differences in ecosystem respiration between Auradé and Lamasquère for high temperature classes
(during the summer), is that the summer crop grown at Lamasquère (maize) has a much higher biomass than the sunflower crop grown at Auradé.

3.2 Management events

Of the 21 CarboEurope cropland sites (Figure 3), a subset of 15 sites (Table 1) also provided full or partial information on management activities. During the four years 2004–2007, data on a total of 446 management events were documented (Figure 4, Table 1) for a detailed investigation of their impact on cropland respiration (Figures 7 and 8). In two cases, hail during severe summer thunderstorms partially shredded the potato crop at the Swiss CHOe2 site (5 July 2006), and maize at the German DEKli site (20 July 2007). These two events are also included here for reference – although hail is not a management type – since they had a similar effect on ecosystem respiration as mulching or non-inversion tillage.

The management events are loosely grouped on the basis of the apparent similarity of the activity (except for the last group which also includes the digging of drainage grips, residue burning after rice, and hail; Figure 4). Although the heterogeneity in the CarboEurope IP cropland data set does not allow for a more detailed grouping, it should be noted that many of the reported activities are intimately associated with local traditions, customs, habits, and environmental constraints that are beyond the scope of this paper. The few management types that provide sufficient statistical coverage were divided into early season and late season interventions (shallow non-inversion tillage down to 10 cm, inversion ploughing to 30 cm and more, and sowing) since their distribution over the year (Figure 4) clearly indicates they are related to summer and winter crops. The first of July was used as the threshold to distinguish early events from late events.

Figure 7 shows relative changes in ecosystem respiration as box plots (McGill et al. 1978) for each management activity. Three time horizons of ±7 days, ±14 days, and ±28 days are shown, sorted by median relative changes on the ±28 day time horizon. In each box plot, the ecosystem respiration observed during the respective number of days after the day of the management event is compared with that observed during the same number of days prior to the event. A two-tailed Student's t-test was used to examine the impact of each management activity at each site, and the numbers of activities with significant differences (p < 0.05) are reported in brackets behind the total numbers of activities, where there are sufficient data, in Figure 7. This includes the effect of changing temperatures (see below). The range of management activities where the median ecosystem respiration did not change more than ±10% at the ±28 day time horizon is marked with two...
horizontal broken lines in Figure 7. The activities within this ±10% range were: late-season sowing, late-season moldboard ploughing (≥ 30 cm depth), application of organic fertilizer, rolling, weeding, shallow moldboard ploughing (15 cm), and grass-cutting for hay in the crop rotation (ITBCi, Table 1). Thus, there is no indication that late-season ploughing down to 30 cm and more (–7%, n=13) or shallow-depth moldboard ploughing down to 15 cm (+1%, n=7) are prime candidates for substantial carbon loss under current cropland management practice in Europe, as represented by the CarboEurope IP cropland sites. This contrasts with other studies where factorial experiments (with control treatment). We interpret this by the fact that a significant proportion of these treatments took place soon after harvest (cf Fig. 4) and therefore the observed reduction in $R_e$ could be largely due to suppression of autotrophic respiration and/or burying of harvest residuals biomass. However, early-season shallow tillage (10 cm) and moldboard ploughing (≥ 30 cm depth) substantially increased median respiration rates by +83% (n=8) and +29% (n=4), respectively, on the ±28 days horizon (+38% and +16%, respectively, on the ±7 day horizon). Besides early-season tillage/ploughing the largest increases in ecosystem respiration were found after application of pesticide (+47%), herbicide (+44%), mineral fertilizer (+36%), and fungicide (+26%) applications (the largest values were found after application of growth regulators and row cultivation; these estimates are however only based on one single case at one site and thus are statistically not very robust, but a detailed interpretation was presented by Moureaux et al. 2008). In general, a significant part of the fungicide, pesticide, and herbicide applications take place when the crop vegetation is actively growing, the observed increase in $R_e$ in the ±28 day comparison is most likely related to an increase in autotrophic respiration due to crop development.

The strongest decrease in respiration rates was found to be related to flooding and controlled burning of the residues of rice 1–2 weeks after harvest. A very important difference was found between flooding (–74%, –65%, and –57% in the ±7, ±14, and ±28 day comparison) and irrigation (+29%, +35%, +19%) that is adequately documented with available data in the CarboEurope IP data set (7 cases, of which 4 show significant differences on the ±28 day time horizon; Figure 7). Flooding inhibits respiration due to anoxic soil conditions in combination with the moderate temperatures when flooding takes place (May and October, Figure 4) and limits diffusion of $CO_2$ in the water saturated zone, whereas irrigation boosts microbial activity at sites which would experience a strong reduction of heterotrophic respiration due to naturally dry and warm climates.

### 3.3 Influence of soil carbon content

Of special interest is the question whether soil carbon content has a direct influence on $R_e$ from the
observed managements. The BELon site received 66 g C m⁻² yr⁻¹ as lime in 2003/2004 just before sugar beet was grown, and DEKli got 210 g C m⁻² yr⁻¹ as lime marl before the project started. Dutch sites received 6% CaCO₃ mixed with mineral fertiliser, whereas all other cropland sites did not receive special lime applications (Table 1). Soil C content ranged from 0.8 to 5.8% (mean ± SE is 2.1 ± 0.4%). To explore whether soil organic C content (SOC) rather than management could be a driving factor of $R_e$ we made a correlation analysis between SOC and four variables that were determined for each management type: (a) respiration flux density before and (b) after the management, (c) difference in respiration flux densities, and (d) ratios of respiration flux densities after management with respect to before management (Figure 9). Corresponding with Figure 7 this was done for a period of 7, 14, and 28 days before the date of management intervention in comparison with a period of same length after the management. Figure 9 only shows the combinations with more than 10 data points.

Overall, a pattern similar to a random outcome is seen in Figure 9: 42 of 72 correlations (58%) show negative responses to soil carbon content. Statistically significant correlations are found in 10 cases (black bars in Fig. 9; 14% of all correlations) of which 2 show significant dependencies of respiration fluxes already before the respective management treatment and should thus be interpreted with caution. Tillage down to 10 cm (7 day and 28 day reference periods) and late sowing (28 day reference period) suggest a net decrease in respiration with treatment. In the case of tillage this is finding is strongly biased by NLLan with it's high SOC of 5.7%. If this site is excluded from the analysis, the reduction in respiration becomes insignificant. In contrast, the negative correlation between late sowing and respiration fluxes also holds for sites with SOC below 3% (p = 0.005), but only if a ±28 day period is considered. This strongly suggests that surface albedo feedbacks in combination with the declining insolation at the end of the growing season should be investigated in more detail to explore the potential of late sowing in climate mitigation questions. With climate warming it is expected that there is a potential for later sowing of winter crops.

The positive correlation between pesticide application and increase in respiration flux (p = 0.03 for the ±7 day comparison) is primarily determined with the ESES2 rice paddy site with 3.7% SOC. If this site is excluded, then the relationship becomes insignificant (p = 0.92). In summary, in our site survey of cropland respiration fluxes it appears that SOC is not primarily responsible for the management effects on respiration that we found. Since only two sites with >3% SOC participated in this study (ESES2 and NLLut), the effect of high-organic vs. low-organic mineral soils could
however not be addressed in full detail here.

3.4 Separating temperature effect from management effect

In most cases, there is a confounding effect of seasonal changes in temperature, which is clearly revealed by separating early-season from late-season treatments in Figure 7. Also fertilizers are typically applied early in the season (Figure 4), thus a comparison from conditions before the event and after the event also tend to be biased by changes in temperature. On the other hand, crops are typically harvested during peak season (winter crops, maize for silaging) to late season (potatoes, rice, maize), so that one must expect opposing effects of decreasing temperature, even in cases where the net effect of management alone might have increased $R_e$.

To address this particular confounding effect related to temperature, we selected the few events that have sufficient statistical coverage ($n \geq 5$ events reported from 1 or more sites) and eliminated the influence of temperature to produce Figure 8 (see Appendix for details). The $\pm 28$ days comparison (Figure 8, right) of the corrected results reveal a similar picture as those shown in Figure 7, except for irrigation, which clearly has the largest effect, not only in relative terms (+23%, Figure 8a), but also in absolute terms (+1.3 $\mu$mol m$^{-2}$ s$^{-1}$, Figure 8b). The group of chemical treatments with herbicide (+0.40 $\mu$mol m$^{-2}$ s$^{-1}$ or +22%), pesticide (+0.36 $\mu$mol m$^{-2}$ s$^{-1}$ or +17%), and fungicide (+0.36 $\mu$mol m$^{-2}$ s$^{-1}$ or +12%) applications leads to similar relative increases in respiration rates, but the absolute increase in these fluxes is only one third to one quarter of that observed within 28 days after irrigation. It is also worth noting that the increase in respiration of this group is not an immediate effect ($\pm 7$ days median changes are all within $\pm 10\%$), which contrasts with mechanical disturbances such as late-season moldboard ploughing ($\geq 30$ cm depth) and harvest, where rapid relative changes are apparent in the short-term comparison (+0.44 $\mu$mol m$^{-2}$ s$^{-1}$ or +43% and +0.39 $\mu$mol m$^{-2}$ s$^{-1}$ or +14%, respectively, on the $\pm 7$ days horizon).

A special case is shallow-depth moldboard ploughing (15 cm depth), which yields similar results as flooding. This is clearly due to the close linkage of the two treatments which are only done at the ESES2 rice paddy site (Table 1). Although statistically quite clear for this one site, this cannot be considered a general finding for European croplands. In contrast, late-season tillage to 10 cm is represented by 9 sites, and thus the finding that its effect on respiration losses is highly variable but with a relatively small impact (+0.09 $\mu$mol m$^{-2}$ s$^{-1}$ or +12%, +0.10 $\mu$mol m$^{-2}$ s$^{-1}$ or +5% in the $\pm 7$ and $\pm 28$ days comparison, respectively, Figure 8) is statistically quite robust and likely representative for most of Europe.
In all comparisons, a huge variability between events of the same type (Figures 7 and 8) was observed that was not simply attributable to differences in the site conditions. Even at individual sites, the variability among management events of the same type is large. In the 7-day comparison >50% of the management activities in 6 out of 12 types (Figure 8a) led to a net increase in daily ecosystem respiration, and only in two types (irrigation and late-season moldboard ploughing ≥ 30 cm depth) did more than 75% of all events lead to an increase in daily ecosystem respiration. It is, therefore, important to recognise, that (a) some management types that increase respiration rate at one site might actually reduce respiration rate at another site, and (b) even if respiration rates are increased then this does not necessarily imply that the increases are leading to substantial carbon losses. On the basis of this analysis it was therefore of interest to address the question of whether there might be even shorter-term peaks in respiration that might have been missed in our analysis covering the 7 to 28-days timescale. For this, we analysed the statistical distribution of extreme values in ecosystem respiration.

3.5 Extremes in cropland ecosystem respiration

The Gumbel plot approach (Gumbel 1958, Maniak et al. 2005) was used to determine the extreme values in daily ecosystem respiration rates of all 21 cropland sites. This allows sites with shorter measurement duration to be compared directly with those that cover most of the 4 years of this study. Figure 10 combines the Gumbel plots of all sites in one single graph. The interpretation is as follows. Each point on a line of a specific site shows the maximum respiration rate observed at a given return interval. Thus, the return interval corresponds to the probability of occurrence of a respiration rate smaller or equal to the rate given by the line. The longer the observation period, the higher the maximum respiration rate that might be expected on purely statistical grounds. For reference, the theoretical curvatures (but not location and scale) of three frequently used statistical distributions are shown in the inset in Figure 10: (1) for the log-normal distribution, (2) for the double exponential distribution (known as the Gumbel distribution, see e.g. Maniak et al. 2005), and (3) for the normal distribution.

In general, the sites that cover more than 1 year with continuous flux data correspond quite well with the expected Gumbel distribution. The sites with the lowest probability of high respiration rates (that is, long return intervals for higher respiration rates) such as ESES2, FRAur and BELon, tend to be subject to a distribution closer to the normal distribution, although the normal distribution is a rather rare case in extreme statistics (Gumbel 1958). At the upper end of the distribution, the UKESa and ITBCi sites show a curvature which is indicative of a log-normal distribution of
extremes.

Overall, however, the Gumbel distribution adequately describes the statistical distribution of extreme ecosystem respiration values. This facilitates a highly aggregated comparison of maximum cropland respiration rates for all sites using the two parameters of the Gumbel distribution for each site. In the log-linear display in Figure 10, we thus fitted a straight line by least-squares fitting to the data points (circles) with return intervals of 3 months or longer (note that daily \( R_e \) are autocorrelated, and thus a lower threshold of 3 months for the return interval minimizes the influence of this autocorrelation in our fits with the Gumbel distribution). The significance levels for the intercept and slope of these straight lines was better than \( p < 0.014 \) and \( p < 0.087 \), respectively, and 95\% of all sites had an intercept and slope significant at \( p < 0.0001 \) and \( p < 0.004 \), respectively.

The two parameters of these lines of best fit were then correlated with the available climatic information, of which only annual precipitation showed a statistically significant correlation with one or both parameters (Figure 11). The yearly maximum \( R_e \) was highly significantly correlated with annual precipitation (\( p = 0.003 \)) whereas the two fold rate of maximum \( R_e \) was only marginally correlated with annual precipitation (\( p = 0.088 \)). If the two sites with highest annual precipitation (CHOe2, ITBCi) are removed to test the robustness of these fits, the correlation between yearly maximum \( R_e \) and precipitation remains significant (\( p = 0.023 \)), whereas the two fold rate of maximum \( R_e \) becomes insignificant (\( p = 0.194 \)). Although ecosystem respiration at each single site was found to be strongly related to air temperature (and thus soil temperature) as stated earlier, the Gumbel parameters did not show any correlation with annual mean temperature of the sites. Thus, the interpretation of our finding is that temperature is the first climatic driver on the local scale for average ecosystem respiration, whereas the differences in extreme respiration rates between sites is more strongly related to differences in precipitation and thus soil moisture status. In other words: the highest daily respiration rates do not occur at the highest temperatures, because respiration becomes limited by lack of soil moisture at most sites. Thus, extremes in \( R_e \) across Europe (at daily resolution) are most likely limited by moisture (expressed by annual precipitation in this analysis), not by temperature.

The two Gumbel parameters are highly intercorrelated (Figure 12) and thus they cannot be interpreted as independent from each other. This means that sites experiencing relatively high respiration rates in comparison to other sites, also tend to have the steepest increase of extreme daily respiration rates with increasing duration of the measurements. This finding is quite consistent among CarboEurope IP cropland sites. Moreover, it does not primarily depend on the length of the
overall time series. This suggests that it is very unlikely that sites which generally have low respiration rates will have exceedingly high respiration rates as a result of certain specific management events. This interpretation is correct under the assumption that unexpected large extremes in $R_e$ (which were not found in our dataset) would follow a different statistical distribution than the generally observed daily $R_e$.

### 4. Discussion

#### 4.1 The effects of tillage and ploughing

The comparison of ecosystem-scale eddy covariance flux measurements with small-scale chamber measurements (Reicosky and Lindstrom 1993, Reicosky et al. 1995, Prior et al. 1997, Reicosky et al. 1997, Morris et al. 2004, Reicosky et al. 2005, Johnson et al. 2006, Gesch et al. 2007, Reicosky et al. 2007, La Scala et al. 2008, Reicosky et al. 2008) is not quite straightforward, but essential to increase our understanding of management effects on carbon losses from croplands. Since eddy covariance flux towers are rather bulky and need to be removed during certain management events (Osborne et al. 2010 [this issue]), or measurements are disturbed (e.g. by CO$_2$ from engine exhausts during mechanical field work), we had to exclude the day of management from our analysis. Thus, we can only compare changes in respiration fluxes that last longer than 1 day. This means that we may have missed a number of transitory fluxes that last for less than 1 day, such as for example diffusionaly-derived fluxes that follow mechanical disturbance. Moreover, in field-scale experiments as presented here, usually no parallel control plots without the specific management activities are available. Therefore, our approach to compare conditions before each treatment with the conditions after does not exactly match the concept of a controlled experimental design.

Nevertheless, the order of magnitude and the direction of change should be comparable with existing studies. For comparison of the values presented in Figures 7 and 8, we used the empirical models presented by La Scala et al. (2008) and computed the expected relative changes for our 7-days and 28-days comparisons (Table 2). Most of the CarboEurope IP sites and management cases do not reveal an exponential decay of respiration after management, and thus a more intensive comparison with short-term studies (e.g. Gesch et al. 2007) is not possible. Moreover, the day-to-day variation in $R_e$ before and after an event is usually quite large in comparison to the change induced by the event. This large variability has also been found in chamber studies (over 8 days;
Thus, our choice of 7 and 28 days represents short-term effects that could still be resolved by eddy covariance flux measurements (that lack a direct control treatment), and the potential duration over which an effect of treatment possibly could be seen, respectively. It has been speculated in earlier work that there might be a delay between tillage and increases in microbial respiration of roughly 7 days (Hendrix et al. 1988) to 14 days (Buyanovsky et al. 1986). Prior et al. (1997) found similar delays, but associated them with rainfall events during the observation period. As Prior et al. (1997) clearly state, their finding contrasts with that of Reicosky and Lindstrom (1993) who found a depression of $R_e$ during and a few days (<3 d) after rain events. This clearly shows that the high variability of eddy covariance fluxes observed in this study reflects the nature of the combined underlying processes, namely the effect of the management itself together with the changes in weather conditions that follow such an event, which requires a certain level of integration over several days to allow for comparison with other studies.

The expected changes based on La Scala et al. (2008)'s model are +47 ± 5% for rotary tiller tillage (RT), +72 ± 12% for heavy offset disk harrow tillage (HO), +94 ± 10% for inverting disk plough offset disk harrow tillage (DO), and +158 ± 13% for chisel plough tillage (CP) for the 7-days comparison, and +34 ± 8%, +86 ± 23%, +91 ± 28%, and 152 ± 25% for the 28-days comparison, respectively. In our study, CO$_2$ losses from most of our sites were clearly below these estimates (Table 2). Some, but not all early-season tillage/ploughing events reached the same order of magnitude as RT and HO. However, the high values reported for DO and CP treatments could not be generally found in the CarboEurope IP flux data set, except for a limited number of site-specific values (see inter-quartile range given in Table 2).

What differs considerably from earlier studies is that some of the management practices, including tillage/ploughing, actually led to reduced CO$_2$ losses at a considerable number of sites reporting these events (Figures 7 and 8; Table 2). With moldboard ploughing, only moderate increases in respiration rates (+1 to +22%, see Table 2) were found, and if the rates were corrected for concurrent temperature changes, then respiration rates were reduced by –47 to –50%. One potential explanation could be, that some farmers involved in the management of CarboEurope IP sites are well aware of the problem of significant carbon losses during mechanical field work and try to optimize their management to preserve organic carbon and thus soil fertility. Some farmers take care to do only shallow tillage shortly before seedbed preparation when deeper ploughing is not necessary. This interpretation appears realistic at some sites (particularly in Switzerland where there are special requirements of the Swiss Integrative Pest Management system), but was strongly
questioned at other sites in Belgium, France, Denmark, and Ireland where no active attempts of farmers have been observed that could indicate awareness of potential carbon losses during management. With one example it could however be shown that no substantial carbon losses were observed even though the farmer left his field bare for five months after ploughing: Aubinet et al. (2009) found the impact of ploughing to be limited in intensity (1–2 $\mu$mol m$^{-2}$ s$^{-1}$) and duration (not more than 1 day) at the BE-Lon site. In our Europe-wide comparison, the BE-Lon site has a temperature dependency of $R_e$ that is quite representative of the CarboEurope IP croplands (Figure 5), but the extreme value statistics (Figure 10) reveals that the distribution of extreme $R_e$ is at the low end of all sites, and the two fold rate of daily maximum $R_e$ (seen in the very flat slope for BE-Lon in Figure 10) is among the lowest. This indicates that the European average impact of ploughing effects must be above that reported by Aubinet et al. (2009).

Intensive tillage such as ploughing was reported to have a longer-term effect on soil respiration than the 28-day period considered in this study (Chatskikh et al. 2008). This effect is probably related to changes in soil structure, aeration and availability of soil organic matter for microbial turnover. However, such effects could not be estimated in this study, most likely because the effects of tillage on soil heterotrophic respiration was overshadowed by plant respiration. The relatively small effect of ploughing on respiration shown in Figures 7 and 8 compared with other studies (Table 2) may be due to the interacting effects that tillage/ploughing has on vegetation. For example voluntary regrowth can occur quickly (well within the 28 days studied here) at some sites, which consumes part of the soil respired CO$_2$ such that eddy covariance flux measurements observe an apparent reduction in $R_e$. In other cases where inversion ploughing is done on a field with photosynthetically active green plants (e.g. fallow crops), then this may immediately reduce $R_e$ because the contribution of autotrophic respiration is eliminated, whereas heterotrophic respiration is not immediately increased. That bare soil tends to have lower respiration than vegetated soil is not new (e.g. Ding et al. 2007). But such effects are still poorly understood at the agroecosystem level, and might be of relevance when scaling up field-scale flux information to national greenhouse gas inventories. The advantage of eddy covariance flux measurements is that they measure net exchange from an ecosystem, but at the expense of not providing a full insight into each single contributing process (see Smith et al. 2010 [this issue], Desai et al. 2008). A number of supplementary measurements are therefore required to quantify individual processes (see Smith et al. 2010 [this issue]).
4.2 Effects of other management types

For interventions involving herbicide, pesticide, and fungicide applications, almost no effect was found on the 7-days timescale, which would suggest, on average, a neutral effect. But losses were found at the majority of sites in the 28-days comparison, which were very comparable in absolute flux magnitudes (Figure 8b). Most likely, this is an indirect effect that enhances plant growth (reducing stress from pests and fungi), that in turn enhances autotrophic respiration. In fact, laboratory incubations of soils rather indicate a reduction in soil respiration after fungicide applications (Chen et al. 2001, Motonaga et al. 1998). Peak soil respiration was reduced by 30–50% in Chen et al.’s (2001) experiment, and 15 to 32% reduction was reported by Motonaga et al. (1998) for soil microbial respiration. Hence, if $R_e$ increases while microbial respiration is expected to decrease, then a substantial increase in autotrophic respiration is required, which is in agreement with the agronomic concept of applying these chemicals (to increase plant productivity). On the other hand, conventional application of fungicides should not strongly affect the soil organisms, if the application is not immediately followed by rain and if chemicals are not applied in excess amounts.

It however cannot be ruled out that increased $R_e$ is a result of the changes in substrate availability for respiration in the case of herbicide applications, which kills the living organic matter. The resulting debris/litter then becomes an additional carbon pool for decomposing microorganisms. This may also hold for pesticide and fungicide applications. At most sites this alternative explanation is however questionable since it is unlikely that the total amount of living organic matter that is killed in this way is a substantial addition to the carbon pool. Moreover, effects of crop protection (herbicides, pesticides, fungicides) and effects resulting from the use of growth regulators are further confounded by the fact that herbicides are mostly applied very early in the growing season and sometimes even outside of the growing season. In contrast, pesticides, fungicides and growth regulators are mostly applied in the early part of the growing season and may therefore be particularly prone to give an artificial increase in $R_e$ simply because the crop is growing during that period.

It is however not surprising that such chemical treatments do not show an immediate response as compared to physical disturbances such as tillage/ploughing. But we are not aware of any earlier studies that have shown the relevance of chemical managements in croplands for ecosystem-scale carbon fluxes. In principle, the three terms herbicide (treatment against weeds), pesticide (treatment against insects and other pests), and fungicide (treatment against fungi such as those associated with
mould) should be distinct, but some sites reported the combination of fungicides plus insecticides as pesticides, and it cannot be ruled out that pesticide is used as an all-inclusive term (including herbicides and fungicides) by some farmers. In future studies it would therefore be advisable to establish a consistent and clear terminology for all management types in order to reduce the uncertainty of wrong classifications.

Harvesting showed an opposite effect to that of the herbicide applications with an increased respiration on the 7-day timescale, but decreased respiration in the 28-day comparison (Figure 8a). Additionally, the scatter observed in absolute changes in $R_e$ was among the largest within any of the management types (Figure 8b). This is related to the fact that harvest alone does not indicate whether living green plant matter is harvested, or ripe and senescent crops. In the former case, a rapid increase in ecosystem respiration might be expected when the above-ground material is removed, and the root system starts to decay and decompose. If respiration is dependent on immediate photosynthesis there would be a rapid decrease in $R_e$ after removal. Silage cutting reduces respiration rather quickly. In the latter case, senescence processes in ageing roots should already have led to a reduction in physiological activity below-ground, and harvesting also changes the near-surface microclimate in a more or less abrupt manner. For example, when cereals are harvested, the soils become exposed to the sunlight. Depending on the fraction of straw residues remaining on the ground, the albedo might still be high (large amounts) or become much lower (darker soil exposed if no residues besides stubbles are left behind). Vegetation removal leads to higher soil surface temperatures reducing near surface soil water contents over the course of a few days. This tends to first increase $R_e$ with increasing temperature until soil moisture becomes the limiting factor for microbial activity. This then tends to reduce respiration levels below those observed before harvest. The impact of this would be site-specific and show large inter-annual variability, but in less productive years the effects may be quite small. Additionally, the timing for cereal harvesting in summer is often constrained because of logistical as well as economic considerations, and the uncertainty that suitable weather conditions will be maintained. This is exacerbated because of the increasing use of contractors for harvesting. Earlier harvesting leads to cooler temperatures despite soils being exposed to more sunlight after harvest, or wetter soils after rain. Depending on the amounts of rain increases or decreases in respiration are possible.

4.3 Extremes in daily respiration

The three sites with the highest daily maximum respiration rates, UKESa, ITBCi and CHOe2 (Figure 10) are found in climatic regions in Europe with abundant annual precipitation (Figure 1)
that do not typically experience a summer drought. This indicates that over these sites soil moisture should not be an important factor determining soil respiration. At all other sites the lower amounts of annual precipitation (Figure 11) are indicative of drier climates, particularly in the South-West (France, Spain). Although the Gumbel plots (Figure 10) indicated that extreme values in daily respiration rates are comparable between sites, it was not a priori clear that sites with short data coverage and sites with the full 4-year data coverage could be combined in such a way. The successful interpretation of the two Gumbel parameters with climatic information is, however, limited by how far short-term data represent long-term climatic conditions. This limitation could only be overcome by long-term (>10 years) flux measurements. Still, the CarboEurope IP cropland team appears to have been successful in covering a representative range of European cropland respiration fluxes with longer and shorter term flux measurements: the conditions with lowest respiration rates are represented by ESES2 (rice paddy cultivation), FRAur (rapeseed–winter wheat–sunflower crop rotation), and BELon (sugar beets–winter wheat–potatoes; Aubinet et al. 2009, Moureaux et al. 2006), all covering 2–4 years of the full measurement period. At the high end UKESa (winter barley) might be partially biased due to a large data gap in the winter of 2004/2005, whereas CHOe2 (winter barley–winter wheat–potatoes; Dietiker et al. 2010 [this issue]) and ITBCi (corn–fennel with Lolium italicum intercropping) belong to the group of longest cropland measurements with shorter and more evenly distributed data gaps.

The two other sites with high respiration maxima, ITBCi (a wet but warm site in southern Italy), and CHOe2 (a wet temperate climate at the boundary of the geographical distribution of wheat growing), clearly illustrate the need for continued long-term cropland flux measurements, which will be explained using these two sites as an example. The CHOe2 curve appears smooth for return intervals longer than a few months, whereas there is a clear jump in maximum daily respiration rates with return intervals beyond 1 year at ITBCi. In the first case (CHOe2) it appears that a consistent statistical distribution is represented in the data set, but the question arises, why the curve does not follow the expected straight line (variant 2 in the inset in Figure 10) as would be expected from the considerations made by Gumbel (1958). In the second case (ITBCi) the two largest extremes do not fall onto the line of best fit for the remaining data points. This either indicates (a) that two specific days within the data set should be associated with a much longer return interval than what the 4-year data set actually covers, or (b) the true distribution of extreme values does not follow the exponential Gumbel distribution, but rather a log-normal distribution, which would raise the same question as for CHOe2. Since such extreme values are always only covered by exactly one event within the full observation period, only longer-term measurements can firmly establish
whether our interpretation—that it is very unlikely that sites which generally have low respiration rates will have exceedingly high respiration rates as a result of certain specific management events—is correct.

5. Conclusions

Our analysis of cropland respiration rates at daily resolution showed clear and mostly consistent effects of managements at time scales of 7 to 28 days. The general expectation that tillage/ploughing leads to increases in respiration rates has been confirmed for inversion ploughing (≥30 cm depth) and early-season tillage (10 cm depth). The magnitude of the impact is, however, rather small and comparable with the lower end of the range given in the scientific literature. Our statistical analysis of extreme respiration rates confirmed that there are no signs of unexpectedly high respiration rates found in the CarboEurope IP data set.

The far stronger influences have been found for rice paddy flooding (inhibition of respiration due to anoxic soil conditions) and irrigation (boosting microbial activity at sites which would otherwise experience a strong reduction in heterotrophic respiration due to naturally dry and warm climates).

With respect to continental-scale greenhouse-gas budgets from agroecosystems, the consistent increase in respiration rates after herbicide, pesticide, and fungicide applications deserves more attention. Our results suggest that the effect of such management types – which are widespread in all areas of Europe – may have a similar influence on climate change (via greenhouse-gas induced radiative forcing) than tillage and ploughing. Regarding mitigation options for European croplands relative changes in respiration rates are less important than absolute changes. Early sowing – which can be considered a logical adaptation to a warmer climate – and shallow inversion ploughing (down to 10–15 cm) instead of late-season plowing down to 30 cm reveal the highest mitigation potential. This positive potential could however easily be used up by an extension of irrigated cropland areas in Europe if climate change is associated with reduced precipitation during the growing season.
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Appendix

Temperature correction for management effects

In Figure 8 we eliminated the influence of temperature as compared to the analysis presented in Figure 7. This was only possible for the few events that have sufficient statistical coverage (n ≥ 5 events reported from 1 or more sites). The correction was done in a four-step procedure (steps 2–4 are shown in the example in Figure A1): (1) For each event we determined the site-specific empirical cumulative distribution function (ECDF) for daily respiration fluxes within the observed temperature range, using all available data. (2) Then we computed the site-specific quantile of mean respiration rates measured before each event, $Q_{R_{\text{before}}}$ (3) Finally, we back-calculated the ECDF for the temperature conditions after the event and (4) predicted the respiration value $R_{expected}$ for the same quantile $Q_{R_{\text{before}}}$. This can be considered a best estimate that corresponds to the expected respiration that would be observed in the absence of any influence of management, that is, the change that can be explained purely by changes in temperature. The difference between the mean respiration actually observed during the period after the event and $R_{expected}$ is then considered the net effect of the management event, as shown in Figure 8. This exercise of combining respiration data with temperature data, however, reduced the useful data to 12 sites with 335 events. Also at some sites, not all days with respiration data have corresponding measurements of temperature. Air rather than soil temperatures were used for this analysis because they show better data coverage and reliability. We also did not find relevant differences in the temperature response curves based on air temperatures (Figures 5 and 6) when compared to the same curves with top-soil temperatures (not shown).
Management Effects on European Cropland Respiration (Tables)

Eugster et al.

February 11, 2010

Table 1: Site specific management events (number of events included in analysis during years 2004–2007), sorted by total number within each event type.

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<th>DEKli</th>
<th>ESES2</th>
<th>FRAur</th>
<th>FRGri</th>
<th>FRLam</th>
<th>IECa1</th>
<th>ITBCi</th>
<th>NLDij</th>
<th>NLLan</th>
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* BELon and DEKII received lime applications in the year before the project began, but not during the project period.
* Dutch sites receive 6% CaCO$_3$ mixed with mineral fertilizer; other sites did not receive lime applications during the project duration.
Table 2: Relative increases in ecosystem-scale respiration fluxes (% increase with respect to conditions before treatment or no-tillage treatment) after tillage/ploughing events. The results from this study are presented for the two time periods (±7 and ±28 days) and, where appropriate, with and without temperature correction.

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<td>Morris et al. (2004)</td>
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<tr>
<td>Disk harrow – residue field</td>
<td>42 days</td>
<td>69</td>
<td></td>
<td>Morris et al. (2004)</td>
</tr>
<tr>
<td>Heavy offset disk harrow tillage (HO)</td>
<td>7 days</td>
<td>72</td>
<td>60 ... 84</td>
<td>La Scala et al. (2008)</td>
</tr>
<tr>
<td>Early-season ploughing (noninverting), 10 cm depth</td>
<td>±28 days</td>
<td>63</td>
<td>36 ... 172</td>
<td>this study</td>
</tr>
<tr>
<td>Spring tine cultivation done twice – residue field</td>
<td>42 days</td>
<td>85</td>
<td></td>
<td>Morris et al. (2004)</td>
</tr>
<tr>
<td>Heavy offset disk harrow tillage (HO)</td>
<td>28 days</td>
<td>86</td>
<td>63 ... 109</td>
<td>La Scala et al. (2008)</td>
</tr>
<tr>
<td>Inverting disk plough offset disk harrow tillage (DO)</td>
<td>28 days</td>
<td>91</td>
<td>74 ... 109</td>
<td>La Scala et al. (2008)</td>
</tr>
<tr>
<td>Inverting disk plough offset disk harrow tillage (DO)</td>
<td>7 days</td>
<td>94</td>
<td>84 ... 104</td>
<td>La Scala et al. (2008)</td>
</tr>
<tr>
<td>Chisel plough tillage (CP)</td>
<td>28 days</td>
<td>152</td>
<td>127 ... 177</td>
<td>La Scala et al. (2008)</td>
</tr>
<tr>
<td>Chisel plough tillage (CP)</td>
<td>7 days</td>
<td>158</td>
<td>144 ... 171</td>
<td>La Scala et al. (2008)</td>
</tr>
</tbody>
</table>

* Values corrected for concurrent temperature changes (see text for details)

# This treatment is specific to the ESES2 rice paddy culture and strongly reflects the effect of flooding

Mean and range given by ±standard error is reported

Mean over 42 days computed from oxidation potential in Morris et al. (2004), Table 1
Management Effects on European Cropland Respiration (Figures)

Eugster et al.

February 11, 2010

Figure 1: European cropland sites included in this study. Background map shows annual precipitation of 2002. Base map and precipitation data © 2010 swisstopo (JD082776).
Figure 2: Examples of cropland light response curves. Almost linear curves at the Spanish site (a, b) and at the Belgian site (b, c) from two subsequent days were selected, where in the first case the light response curve fit of Eq. (1) failed due to lack of curvature (a, c), whereas it was successful on the following day (b, d). The example (e) shows a linear fit for a day where no light response was found, and (f) shows an example where a clear maximum assimilation at PPFD >750 μmol m⁻² s⁻¹ was found.
Figure 3: Availability of ecosystem respiration data for each month of the period 2004–2007 of all 21 CarboEurope IP cropland sites. The size of each bar indicates the relative share of days that had a sufficient number of 30-minute fluxes of sufficiently high quality to extract daytime respiration from a light-response curve fit (see text for details). The largest bars correspond with 100% of all days of the respective month, whereas thin lines show the 0% level for each site.
Fangeo is a management practise in rice paddies that mixes the topsoil with water. Although hail is not a management event (CHOe2 and DEKli sites), it had a similar effect on ecosystem respiration as management. Ploughing denotes inverting mouldboard plough tillage down to ca. 15 cm and 30 cm or more (max. 45 cm). Tillage refers to shallow-depth mechanical treatments with chisel plough, harrow, or rotary disk.

Figure 4: Stripchart of management events during the course of the year documented at 15 CarboEurope IP cropland sites during the period 2004–2007 (n = 445 events in total).
Figure 5: Ecosystem respiration, median values for 2°C air temperature bins. Only bins with ≥10 days (not necessarily consecutive days) with available respiration estimates are shown.
Figure 6: Ecosystem respiration of the northernmost site (UKESa) and the five mediterranean sites, boxplots for each 1°C air temperature bin.
### Figure 7: Change in ecosystem respiration of 15 European croplands as a function of management activity (n = 384 events in total). Each panel shows the relative change in ecosystem respiration rate after the management activity, with respect to the respiration level before that activity (the day of management is excluded). Symmetric time periods of 7 (left), 14 (center), and 28 days (right) are shown. The numbers to the right side of each panel show the total number of cases of the respective activity that was available for analysis, and the numbers in parentheses show how many cases showed a significant ($p < 0.05$) difference of means in the direct comparison via Student's t-test. Grayshading of boxes is related to number of events. Vertical lines are drawn at −50, −20, −10, 0, 10, 20, 50, and 100% change. Each boxplot shows the median (bold line), the inter-quartile range (box) and the total range (whiskers and circles). In cases where the total range exceeds 1.5 times the inter-quartile range, whiskers are restricted to 1.5 times the inter-quartile range, and outliers are displayed as circles. Relative changes in respiration rates of the management activities between the two horizontal broken lines are within ±10% in the 28-day comparison.
Figure 8: Change of ecosystem respiration of 12 European croplands as a function of management activity after elimination of temperature effects (n = 335 events in total) on the timescale of ±7 days and ±28 days, (a) relative changes with respect to conditions before management event, and (b) absolute changes in daily mean respiration fluxes. Only management types that are represented by at least 5 events are shown. Note that these additional restrictions further reduced the number of sites and events in this comparison.
Figure 9: Influence of percent soil organic carbon content on management-related respiration. Linear correlation coefficients with soil C are shown as vertical bars in black ($p \leq 0.05$), with hashes ($0.05 < p \leq 0.2$, or without color ($p > 0.2$). The four bars represent (a) respiration before and (b) after management intervention, (c) absolute increase in respiration, and (d) ratio of respiration after compared to before management intervention. Only cases with $N > 10$ are shown.
Figure 10: Gumbel plots of 21 CarboEurope IP croplands showing the relationship between daily ecosystem respiration and probability of occurrence expressed by the return interval. Each line represents the upper boundary of daytime ecosystem respiration rate (expressed in $\mu$mol m$^{-2}$ s$^{-1}$ as was determined on a daily basis using a light-response curve approach) as a function of return interval. For example, for a return interval of 1 year ($T_x$) the ITBCi site experienced daytime respiration rates $R_x$ that were at most 13.5 $\mu$mol m$^{-2}$ s$^{-1}$. Symbols show the data points that were used for the log-linear fits analysed in Figure 11. The inset shows theoretical curve shapes for (1) log-normal distribution, (2) exponential (Gumbel) distribution, and (3) normal distribution.
Figure 11: Dependence of Gumbel distribution parameters on annual climate of sites. Left: maximum daily respiration expected within a 1-year observation period. Right: increase of expected maximum respiration with doubling of observation period. Gray symbols indicate sites, where climatic information was available from CarboEurope IP database, black symbols use precipitation data from the nearest Dutch KNMI weather station, and open symbols indicate that available data had to be scaled up to annual estimates for the respective years using long-term climate data from Müller (1996).
Figure 12: Correlation between the two parameters of the Gumbel distribution for the 21 CarboEurope IP cropland sites. At sites with high yearly maximum respiration the expected increase in maximum respiration tends with to increase more strongly with increasing observation period (expressed by two fold rate of maximum $R_e$) than at sites where respiration is already low. Symbols are the same as in Figure 11.
Figure A1: Example of how temperature effects were eliminated in the comparison shown in Figure 8. For simplicity an example was chosen where there was no overlap in the temperatures observed before the management event ($\Delta T_{\text{before}}$ with 5 out of 7 days with high-quality data) and those observed after the event ($\Delta T_{\text{after}}$ with 6 out of 7 days with high-quality data). The means of both groups are shown with crossed rectangles, which show the observed difference in ecosystem respiration (A). Using the empirical cumulative distribution function of all available fluxes (gray open symbols), the temperature response of ecosystem respiration should have followed the schematic exponential black line and resulted in the value shown with a crossed circle. Thus, the increase B is the temperature effect (temperature increased after ploughing), and only the increase C (which is A–B) is attributable to management effects. In the same way the temperature effects in 28 day comparisons was determined. The component C was then used for the statistical analysis shown in Figure 8.