Variability in carbon exchange of European croplands

Eddy J. Moors\textsuperscript{a}, Cor Jacobs\textsuperscript{a}, Wilma Jans\textsuperscript{a}, Iwan Supit\textsuperscript{a}, Christian Bernhofer\textsuperscript{b}, Nina Buchman\textsuperscript{c}, Arnaud Carrara\textsuperscript{d}, Eric Ceschia\textsuperscript{e}, Jan Elbers\textsuperscript{a}, Werner Eugster\textsuperscript{c}, Bart Kruijt\textsuperscript{a}, Werner L. Kutsch\textsuperscript{f}, Benjamin Loubet\textsuperscript{g}, Enzo Magliulo\textsuperscript{h}, Christine Moureaux\textsuperscript{i}, Albert Olioso\textsuperscript{j}, Matt Saunders\textsuperscript{k}, Henrik Søgaard\textsuperscript{l}

Addresses:
\textsuperscript{a} Wageningen UR, Alterra, Earth System Science and Climate Change Group, P.O. Box 47, 6700 AA Wageningen, The Netherlands
\textsuperscript{b} Christian Bernhofer: Institute of Hydrology and Meteorology, Technische Universität Dresden, Pienner Str. 23, D–01737 Tharandt, Germany
\textsuperscript{c} Nina Buchman, Werner Eugster: ETH Zurich, Dept. of Agricultural and Food Sciences, Institute of Plant, Animal and Agroecosystem Sciences, Universitätstrasse 2, CH–8092 Zurich, Switzerland
\textsuperscript{d} Arnaud Carrara: Fundación CEAM, c/Charles Darwin 14, Parque Tecnológico, 46980 Paterna, Spain
\textsuperscript{e} Eric Ceschia\textsuperscript{e}: CESBIO - CNES-CNRS-IRD- UMR 5126, 18 Avenue Edouard Belin, 31401 Toulouse Cedex 9, France
\textsuperscript{f} Werner L. Kutsch\textsuperscript{f}: Johann Heinrich von Thünen Institute (vTI), Institut für Agricultural Climate Research, Bundesallee 50, 38116 Braunschweig, Germany
\textsuperscript{g} Benjamin Loubet\textsuperscript{g}: INRA Unité Mixte de Recherche INRA / AgroParisTech "Environnement et Grandes Cultures", 78850 Thiverval – Grignon, France
\textsuperscript{h} Enzo Magliulo\textsuperscript{h}, CNR-ISAFOM, Via Patacca, 85, 80056 – Ercolano (Napoli), Italy
\textsuperscript{i} Christine Moureaux\textsuperscript{i}: Université de Liège – Gembloux Agro-Bio Tech, Crops Management Unit, 5030 Gembloux, Belgium
\textsuperscript{j} Albert Olioso\textsuperscript{j}: Environnement Méditerranéen et Modélisation des Agro-Hydrosystème, UMR 114 INRA-UAPV, Domaine Saint Paul, Site Agroparc, 84914 Avignon, Cedex9, France
\textsuperscript{k} Matt Saunders\textsuperscript{k}: UCD School of Biology & Environmental Science, University College Dublin, Belfield, Dublin 4, Ireland
\textsuperscript{l} Henrik Søgaard\textsuperscript{l}: Institute of Geography and Geology. Oster Voldgade 10, 1350 Copenhagen, Denmark

Corresponding author: Eddy Moors
Tel: +31 317 486431, Fax: +31 317 419000, e-mail: eddy.moors@wur.nl

Eddy Moors, ESS-CC, Alterra-WUR, P.O. Box 47, 6700 AA Wageningen, The Netherlands

Special Issue CEIP – croplands
Abstract

The estimated Net Ecosystem Exchange (NEE) of CO₂ based on measurements at 17 flux sites in Europe for 44 cropping periods showed an average loss of 35 gC m⁻² per cropping period. Where the cropping period is defined as the period after sowing or planting until harvest. The variability taken as the standard deviation these cropping periods was 249 gC m⁻². These numbers do not include lateral inputs such as the carbon content of applied manure, nor the carbon exchange out of the cropping period. Both are expected to have a major effect on the C budget of high energy summer crops such as maize.

NEE and Gross Primary Production (GPP) can be estimated by crop net primary production based on inventories of biomass at these sites, independent of species and regions. To a lesser extent NEE and GPP can also be estimated by the measured yield at these sites and the NUTS2 level yield dataset of EUROSTAT.

To investigate the difference in the variability in CO₂ emissions of different crops at the same location and to compare this variation with the variation of the same crop at different locations and with the inter-annual variation the measured dataset at the flux sites was extended with simulated data.

These simulations show that the variability in carbon exchange is determined by: firstly the choice of crop and the location and to a lesser extent by the yearly differences in climate.
Keywords: cropland, carbon dioxide exchange, yield, variability, land use, climate
1 Introduction

Changes in carbon stores of croplands under unchanged management are at present not reported for two main reasons: 1) it is considered too complicated to measure the net carbon exchange accurately and 2) it is assumed that the carbon input and output of croplands are in equilibrium. Indeed, in the default requirements of the UNFCCC reporting guidelines croplands are taken to be carbon-neutral as far as the carbon dioxide fluxes are concerned. As a consequence, mostly only the effects of land management changes affecting fossil fuels used for management of the croplands, the nitrogen emissions resulting from fertilizer use and the decomposition of drained peatlands are taken into consideration.

Since arable land constitutes 100.117 $10^6$ ha, in Europe (EU-27), that is, 62% of the total agricultural area utilized in Europe (based on EU-27 statistics in 2005; EUROSTAT, 2008) a small uptake or release of carbon per m² of cropland can represent a considerable amount of carbon over Europe. For example, Janssens et al. (2005) estimated from modeling results the change of carbon stocks in arable soils for Europe to be -70 gC m⁻² yr⁻¹ on average.

The photosynthetic capacity of the different crops grown can differ by a factor of two. Thus, if the assumption is correct that the carbon in- and outflows of croplands are in balance on average, the variation in carbon exchange related to differences in photosynthetic capacity must be averaged out by variations in other factors such as differences in climate, soils and land management, or by the lateral flux of carbon implied by harvested products from the croplands.
Because direct measurements of the carbon exchange are difficult to obtain, the carbon exchange is usually estimated from relatively simple empirical relations. This allows the use of readily available data such as annual yield statistics, air temperature and precipitation. Such estimates are based on the assumption that there is a direct relationship between yield and Net Primary Production (NPP), yield and carbon inputs into the soil and thus between NPP and plant respiration and between temperature and soil respiration (see among others Andrén et al., 2008; Vleeshouwers and Verhagen, 2002).

The collaborative European effort to measure the Net Ecosystem Exchange (NEE) of a large number of croplands over Europe within the CarboEurope Integrated Project (CEIP) enables us to test these hypotheses. The overall objective of this paper is to analyze the inter-species, inter-annual and spatial variability in carbon exchange for croplands over Europe based on direct measurements of NEE and supported by model simulations. It should be noted that only carbon in CO$_2$ and biomass, either harvested or remaining on the field is taken into account. This implies that the carbon exchange studied in this paper does not include the carbon in methane and VOC’s.

We quantify the variability of carbon exchange of crops over Europe, investigate its causes and assess the validity of some simple scaling rules of carbon exchange from croplands. To this end, we use three data sources:

1) NPP and carbon dioxide flux data obtained at 17 CEIP sites across Europe
2) European yield data from the EUROSTAT database
3) Results from the Crop Growth Modeling System (CGMS), a model used to interpret and predict trends in yield in the countries of the European Union (EU). From these datasets, differences in carbon flux variation of different crops at the same location are estimated and compared with the variation of the same crop at different locations and with the inter-annual variations.

2 Material and methods used

2.1 Sites and processing of eddy covariance data

Data were collected from 17 sites across Europe (see Fig. 1) where detailed measurements of NEE were performed during one or more years, over different crops, adding up to 46 cropping periods. These sites were part of the CarboEurope flux network (see http://www.carboeurope.org/). Table 1 shows the characteristics of these sites including the years when the measurements were taken, crop history, main management activities and length of the cropping period.

Fig. 1:

At the sites, carbon dioxide fluxes were measured at 30-minute intervals using the eddy covariance method (e.g., Baldocchi et al. 2003). Typically, the eddy covariance station had a 3D sonic anemometer and an open or closed path infrared carbon dioxide and water vapor gas analyzer mounted on an extendible mast. In general, a second extendible mast was used to install sensors to measure air temperature, photosynthetically active radiation, global radiation (incoming and outgoing), longwave radiation (incoming and outgoing), relative humidity and air pressure. Soil temperature, soil moisture, soil heat flux and precipitation were measured close to the
masts. To derive NEE from the raw data the Euroflux methodology was followed (Aubinet et al., 2000). Data processing software packages were intercompared to minimize systematic differences among sites (Mauder et al., 2008).

For this study, Level 4 data of the CarboEurope database were used. This implies that the data were quality-checked and gap filled using the standard CarboEurope procedures, based on Reichstein et al. (2005). To estimate GPP and Ecosystem Respiration ($R_{eco}$) from the observed NEE the CarboEurope flux partitioning procedure was used. The method is based on the Lloyd and Taylor (1994) respiration model using nocturnal flux measurements of acceptable quality according to the CarboEurope quality control procedures.

An inventory of the above and below ground biomass to derive NPP and yield was also standard procedure at these sites. Conversion of fresh weight to Dry Matter (DM) and subsequently to the amount of carbon was done for each part of the plant separately, using crop-specific data obtained at the sites. For more specific details of the sites and methodology the reader is referred to the other papers in this issue.

Table 1

2.2 EUROSTAT yield data

Although the number of eddy covariance sites with detailed measurements was large for this type of measurements, the number was still relatively small compared to the total area of croplands in Europe, which would limit our variability assessments. To overcome this problem, we used the dataset released by EUROSTAT to extrapolate
the variations found to a larger area and longer time series. The dataset contains 
statistics on planted area, yield and production volume, which are collected from 
national statistical services of all EU member states and Switzerland. To capture the 
spatial variability only data available at the regional NUTS2 scale were used.

In the EUROSTAT database, yield was reported as the amount of DM suitable for 
consumption, i.e. “consumable parts”. This differs from the yield reported at the eddy 
covariance sites, which was the total DM exported from the field. Especially for 
cereals this difference between the two definitions of yield had to be taken into 
account, since usually only the exported amount of grains was reported in the yield 
statistics. Using allometric relations for the plants, the differing yield numbers were 
converted into each other. In the text and in the figure captions it is mentioned which 
definition of yield is used.

2.3 Biomass modeling

To estimate the variations in biomass production caused solely by variations in 
climate the Crop Growth Modeling System (CGMS) was used. The heart of CGMS is 
the WOFOST crop growth simulation model, of which the underlying principles have 
been discussed by van Keulen and Wolf (1986). Implementation in CGMS and its 
structure is described by Supit et al. (1994a).

Using CGMS we simulated two production situations: potential and water-limited. 
The potential situation was defined by temperature, day length, solar radiation and 
crop characteristics like leaf area dynamics, assimilation characteristics and dry matter 
partitioning. The water-limited situation was characterized by water availability
derived from root characteristics, soil physical properties, precipitation and evapotranspiration. In both situations optimal supply of nutrients was assumed. For each situation, both total aboveground dry matter and grain dry matter per hectare were calculated.

The results presented in this paper are based on the NUTS2 regions and are averaged using the soil distribution in each region. To determine the variation in carbon exchange because of different crops, different years and different locations, biomass production of eight crops (maize, winter wheat, spring barley, sunflower, potatoes, sugar beet, rapeseed and field beans) in ten NUTS2 regions corresponding to the location of sites was simulated for the period 1976 to 2007. Also, simulations for two main crops (maize and winter wheat) were performed for all NUTS2 regions in EU-27, for two climatically contrasting years (2003, a dry year in large parts of Europe, and 2007, a wet year).

### 2.4 Analysis of variability

We analyzed the variability on the basis of cropping periods. Thus, the flux data were summed over the length of the cropping period only. The definition of the length of the cropping period adopted for this study is the number of days between the sowing date of the crop studied and the day of harvest. This implies that, depending on the crop, the number of days incorporated in the sums may differ (see Table 1). Moreover, CO₂ exchange during the fallow periods was not attributed to a crop rotation period. This procedure assured consistency between the analysis of the CO₂ flux data and the analysis of the EUROSTAT and CGMS data.
We analyzed variability by studying differences between the NEE observed directly at the sites, and simple scaling rules for CO\textsubscript{2} flux components (NEE, GPP, R\textsubscript{eco}). We also compared carbon exchange data from the different data sources. Variability was quantified using standard deviation as a measure. To analyze the variation in the biomass simulations we tested the null hypothesis (ANOVA) that there are no differences because of variations in crop, location or year.

3 Results

3.1 Variability based on NEE measurements

The changes in carbon stocks have been estimated based on the flux measurements of NEE during the cropping period corrected for carbon contained in the harvested biomass, but not for the imported carbon. Figure 2 shows the variation of this carbon exchange among crops and sites. In this graph uptake of carbon is presented as a positive number.

For the sites and cropping periods considered here there is an average loss of 35 gC m\textsuperscript{-2}. However, a large variation is found as well: the standard deviation is 249 gC m\textsuperscript{-2}. Not including the rice crop, which covers a relatively small area in Europe, increases the average loss to 77 gC m\textsuperscript{-2} and the standard deviation to 220 gC m\textsuperscript{-2}. Maize, rapeseed, potatoes and sugar beet show mainly net losses, whereas spring barley and sunflower represent mainly small net uptakes. Winter wheat shows both net uptake and net loss of carbon. Rice shows a relatively large gain of carbon, not taking into account the large carbon loss emitted as CH\textsubscript{4}. Rice also shows a remarkable lack of
variability. The two main crop types in Europe, maize and winter wheat have an average carbon release of 228 gC m\(^{-2}\) and 54 gC m\(^{-2}\), respectively. The variability within these two crops, expressed as the standard deviation, is 230 gC m\(^{-2}\) and 256 gC m\(^{-2}\), respectively.

### 3.2 NPP and yield as predictors of NEE

In Figure 3 we explore the relationship between NEE and NPP (left panel) and harvested yield and NEE measured by researchers at the eddy covariance sites. NPP refers to total biomass production at the sites, including belowground parts. Harvested yield in this case refers to above-ground DM export in the case of grain crops and below ground DM in the case of potato and sugar beet. In the case of maize, except for the FRGri site, harvested yield includes the leaves and stems, because it is used for fodder production. Figure 3a shows that crop NPP scales quite well with NEE (\(R^2 = 0.63, p < 0.0001\)), if species and regions are disregarded. Slightly less good results (\(R^2 = 0.45, p < 0.0001\)) are found for scaling of NPP with GPP (not shown). The ratio \(R_{\text{eco}} : \text{GPP} = 0.56\) (\(R^2 = 0.50, p < 0.0001\)). On the other hand, we observe that within crop species, these relationships are only very weak. Moreover, NEE scales much less well with harvested yield (Fig. 3b). The relationship is less pronounced than in the aforementioned cases (\(R^2 = 0.23, p = 0.0011\)).

*Fig. 3:*

In Figure 4 we compare the results from the site inventories with the EUROSTAT data and simulated yield for water-limited and non-limited conditions at the level of NUTS2 regions. It can be seen that for a number of sites and regions the EUROSTAT data and the water limited simulated yield compare remarkably well. The most
pronounced differences are found for the maize site, in especially the Italian (ITF3) site, for which the EUROSTAT data compare better with the simulations without water limitations. At the Italian site (ITF3), this corresponds with the applied irrigation amounts (see Table 1). If we do not take this site into account, the consumable part of the yield as measured at the sites, correlates well with the water-limited simulated yield, \( R^2 = 0.43, p < 0.0001 \).

Fig. 4:

3.3 Variability because of location, crop choice and year

By using the simulations for water-limited conditions the climatological effects can be separated from the management and the spatial effects such as differing soil characteristics. In Figure 5 the simulated water-limited biomass under optimal management conditions is depicted for each NUTS2 region. Simulated dry matter weight has been converted to carbon content using the average conversion factors obtained at the CEIP sites: 0.45 for maize and 0.47 for wheat. The standard error in these estimates is less than 4%. This figure reveals the large spatial variability in modeled biomass for the main crops winter wheat and maize, and some differences in the variability. The graph also shows how these differences change between a “normal year” like 2007 and an extremely dry and hot year like 2003. Using the standard deviation as a measure of spatial variation, the increase in spatial variation is 1.51 gC m\(^{-2}\) in 2003 to 1.79 gC m\(^{-2}\) in 2007 for winter wheat. For maize the spatial variation changes from 1.66 gC m\(^{-2}\) in 2003 to 2.56 gC m\(^{-2}\) in 2007. These changes from year to year imply that the spatial variation of a crop that depends largely on a relatively short but intense growing season in summer such as maize may change radically under extreme weather conditions. The spatial variation in biomass of crops like winter
wheat, growing mainly outside the summer season, is much less affected by drought conditions.

Fig. 5:

Using the results from the 32 years of simulations of the 8 crops for 14 regions we tested the null hypothesis that there are no “real” differences in carbon exchange because of crop, location or year. The p-value of the variance analysis is $p = 0.003$. Thus, we reject the null hypothesis and conclude that differences in yield for different years, crops and locations do exist.

The inter-annual variability in biomass due to meteorological conditions is $1.03 \text{ gC m}^{-2}$ for winter wheat and $1.33 \text{ gC m}^{-2}$ for maize. Thus, both crops show much less inter-annual variation due to climatic differences than spatial variation over Europe (Figure 5).

The spatial variability in biomass averaged over the 32 years, but based only on the 14 NUTS2 regions, is for winter wheat $1.90 \text{ gC m}^{-2}$ and for maize $1.77 \text{ gC m}^{-2}$. This variability is for winter wheat more and for maize less than the one found for the whole of Europe for 2003 and 2007. In both cases the spatial variability is larger than the inter-annual variation.

The average variation in biomass caused by different crops, based on simulations for eight crops in 14 NUTS2 regions, is $1.70 \text{ gC m}^{-2}$. 

These results suggest that the variations in carbon exchange are firstly determined by the choice of crop and by the location and to a lesser extent by the annual differences in climatic conditions.

4 Discussion

4.1 Carbon budget

Freibauer et al. (2003) reported for the 2008-2012 commitment period, based on the CESAR model (Vleeshouwers and Verhagen, 2002), a carbon exchange of arable land varying between a source of -293 and a sink of 31 gC m\(^{-2}\) yr\(^{-1}\), resulting in a mean source of -83 gC m\(^{-2}\) yr\(^{-1}\) with a standard deviation of 40 gC m\(^{-2}\) yr\(^{-1}\). In their study the standard deviation reflects the uncertainty in the assumed mean soil organic carbon content. Also other researchers, for example Janssens et al (2005) and Smith (2004) and Smith et al. (2005), reported croplands to be a source of carbon. However, according to the most realistic simulations of Gervois et al. (2008) for the period 1901 to 2001, the current cropland carbon balance is a net sink of 16 ± 15 gC m\(^{-2}\) yr\(^{-1}\). From an analysis based on inventories of net biome production Ciais et al. (2009) found the carbon balance of European croplands to be a small source or sink, -13 ± 33 gC m\(^{-2}\) yr\(^{-1}\).

The data from the cropland sites of the present study also reveal an average source of carbon amounting to 35 gC m\(^{-2}\) and not including the rice sites 77 gC m\(^{-2}\) (see Fig. 2). Using harvested area in Europe as a simple scaling technique to calculate an average of the carbon exchange of all sites gives a source of 62 gC m\(^{-2}\). For the croplands studied here to be carbon neutral, a large external carbon input is required. As an
example, the Oensingen site (Switzerland) received 550 ± 62 gC m\(^{-2}\) in early 2006, and a similar amount in January 2010. Such an import once per cropping cycle of 4 years appears to compensate for the excess carbon removed from the field by harvest (Kutsch et al., this issue). Additionally, Figure 2 also shows that crop rotation can at least partially compensate the output of other crops within the cropping cycle even without organic manure applications. Another means of compensating carbon losses is the application of lime. For the sites studied here, this was restricted to the Lonzée site in Belgium and the Dutch sites where 6% CaCO\(_3\) is generally applied as an additive to mineral fertilizers (Eugster et al., this issue).

The numbers reported here are only indicative because they represent the summed NEE over the cropping period only, and do not include the fallow periods, nor the imported carbon. Especially summer crops such as maize have a short cropping period (see Table 1) and thus, the annual carbon exchange may be changed drastically by the activities of the farmer outside this period (see, for example, Jans et al., this issue).

An important factor in the carbon balance of croplands is the management applied (e.g., Ciais et al., 2009). A number of authors have demonstrated the possible contributions of changes in land management, such as reduced tillage, to increase the carbon soil pool (e.g. Billen et al., 2009, Andrén et al., 2008, Hutchinson et al., 2007, Smith et al., 2005, Freibauer et al. 2003, Smith et al., 2001, Lal, 2000). The more recent studies show that the possibilities to reduce the carbon emissions of crop lands are less than previously assumed. All studies show a large variability in the projected contributions. The variability was mostly attributed to differences in climate, soil properties, and management history. Yield data play an important role in these
simulations, not only as a validation option for models, but also as one of the most crucial factors to determine the historic and present carbon input into the soil (Andrén et al., 2008).

In conclusion, whether or not these sites are actually sources of carbon in the long run depends on the crop rotation used, the contribution of the fallow period and the carbon content of the manure and fertilizer applied. Our analysis also ignores the contribution from methane and nitrous oxide. An analysis by Ceschia et al. (this issue) includes other sources of green house gas emissions such as effects of farm operations.

### 4.2 Predictors of NEE

Our results suggest that across crops, given that they grow within their normal agricultural range, NPP and to a lesser extent crop yield data are a reasonable predictor of NEE. Thus, NPP and crop yield could be used in Europe-wide assessments of carbon exchange of crops, based on productivity statistics. Also, the relationships found here imply that heterotrophic respiration (that is, decomposition processes in the soils) scales well with plant productivity in the crop systems studied here. In its turn, this suggests that microbial activity is largely governed by production of dead roots and root exudates, and additionally, manure gifts are well tuned to NPP (or vice versa). The fact that the relationship with total NPP is better than the one with yield implies that the proportion of yield to NPP is not always the same. Variable amounts of stubble, straw and roots remain in the field after harvest and carbon losses from the soil may differ among crop systems. For example for wheat the ratio of the harvested DM to the total DM ranged from 0.35 to 0.94.
The fact that within-species variation in NEE is poorly predicted by NPP primarily calls for caution in applying any simple scaling functions to predict the carbon budget of crops from productivity, regardless where they grow. This is mainly caused by the limited range in the NEE and NPP data per crop species, despite the geographical spread in study sites. Clearly, either certain crops are only cultivated in specific regions of Europe, or these crops reach very similar productivity regardless where they grow, like in the case of Maize. In both cases this leads to narrow ranges in variability of NPP and NEE. Wheat seems to be an exception, but then we see that the predictability of NEE is also least for this crop. This is also reflected in the results of the CGMS simulations.

The usefulness of the yield data depends among others on the relations between yield and NPP and between NPP and NEE. Luyssaert et al. (2007) analyzed a large global dataset of carbon productivity (GPP, NPP and NEE) for forest. In these data, the ratio of NPP to NEE is about 1.5. Figure 3 of our study shows roughly the same ratio, i.e. 1.6 for croplands during their growing season if both quantities are summed over all sites and years. The relation between yield and NEE for the sites of our study shows more scatter. The many cases with good agreement between the yield at the sites and the EUROSTAT dataset as well as the simulated yield is promising, but clearly, significant deviations are found for some crops. In particular the two main crops maize and winter wheat show large differences.

4.3 Uncertainty in EUROSTAT and crop simulations
When using yield inventory data such as the dataset of EUROSTAT to estimate NPP, there are a number of sources of uncertainty that should be taken into account. Firstly there is the intrinsic uncertainty associated with the collection of the data. Secondly, the precise definition of what is included in NPP and yield may cause a bias. Thirdly, the allometric relations used to convert yield into NPP, and *vice versa*, are uncertain.

An overview of the strong and weak points of the different methods and datasets is given by Smith et al. (2008). They point out that one of the drawbacks of the yield statistics often used is the low spatial resolution implied by providing data only at country level. The NUTS2 regions of the EUROSTAT dataset used for this study partly overcomes this problem. For example, Andrén et al. (2008) showed that at the resolution of the NUTS2 regions the soil properties in Sweden do not cause large errors anymore. But it remains questionable if in these NUTS2 regions the applied management for a certain crop can be considered homogenous. To this end, efforts to produce the yield data and other management information at the NUTS3 level could be useful. Moreover, within the EU, no single system to establish the yield statistics exists. The methods applied vary from country to country and thus, the aforementioned uncertainties vary as well. Bradbury (1994) investigated the applied methods to establish these statistics for cereals in various EU member states. He concluded that “most member states attempt to estimate sampling errors, and usually manage to show that the margins are close enough to those set out in regulation 837/90, but with greater or lesser amount of convincing detail. For judgmental assessment of yield/production (…) no fully satisfactory methods to establish the estimating error are available, for the simple reason that it is not a scientific method.”
The main causes of differences between simulated and observed yield are associated with additional irrigation in dry years giving higher yields than simulated. Also, diseases and pests in primarily wet years sometimes reduce yields by more than 30% as compared to the simulated yields. In addition, inaccessible fields due to very wet conditions or lack of sufficient available labor to collect the harvest may also reduce the yield reported to EUROSTAT.

In all crop simulations an optimal supply of nutrients was assumed. The relatively good agreement between the simulated crop growth with the NUTS2 data of the EUROSTAT dataset suggests that in large parts of Europe farmers apply an optimal management. To minimize losses, after one or two years with low yields, farmers will adjust their management in such a way that extreme effects of, for example, weather will be reduced. Applying irrigation is one important management option to reduce the effects of extremely dry weather.

Billen et al. (2009) used the EPIC model for a number of sites in Germany and found similar differences between simulated and observed yield as in our study (i.e. -40% to +15%). They attributed the main causes of these differences to uncertainties in specific crop parameters and differences between used and actual weather data. Gervois et al. (2008) using the ORCHIDEE-STICS model simulated for maize in France an underestimation of 30% compared to the reported maize yield at country level.
5 Conclusions

An average loss of 35 gC m$^{-2}$ was found for the sites and cropping periods measured. The variability taken as the standard deviation between these sites and cropping periods was 249 gC m$^{-2}$. This number does not include lateral input such as from the carbon content of applied manure, nor the carbon exchange outside the cropping period. Both are expected to have a major effect on high energy summer crops such as maize. Especially for rice the exchange of CH$_4$ will have a major contribution to the total carbon exchange.

Disregarding species and regions, over the whole of Europe crop NPP scales well with NEE and GPP as measured at specific sites. Simulated water-limited yield and EUROSTAT yield compare reasonably well with the yield measured at the flux sites, except for the irrigated maize site. This site compares better with simulated non-water-limited yield.

To investigate the differences between the variation in emissions of different crops at the same location compared with the variation of the same crop at different locations and with the inter-annual variation the measured dataset at the flux sites was extended with the simulated data. These simulations show that the variability in carbon exchange is determined by: firstly the choice of crop and the location and to a lesser extent by the annual differences in climatic conditions. For summer crops such as maize the spatial variability may increase significantly during dry years.

A good estimate of the annual carbon uptake or release for a larger region is only possible after a number of crop rotations and when all lateral fluxes are taken into account.
account. This may be done by using simulation models. As such the data at the flux sites will be of great value to calibrate process models and validate the results.

Although the sites used for the present study cover a large transect across Europe, the number of data points are still limited. More data becoming available will help to improve the estimates the carbon exchange of croplands.

6 Acknowledgement

This research was supported by European commission (CarboEurope IP contract GOCE-CT2003-505572). Authors of Alterra WUR were also supported by the Dutch National Research Program Climate Changes Spatial Planning, project nr. ME1, and the Climate Research Program of the Ministry of Agriculture and Food Safety of the Netherlands. We acknowledge Wietse Franssen’s help in preparing the graphics. We thank two anonymous reviewers for their valuable comments on the manuscript.
References


CarboEurope-IP website: http://www.carboeurope.org/


Kutsch, W., Aubinet, M., Buchmann, N., Smith, P., Osborne, B., Eugster, W., Wattenbach, M., Schulze, E.-D., Tomelleri, E., Ceschia, E., Bernhofer, C., Béziat, P., Carrara, A., Di Tommasi, P., Grünwald, T., Jones, M., Magliulo, V., Marloie, O.,


Table caption:

Table 1: Site characteristics including: CarboEurope database Site name and ID, coordinates, identification of the EUROSTAT NUTS2 region, crop history, years, crop type, management practices, starting date of the period used for calculation of annual NEP, i.e. either the date between harvest of the previous crop and ploughing for the following crop or the date between harvest of the previous crop and sowing of the following crop when there was no soil preparation before sowing, and length of the cropping period indicating the number of days between sowing or planting and harvest. (na = not available)
List of figure captions:

Fig. 1: Location of the sites used overlying a land cover map. The land cover map shows aggregated land cover classes of the PELCOM 1 km pan-European land cover database (Mücher et al., 2000).

Fig. 2: Net uptake or release taking into account the main lateral output, i.e. NEE minus yield (exported harvested biomass).

Fig. 3: NEE as a function of NPP (a) and yield (exported from the field, i.e. including stalks for the grains) (b) as measured at the sites.

Fig. 4: Yield (consumable part only) based on site inventories, EUROSTAT NUTS2 regions and simulations with a crop growth model (with and without water limitation). For the DK02 and CH02 regions national scale, i.e. EUROSTAT NUTS1, data are used.

Fig. 5: Simulated water-limited biomass under optimal management (gC m$^{-2}$) of maize and winter wheat for 2003 and 2007.
Fig. 1: Location of the sites used overlying a land cover map. The land cover map shows aggregated land cover classes of the PELCOM 1 km pan-European land cover database (Mücher et al., 2000).
Fig. 2: Net uptake or release taking into account the main lateral output, i.e. NEE minus yield (exported harvested biomass).
Fig. 3: NEE as a function of NPP (a) and yield (exported from the field, i.e. including stalks for the grains) (b) as measured at the sites.
Fig. 4: Yield (consumable part only) based on site inventories, EUROSTAT NUTS2 regions and simulations with a crop growth model (with and without water limitation). For the DK02 and CH02 regions national scale, i.e. EUROSTAT NUTS1, data are used.
Fig. 5: Simulated water-limited biomass under optimal management (gC m$^{-2}$) of winter wheat and maize for 2003 and 2007.