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**Global warming
potential of
agro-ecosystems**

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Predicting the global warming potential of agro-ecosystems

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Abstract

Nitrous oxide, carbon dioxide and methane are the main biogenic greenhouse gases (GHG) contributing to the global warming potential (GWP) of agro-ecosystems. Evaluating the impact of agriculture on climate thus requires a capacity to predict the net exchanges of these gases in an integrated manner, as related to environmental conditions and crop management. Here, we used two year-round data sets from two intensively-monitored cropping systems in northern France to test the ability of the biophysical crop model CERES-EGC to simulate GHG exchanges at the plot-scale. The experiments involved maize and rapeseed crops on a loam and rendzina soils, respectively. The model was subsequently extrapolated to predict CO_2 and N_2O fluxes over an entire crop rotation. Indirect emissions (IE) arising from the production of agricultural inputs and from cropping operations were also added to the final GWP. One experimental site (involving a wheat-maize-barley rotation on a loamy soil) was a net source of GHG with a GWP of $350 \, kg \, CO_2$-C eq ha^{-1} yr^{-1}, of which 75% were due to IE and 25% to direct N_2O emissions. The other site (involving an oilseed rape-wheat-barley rotation on a rendzina) was a net sink of GHG for $-250 \, kg \, CO_2$-C eq ha^{-1} yr^{-1}, mainly due to a higher predicted C sequestration potential and C return from crops. Such modelling approach makes it possible to test various agronomic management scenarios, in order to design productive agro-ecosystems with low global warming impact.

1 Introduction

Agricultural soils contribute about 15% of global greenhouse gases (GHG) emissions, a share expected to rise in the future due to the increasing land use and management intensity of agriculture worldwide (Duxbury et al., 1993; Gitz and Ciais, 2003). In the case of arable crops, these emissions include both exchanges of GHG in the cultivated field, and the upstream (indirect) emissions arising from the production of agricultural inputs (fertilizers, pesticides and lime), fuel combustion and use of machinery on the

farm. Indirect emissions of GHG may contribute as much as half of the total GHG budget of agricultural crops (Robertson et al., 2000; Mosier et al., 2005). Thus, this term provides good leverage to mitigate their impact on global warming (West and Marland, 2002). The global GHG balance may be expressed as the global warming potential (GWP) of an agro-ecosystem considered, in CO_2 equivalents, using the GWPs of all the trace gases with radiative forcing (IPCC, 2001).

The direct emissions of GHG by agro-ecosystems are made up of three terms: emissions of nitrous oxide, net carbon fluxes between soil-plant systems and the atmosphere, and methane exchanges. Nitrous oxide (N_2O) is produced by soil microorganisms via the processes of nitrification and denitrification (Wrage et al., 2001). Arable soils are responsible for 60% of the global anthropogenic emissions of N_2O (IPCC, 2001), and their source strength primarily depends on the fertilizer N inputs necessary for crop production. Other environmental factors regulate these emissions: soil temperature, soil moisture, soil NO_3^- and NH_4^+ concentrations, and the availability of organic C substrate to micro-organisms (Hutchinson and Davidson, 1993). The effect of these factors results in a large spatial and temporal variability of N_2O emissions (Kaiser and Ruser, 2000; Jungkunst et al., 2006). The second term in the GHG balance, net C exchanges, is generally taken as the variations in topsoil organic C content (SOC). These variations reflect the balance between C inputs to the agro-ecosystems, via crop residue return, root deposition and organic amendments, and soil organic matter mineralization. Lastly, non-flooded cropland are usually considered as a weak methane-sink that mitigates the global warming potential (GWP) of cropping systems by 1% to 3% (Robertson et al., 2000, Mosier et al., 2005). Neglecting CH_4 exchanges, which is justified for non-flooded cropland in temperate climate, implies that only three terms contribute in the net GWP: soil organic carbon changes, N_2O emissions, and indirect emissions.

Various agricultural practices impact the GHG balance of agro-ecosystems. Some of them may first enhance the carbon sink-strength of soils: conversion to no-tillage practices, the introduction of catch crops, and the incorporation of crop residues into

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the topsoil were shown to lead to possible C sequestration into the organic carbon pool of the agricultural soils (Smith et al., 2001; Arrouays et al., 2002). The evaluation of candidate agricultural practices to reduce the GWP of agro-ecosystems should encompass indirect and direct emissions of all GHG, to avoid trade-off effects. For instance, because the C and N biogeochemical cycles are interconnected, CH_4 and N_2O emissions may offset the beneficial C storage associated with practices targeting at C sequestration (Six et al., 2004; Desjardins et al., 2005; Li et al., 2005).

In the literature, the GWP of agro-ecosystems is either calculated to assess the effect of the conversion to a new management practice (e.g. no-till, catch crops, farmyard manure application, or land use change; Robertson et al., 2000; Bhatia et al., 2005; Mosier et al., 2005), or for inclusion into the life cycle assessment of a crop-derived product. These include biofuels, animal feed, or human food (Kim and Dale, 2005; Gabrielle and Gagnaire, 2007). Direct GHG emissions may be either estimated from direct field measurements (Robertson et al., 2000; Bhatia et al., 2005; Mosier et al., 2005), or by using biogeochemical models simulating GHG emissions (Del Grosso et al., 2005; Desjardins et al., 2005; Pathak et al., 2005). Most agro-ecosystems have a positive net GWP (meaning they enhance global warming), but this trend is mainly controlled by the C storage potential of the soil. In the US Midwest, Robertson et al. (2000) measured the GWP of an annual crop rotation (maize-soybean-wheat) as 40 and 310 kg CO_2-C eq ha^{-1} yr^{-1} for no-till and conventional tillage systems, respectively. In Colorado, for rainfed crops under no-till practices, Mosier et al. (2005) measured a topsoil C-storage of about 300 kg CO_2-C eq ha^{-1} yr^{-1} in perennial, rainfed crops under no-till, which offset the other terms in the GHG balance and resulted in a negative net GWP of –85 kg CO_2-C eq ha^{-1} yr^{-1}.

The various terms of the net GWP should be predicted with similar accuracy. Indirect emissions may be easily calculated thanks to databases of life cycle inventories (West and Marland, 2002; Nemecek et al., 2003), but direct field emissions of N_2O and C storage in soil are extremely dependant of pedoclimatic conditions and agricultural management practices. To take into account these sources of variability, and to de-

vise mitigation strategies, the processes occurring in the soil-crop-atmosphere system should be modelled simultaneously, together with the effect of agricultural practices. In the past, modelling approaches were developed in parallel either by agronomists seeking to predict crop growth and yields in relation to their management (Boote et al., 1996), or by ecologists focusing on biogeochemical cycles and in particular mineralization, nitrification and denitrification in soils (e.g., Li et al., 2005). With the increasing interest for the prediction of trace gas emissions from arable soils (or pollutants in general), both approaches should be linked together in a more holistic perspective (Gijsman et al., 2002; Zhang et al., 2002). The CERES-EGC model was designed following this philosophy to estimate site-and-management specific environmental balance, or regionalised inventories of trace gas emissions (Gabrielle et al., 2006).

The objectives of this work were: i/ to test the CERES-EGC crop model with experimental data from two cropping systems representative of northern France: a maize-wheat-barley rotation on a loamy loess soil and a rapeseed-wheat-barley rotation on a rendzina, and ii/ to apply the model to assess the GWP of these two cropping systems, including direct and indirect emissions of GHG.

2 Materials and methods

2.1 Experimental data

2.1.1 Field sites

The field experiments were carried out at two locations in northern France, at Rafidin (48.5° N, 2.15° E) in the Champagne region in 1994–1995 (Gosse et al., 1999), and at Grignon near the city of Paris (48.9° N, 1.95° E) in 2005.

In Rafidin, the soil was a grey rendzina overlying a subsoil of mixed compact and cryoturbed chalk. The topsoil (0–30 cm) has a clay loam texture, with (31% clay and 28% sand, an organic matter content of 19.5 g kg^{-1}, a pH (water) of 8.3, and a bulk

density of $1.23\,\mathrm{g\,cm^{-3}}$. Other soil properties are available in the dedicated world wild web server on the following address: http://www-egc.grignon.inra.fr.

In Grignon, the soil was a silt loam with 18.9% clay and 71.3% silt in the topsoil. In the top 15 cm, organic carbon content was $15.9\,\mathrm{g\,kg^{-1}}$, the pH (water) was 7.6 and the bulk density $1.30\,\mathrm{g\,cm^{-3}}$.

The Rafidin site involved a winter rapeseed – winter wheat – winter barley rotation, and the measurements essentially took place during the rapeseed growing cycle, from its sowing on 9 Sept., 1994 to its harvest on 11 July, 1995. Three fertilizer N treatments (N0=$0\,\mathrm{kg\,N\,ha^{-1}}$, N1=$135\,\mathrm{kg\,N\,ha^{-1}}$ and N2=$270\,\mathrm{kg\,N\,ha^{-1}}$) were established on $30\times30\,\mathrm{m}$ blocks arranged in a split-plot design with three replicates (see Table 1). For this site, we only calculated the GWP of the N1 and N2 treatments, which have a potential agronomic value, and the rotations we simulated were only different regarding the fertilizer N inputs on the rapeseed crop. The other crops in the rotation (wheat and barley) were managed identically in the N1 and N2 rotations.

At the Grignon site, a maize – winter wheat – winter barley rotation was monitored, with more detailed measurements during the maize growing season in 2005. The maize was sown on 9 May 2005 and harvested on 28 September 2005. A mustard was planted following the harvest of barley the year before to serve as a catch crop to reduce nitrate leaching. Dairy cow slurry was applied between the harvest of barley and the planting of mustard on 31 August 2004. The maize was fertilized with $70\,\mathrm{kg\,N\,ha^{-1}}$ of urea and $70\,\mathrm{kg\,N\,ha^{-1}}$ of ammonium nitrate on the sowing date (see Table 1).

2.1.2 Soil and crop measurements

Soil mineral nitrogen content (NO_3^- and NH_4^+) and moisture content were monitored in the following layers: 0–15 cm, 15–30 cm, 30–60 cm and 60–90 cm at Grignon, and 0–30 cm, 30–60 cm, 60–90 cm, and 90–120 cm at Rafidin. Soil samples were taken in triplicates with an automatic (Rafidin) or manual (Grignon) auger every 2 to 4 weeks, and analysed for moisture content and mineral N. The latter involved an extraction of

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soil samples with 1 M KCl and colorimetric analysis of the supernatant. In both sites, soil moisture and temperature were also continuously recorded using TDR (Time Domain Reflectrometry, Campbell Scientific, Logan, Utah, USA) and thermocouples. Soil bulk density was measured once in each site, using steel rings.

5   For both experiments, plants were collected every 2 to 4 weeks, and separated into leaves, stems, ears or pods, and roots. Leaf area index was measured with an optical leaf area meter or analysis of leaf scans. The plant samples were dried for 48 h at 80°C and weighted, and analysed for C, N, P and K content by flash combustion.

2.1.3   Trace gas fluxes and micrometeorological measurements

10 At the Grignon and Rafidin sites, daily climatic data were recorded with an automatic meteorological station, including maximum and minimum daily air temperatures (°C), rainfall (mm day^{-1}), solar radiation (MJ m^2 day^{-1}) and wind speed (m s^{-1}).

At Grignon, the measurements of CO_2 fluxes at the field scale were carried out in the framework of the CarboEurope integrated project (European Commission Frame-
15 work VI research programme). Water vapour and CO_2 fluxes were measured using the eddy covariance method above the maize canopy. Wind speed was monitored with a three-dimensional sonic anemometer (R3-50, Gill Solent, Lymington, UK), and CO_2 concentration with a 20 Hz infrared gas analyser (Li-7500, Li-Cor Inc., Lincoln, NE, USA) located on a mast at two meters above the canopy. Daily net ecosystem car-
20 bon dioxide exchange (g C m^{-2} day^{-1}), and its daily evapotranspiration (mm m^{-2} day^{-1}) were calculated by integrating the 30-min fluxes determined by the micrometeorological measurements over each day. The eddy covariance technique usually produces gaps in the $1/2$ hourly C flux data, making it necessary to fill the missing values before integration at the daily time scale. Here, we used non-linear regression methods to
25 fill the missing NEP data. Daytime and nighttime data were separately calculated with a photosynthesis model based on a Misterlich function for daytime gaps and with a respiration model for the following nighttime period (Falge et al., 2001).

At Rafidin, there were no micrometeorological measurements of CO_2 exchanges.

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Nitrous oxide emissions were monitored by the static chamber method using circular chambers ($0.2\,m^2$), with 8 replicates. On each sampling date, the chambers were closed with an airtight lid, and the head space was sampled 4 times over a period of $2\,h$. The gas samples were analysed in the laboratory by gas chromatography. The measurements were done every 1–3 weeks between September, 1994 and April, 1995 (Gosse et al., 1999).

At Grignon, N_2O emissions were measured with three automatic chambers ($55\,L$, $0.5\,m^2$). The chambers were sequentially closed during $15\,min$ and the complete cycle for the three chambers was then fixed to $45\,min$. The N_2O concentrations were measured using an infrared gas analyser (N_2O Analyser $46\,C$, Thermo Scientific Inc., Waltham, MA, USA) which was connected on line with the chambers. Air was pumped from the chamber to the gas analyser and injected again after the analysis to the chambers. Nitrous oxide fluxes were calculated from the slope of the gas accumulation rate. The electric jacks used to open and close the chambers and the solenoid valves were controlled by a Campbell data logger (CR23X, Logan, Campbell Scientific, Utah, USA) that recorded the N_2O concentration every $10\,s$. Nitrous oxide emissions were monitored for 31 days from 13 May 2005, to 12 June 2005. During this period, the mean value of the emissions was $5\,g\,N\,ha^{-1}\,d^{-1}$, and the spatial coefficient of variation for the three chambers was quite large (79%).

2.2 The CERES-EGC model

CERES-EGC was adapted from the CERES suite of soil-crop models (Jones and Kiniry, 1986), with a focus on the simulation of environmental outputs such nitrate leaching, emissions of N_2O, ammonia, and nitric oxide (Gabrielle et al., 2006). It can therefore be used as an agronomic tool to improve the management of major arable crops, based on crop productivity and environmental criteria. The model simulates the cycles of water, carbon and nitrogen with three main sub-models.

A physical sub-model simulates the transfer of heat, water and nitrate down the soil profile. The evapotranspiration is modelled in relation with climatic demand, and

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according to Ritchie's (1972) model. Soil water content and fluxes are determined by a semi-empirical Darcy's law in the soil profile (Gabrielle et al., 1995).

A microbiological sub-model adapted from the NCSOIL model (Molina et al., 1983) simulates the turnover of the soil organic matter in the plow layer. Decomposition, mineralization and N-immobilization are modelled with three pools of organic matter (OM): the labil OM, the microbial biomass and the humads. Kinetic rate constants define the C and N flows between the different pools.

A biological sub-model simulates the growth and the phenology of the crops. The increase of daily biomass is controlled by net photosynthesis which is modelled by a Monteith approach. The production of biomass ($g\,DM\,m^{-2}\,day^{-1}$) is proportional to the amount of photosynthetically active radiation (PAR, $MJ\,m^{-2}\,day^{-1}$) intercepted by the crop canopy, using the concept of radiation use efficiency (RUE, $g\,DM\,MJ^{-1}\,m^{-2}$). Interception of PAR depends on leaf area index, and is based on Beer's law of diffusion in turbid media.

Direct field emissions of CO_2, N_2O, NO and NH_3 into the atmosphere are simulated with different trace gas modules. Here, we focus on gas emissions with global warming potential, i.e. CO_2 and N_2O.

Carbon dioxide exchanges between soil-plant system and the atmosphere are modelled via the net photosynthesis and SOC mineralization processes. Net primary production (NPP) is simulated by the crop growth module while heterotrophic respiration (Rs) is deduced from the SOC mineralization rates calculated by the microbiological sub-model. The net ecosystem production (NEP), which is calculated as NPP minus Rs, may be computed on a daily basis and directly tested against the net ecosystem exchanges measured by eddy covariance. The confrontation between the daily rates of simulated and measured NEP provides a good opportunity to test the simulation of C dynamics by the soil-crop model.

CERES-EGC uses the semi-empirical model NOE (Hénault et al., 2005) for simulating the N_2O production in the soil through both the nitrification and the denitrification pathways. Denitrification component is derived from the NEMIS model (Hénault and

Germon, 2000) that calculates the denitrification as the product of a potential rate with three unitless factors related to soil water content, nitrate content and temperature. Nitrification is modelled as a Michaëlis-Menten reaction with NH_4^+ as substrate that additionally is controlled by response functions of the soil water content and temperature. Nitrous oxide emissions resulting from the two processes are soil-specific proportions of total denitrification and nitrification pathways.

CERES-EGC runs on a daily time step and requires input data for agricultural management practices, climatic variables (mean air temperature, daily rain and Penman potential evapotranspiration), and soil properties.

2.3 The indirect GHG emissions

The GHG emissions (CO_2, N_2O and CH_4) associated with input production and agricultural operations were calculated from the Ecoinvent life cycle inventory database (Nemecek et al., 2003). The inventory of elementary management operations comprises soil tillage, fertilisation, sowing, plant protection, harvest and transport, and may be translated in terms of GHG emissions thanks to emission factors. Similarly, the production of agricultural inputs (fertilizers, pesticides, seeds and agricultural machinery) induces GHG emissions that arise mainly from fossil fuel combustion, and were included in the indirect emissions.

2.4 Model evaluation

Two statistical indicators were used to evaluate the performance of the model to fit with the observed data. Mean deviation (MD) was defined as: $MD = E(O_i - S_i)$ and the root-mean squared error as: $RMSE = (E\left[(O_i - S_i)^2\right])^{1/2}$ where O_i and S_i are the time series of the observed and the simulated data, and E denotes the expectancy (Smith et al., 1996).

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3 Results and discussion

3.1 Model testing

3.1.1 Crop growth

At Grignon, the crop growth was well simulated, as reported in Fig. 1. The time course of total above ground biomass was correctly captured by the model, along with its partitioning into leaves, stems and ears. The final simulated grain yield (8.8 t dry matter $DM\,ha^{-1}$) was close to the observed value (8.7 t $DM\,ha^{-1}$). The LAI increase during the vegetative period was well predicted, but the senescence phase was a little too early in comparison with the observations (Fig. 1b).

At the Rafidin site, CERES-EGC provided good simulations of rapeseed growth for the N1 and N2 treatments (Fig. 2). The simulated patterns of biomass, LAI and N content variations matched the observations over the entire growing cycle. Final grain yields were correctly estimated, with a simulated value of 3.8 t $DM\,ha^{-1}$ and an observed one of 4.1 t $DM\,ha^{-1}$ for N1, and an exact match at 4.9 t $DM\,ha^{-1}$ for N2. For the N0 treatment (unfertilized), the model overestimated LAI by a factor of 2 throughout the growing season, but total above ground biomass was underestimated by about 25% when compared to the data (not shown). For this treatment, the simulated N stress was too high at the end of the crop's growing cycle to allow sufficient grain filling, and the final grain yield was under-estimated as a result.

3.1.2 Net carbon exchanges

The carbon dioxide exchanges measured with micrometeorological systems are usually used to test soil-vegetation-atmosphere transfer (SVAT) models for forest or cropland surface (e.g. De Noblet et al., 2004; Dufrêne et al., 2005; Wang et al., 2005). Here, the originality of our approach was to use these measurements to test the CO_2 exchanges simulated with a crop model, and more specifically the ability of CERES-

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EGC to simulate the net CO_2 fluxes at the daily time scale. Daily net ecosystem production (NEP) was well predicted (Figs. 1c and d), and was primarily dependent of the net primary production before the soil respiration. The root-mean squared error between model and data NEP values was $1.90\,g\,C\,m^{-2}\,d^{-1}$, the mean difference was -$0.38\,g\,C\,m^{-2}\,d^{-1}$, and the model-data coefficient of determination (R^2) was 0.81. Adiku et al. (2006) have developed a model (PIXGRO) for simulating the ecosystem CO_2 exchange and growth of spring barley by coupling a canopy flux model and crop growth model. Their predictions for CO_2 exchanges were more accurate than ours (R^2=0.92), but they focused their model testing on the gross primary production, without including the soil and plant respiration terms as we did. Because both the accumulation of atmospheric CO_2 into crop biomass and the net ecosystem exchanges at the soil/plant-atmosphere interface were well simulated by the CERES-EGC model, we may hypothesise that the carbon dynamics were correctly predicted over the entire maize growing cycle. Based on this result, we further assumed in the following that CERES-EGC could be extrapolated to calculate the net C exchanges over an entire crop rotation.

3.1.3 Nitrous oxide emissions

Figure 3 provides a test for the simulation of the key drivers of N_2O emissions at the Grignon site. Soil moisture, temperature and inorganic N content control N_2O emissions by their influence on the nitrification and denitrification processes. At Grignon, for the period of measurement (13 May to 12 June 2005), their dynamics were well simulated (Figs. 3a, b, c), except for the nitrate content which was not as much removed by the crop uptake at the end of the crop cycle as it was measured (Fig. 3c). However, the model simulated two peak fluxes of N_2O that were not observed in the field (Fig. 3d). The comparison between simulated and observed data, reported in Table 2, shows, on the one hand, a good performance of the model to simulate the controls of the nitrification and denitrification processes, but also, a large lack of fit in the prediction of N_2O emissions (RMSE=$20.51\,g\,N\,ha^{-1}\,d^{-1}$, MD=$-6.09\,g\,N\,ha^{-1}\,d^{-1}$, R^2=0.004, n=31). The first peak flux of N_2O occurred four days after the application of fertilizer N, in

response to rainfall and high soil N content ($\sim$180 kg N ha^{-1}) in the 0–30 cm topsoil layer. The model anticipated this peak by 3 days compared to the observations. This may be explained by a possible time lag between the production of gaseous N_2O in the soil and its emission to the soil surface via a gas diffusion process in the soil which is

5   not accounted for by the model.

Two additional peak fluxes were simulated by the model on days of year (DOY) 149 and 156–157, as a consequence of rainfall and high nitrate content in soil. Despite these a priori conducive conditions for N_2O emissions, only very small peaks were observed in the field. Therefore, we may hypothesize that for the Grignon' soil the

10 first peak of N_2O emissions might have been produced in response to the high ammonium content in topsoil (110 kg N-NH$_4$ ha^{-1} in 0–30 cm) rather than high nitrate content (70 kg N-NO$_3$ ha^{-1} in 0–30 cm). The absence of N_2O peaks on DOY 149 and 156–157 further supports this hypothesis because in this time period, topsoil ammonium had completely nitrified whereas topsoil nitrate content was still high (60 kg N-NO$_3$ ha^{-1}).

15 There was in addition a good correlation between the measured N_2O fluxes and soil NH_4^+ content. For the Grignon soil, this could mean that nitrifier denitrification could be an important pathway of N_2O production and emission. This is further supported by the fact that during this time period the water-filled pore space (WFPS) predicted by the model was greater than 62% – the threshold that triggers denitrification in the

20 model (Hénault et al., 2000; see Fig. 4). Further investigations in the field and in the laboratory are required to validate this hypothesis.

As a consequence of the discrepancies between the predicted and observed emission pulses, the modelled N_2O emissions totaled 338 g N-N_2O ha^{-1} over the entire measurement period (from DOY 133 to 163), whereas the observed ones totaled

25 145 $\pm$ 104 g N-N_2O ha^{-1} which implies an overestimation of 133% by the model.

Other studies with similar modeling approaches mention that the discrepancies between modelled and observed N_2O data were in the same range of errors than our simulations. For example, Babu et al. (2006) indicate that the DNDC model predicted daily N_2O fluxes with a large lack of fit (RMSE=529.6 g N ha^{-1} day^{-1}, n=134) for rice-based

production systems in India. In the same way, Del Grosso et al. (2005) showed that the DAYCENT model gave daily prediction of N_2O emissions with a quite high discrepancy (RMSE=64%, R^2=0.74, n=21) for major crops in the USA. Frolking et al. (1998) and Li et al. (2005) have compared different models or sub-models for their aptitude to sim-
5 ulate N_2O emissions from cropland, and in most cases, the models were not able to capture the daily N_2O flux patterns because of temporal deviation of the fluxes, time lag between observed and modelled peaks and over- or underestimation of the measured peak fluxes.

At Rafidin, N_2O emissions were very low even for the high-N input treatment (N2).
10 In fact, for this treatment, the highest emission rate measured was 7.4 g N ha^{-1} d^{-1}, which is four times lower than the highest N_2O emission rate recorded at the Grignon site. The microbiological parameters of the Rafidin soil for denitrification-mediated N_2O emission were very low in comparison to other soils previously analyzed (Garrido et al., 2002; Hénault et al., 2005). The potential denitrification rate (PDR) was only
15 1 kg N ha^{-1} d^{-1}, and the fraction of denitrified nitrate evolved as N_2O was equal to 9%. In the literature, this potential was reported to vary between 2.5 and 9.5 kg N ha^{-1} d^{-1} for two Gleyic Luvisols, and was around 16 kg N ha^{-1} d^{-1} for Haplic Calcisol and Haplic Luvisol. In addition, the fraction of denitrified nitrate evolved as N_2O is generally above 20% (Hénault et al., 2005). In our case, this means that the rates of N_2O emissions
20 from denitrification were quasi nil. Hénault et al. (2005) estimated that 98% of the N_2O emissions originated from the nitrification process at the same Rafidin site. In addition, the same authors showed that a high proportion (84%) of nitrification-mediated N_2O was subsequently reduced to N_2 through denitrification, when the two processes were concurrent. We accordingly reduced the proportion of total nitrification evolved as N_2O,
25 which resulted in a better fit between simulated and observed N_2O fluxes. For the three fertilizer N treatments, the key drivers of N_2O emissions were correctly simulated (see Table 2 and Fig. 5 for the N1 treatment), and the predicted rates of N_2O emissions were satisfactory, with RMSEs of 0.31, 1.29 and 2.16 g N ha^{-1} d^{-1} for the N0, N1 and N2 treatments, respectively (see Table 2).

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3.2 Simulation of crop rotations

In the previous section, we tested the CERES-EGC model against datasets from two intensive experiments involving different sets of crop types, pedoclimatic conditions, and agricultural practices. The present section deals with the extrapolation of the model
5 to calculate the GWP of complete cropping systems, including soil C balance and direct emissions of N_2O in the field. The third term of the GHG balance, namely the indirect emissions, was also added.

The different crops occurring within a given rotation are inter-related in terms of pest management, nutrients' turn-over, and soil organic and mineral status. In addition, the
10 nutrients derived from fertilizers or biological fixation may be recycled or stored into the pools of the SOM, and may be re-emitted into air or water in subsequent years (Del Grosso et al., 2005). That is the reason why it is not relevant to calculate the GWP of a single crop, but rather of a complete sequence of crops. The GWP of this rotation may subsequently be re-allocated to a particular crop based on its frequency of occurrence
15 in the rotation, or similar rules.

3.2.1 Net ecosystem production and soil organic carbon dynamic

The carbon dioxide exchanges for a crop growing cycle were assumed to start upon harvest of the preceding crop, and to stop upon harvest of the crop considered. The values of the Fig. 6 were obtained carrying by averaging the fluxes simulated over
20 10 maize-wheat-barley rotations on a 33-yr series of historical weather data (1972–2005), with constant crop management. The 30-yr simulation allowed us to explore the climatic variability and its effect on the net primary production and soil respiration. The net production was highest with the maize crop, amounting to $6590 \pm 1460 \, \text{kg C ha}^{-1}$, whereas the NEP of the wheat and barley crops were close to $4000 \, \text{kg C ha}^{-1}$. For the
25 mustard, the soil respiration term was greater than net photosynthesis, and NEP was $-2000 \, \text{kg C ha}^{-1}$. Inter-annual variability was quite large for the net primary production, showing a strong dependence of the climate on crop growth. The year-round NEP

for the year 2005 (encompassing the maize cropping cycle) was $4100\,\mathrm{kg\,C\,ha^{-1}\,yr^{-1}}$, which is in accordance with Verma et al. (2005) who measured NEP values for irrigated and rainfed maize crops in Nebraska (USA) between 3800 and $5200\,\mathrm{kg\,C\,ha^{-1}\,yr^{-1}}$.

The net stock of C produced by the ecosystem was broken down into harvest products (grain and straw; see Table 3), which were removed from the system, and crop residues (roots, stubble, maize stalks), which were returned to the agro-ecosystem and underwent gradual decomposition by soil microflora.

The variation of SOC storage reflects the difference between net C uptake by plants, manure inputs, and losses from harvested plant products, crop residues decomposition and SOC mineralization. Over 30-yr simulation period with the maize-wheat-barley rotation in Grignon, we estimated a C sequestration of $135\,\mathrm{kg\,C\,ha^{-1}\,yr^{-1}}$ in the topsoil layer (see Fig. 7a), mainly due to the C inputs by the catch crops and crop residues. This value is in accordance with Arrouays et al. (2002), who indicate that the introduction of a catch crop in the rotation may induce a C sequestration of $160\pm80\,\mathrm{kg\,C\,ha^{-1}\,yr^{-1}}$. In Grignon, the straw of wheat and barley was removed for use as litter for animal production, whereas in Rafidin the straw was left on the soil surface at harvest, and subsequently incorporated into the topsoil layer. As a consequence, the C inputs from crop residues were much higher in Rafidin than in Grignon, averaging $4250\,\mathrm{kg\,C\,ha^{-1}\,yr^{-1}}$ for the N1 rotation and $4290\,\mathrm{kg\,C\,ha^{-1}\,yr^{-1}}$ for the N2 rotation. With these levels of C inputs to the soil, the CERES-EGC model predicted a C sequestration of $730\,\mathrm{kg\,C\,ha^{-1}\,yr^{-1}}$ for the N1-rotation and $750\,\mathrm{kg\,C\,ha^{-1}\,yr^{-1}}$ for the N2-rotation, suggesting that the Rafidin soil was a potentially large sink for atmospheric CO_2.

To cross-check the above estimate, we used a simplified, one-compartment SOC model based on a C Input-Output balance (Hénin and Dupuis, 1945). Annual inputs to SOC are calculated as a fixed proportion of residue inputs using a humification rate, and C mineralization losses are proportional to total SOC. The parameters were set according to previous work on rendzina soils of the area (Ballif et al., 1995; Trinsoutrot et al., 2000). The model also predicted a high C storage of $580\,\mathrm{kg\,C\,ha^{-1}\,yr^{-1}}$ for the N2 treatment, which was however 20% lower than the CERES-EGC estimate. This stems

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from the relatively low SOC mineralization rate of rendzina soils (<0.5% of SOC yr^{-1}), due to physical protection process by the formation of calcite formation on the organic fractions. Thus, the high level of biomass production permitted by ample fertilizer inputs and the low SOC mineralization rate of the rendzina soil induced a large potential of C storage, and accordingly a net fixation of atmospheric CO_2.

3.2.2 Indirect emissions

The GHG cost of agricultural inputs contributes a large part of the GWP of agro-ecosystems. For the Grignon cropping system, the mean indirect emissions were 360 kg CO_2-C eq ha^{-1} yr^{-1}, and for the Rafidin system, the mean IE were 410 and 460 kg CO_2-C eq ha^{-1} yr^{-1} for the N1 and N2 treatments, respectively. The production of these inputs – particularly N fertilizer production is the top contributor to the IE by a wide margin, with a 55-65% share (Fig. 8). Cropping operations came next, with a 30-40% in the total IE term, mainly due to from fossil-fuel combustion by farm machinery. The transport of inputs from the production plant to the farm was the lowest contributor to the GWP with less than 1% of IE.

3.3 Global Warming Potential

The 30-yr simulation period enabled us to explore the effect of climate variability on biomass production and N_2O emissions. At Grignon, N_2O emissions averaged 110±40 kg CO_2-C eq ha^{-1} yr^{-1} (CV=36%) over the maize growing cycle, and we finally estimated a GWP of 350±35 kg CO_2-C eq ha^{-1} yr^{-1} (Table 3) for this system. This value is closed to that of 310 kg CO_2-C eq ha^{-1} yr^{-1}, measured by Robertson et al. (2000) for a conventional maize-soybean-wheat system in the Midwest United States, although its breakdown was quite different. The latter authors found no measurable soil C sequestration with conventional tillage, whereas we found a significant storage. Also, the system boundaries they set for the indirect emissions were narrower than ours. They only accounted for the CO_2 emissions occurring during the production of agricultural

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inputs, and not the other GHG (CH_4 and N_2O), although these may account for half of the total indirect emissions of GHG. Consequently, we estimated a twice higher IE term, which was compensated for by a positive SOC storage in the final balance.

At Rafidin, we estimated very low N_2O emissions (<40 kg CO_2-C eq ha^1 yr^1), and a large C storage potential resulting from the high level of residue return. The more than offset the emissions of N_2O and the indirect emissions, so that the GWP was -290±10 kg CO_2-C eq ha^{-1} yr^{-1} for the N1 system and -250±10 kg CO_2-C eq ha^{-1} yr^{-1} for the N2 system (Table 3). The Rafidin crop rotation is an intensive system with a high level of inputs and indirect emissions of GHG as a result, but it is compensated for by the resulting high potential of biomass production and SOC storage. Overall, the Rafidin system emerges a potentially strong sink of GHG.

4 Conclusions

The assessment of the direct emissions at the field scale is paramount in an accurate estimation of GHG balances for agricultural systems. Biophysical modelling of the soil-crop-atmosphere system provides a unique capacity to address this issue while taking into account the complex interactions between C and N cycling, as influenced by anthropogenic actions. Here, we tested the ability of the CERES-EGC model to simulate the GHG emissions, and showed it achieved satisfactory predictions of N_2O and CO_2 fluxes for two cropping systems representing distinct pedoclimatic conditions and agricultural practices. As a result, their GWP were markedly different: the wheat-maize-barley rotation on a loamy soil was a net source of GHG, with a GWP of 350 kg CO_2-C eq ha^{-1} yr^{-1},while the oilseed rape-wheat-barley rotation on a rendzina was a net sink of GHG with a GWP of –250 kg CO_2-C eq ha^{-1} yr^{-1}.

The C dynamics predicted by the model were validated at the daily time scale against micrometeorological measurements of CO_2 exchanges in one of the sites, but it will be necessary to supplement this test by further verifying the ability of CERES-EGC to simulate the rate of changes in the long term. Improvements may also be sought for

the N_2O emission sub-model through tests on a wider range of experimental sites and datasets, in order to broaden its validation field and to develop its robustness, or to include new processes (e.g. nitrifier denitrification) in the modeling system. With a sufficiently large sample of experimental datasets, Bayesian methods may be applied to calibrate some of the parameters of this sub-model, and carry out an uncertainty analysis of the simulations (Van Oijen et al., 2005).

The modeling approach presented here could also be used to devise different strategies to mitigate the GWP of cropping systems. Various scenarios involving some modifications of crop management (e.g., fertilization, rotation, crop types) could be tested for this purpose. Other environmental impacts may be output by the model and included in the analysis, in particular the emissions into air or water of NH_3, NO_3^-, or NO. Thus, the overall environmental balance of the agricultural systems may be approached, making it possible to design agricultural systems with high environmental performance.

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Table 1. Experimental treatments and fertilizer N input rates at the Grignon and Rafidin sites.

| Site | Crop | Sowing date | N Fertilizer | |
			Date	Amount (kg N ha^1)
Rafidin	Rapeseed N1	09/04/1994	20/02/1995	80
			15/03/1995	75
	Rapeseed N2	09/04/1994	12/09/1994	49
			20/02/1995	80
			15/03/1995	75
			29/03/1995	38
	Wheat	27/10/1995	10/02/1996	60
			10/03/1996	95
			10/05/1996	65
	Barley	27/10/1995	10/02/1997	90
			10/03/1997	80
Grignon	Wheat	16/10/2002	26/02/2003	52
			27/03/2003	60
	Barley	17/10/2003	18/02/2004	59
			19/03/2004	59
			02/04/2004	39
	Mustard	02/09/2004	31/08/2004	90 (Manure)
	Maize	09/05/2005	09/05/2005	140

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Table 2. Goodness of fit indicators for the simulation of N_2O drivers by CERES-EGC at Grignon and Rafidin (N1 and N2 treatments).

		Grignon		Rafidin N1		Rafidin N2	
	Unit	MD	RMSE	MD	RMSE	MD	RMSE
Water content	v/v	0.01	0.03	0.02	0.04	0.01	0.03
Ammonium content	$kg\,NH_4\text{-}N\,ha^{-1}$	0.57	1.97	4.43	5.6	5.01	6.72
Nitrate content	$kg\,NO_3\text{-}N\,ha^{-1}$	20.83	25.53	−1.02	7.97	−4.45	15.46
N_2O emissions	$g\,N_2O\text{-}N\,ha^{-1}\,d^{-1}$	−6.09	20.51	−0.64	1.29	−0.03	2.16

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Table 3. Simulations of the grain yields, straw removal rates, and net global warming potential (GWP) of the Grignon and the Rafidin cropping systems, averaged over 30 years of simulation. The three terms included in the GWP are the variations in soil C storage, the N_2O emissions and the indirect GHG costs of agricultural inputs.

	Grain yield	Straw removal	Soil C	N2O	Agricultural inputs	Net GWP
	t DM ha^{-1}		kg CO2-C eq ha^{-1} y^{-1}			
GRIGNON						
Maize	9.3	0	−102	108 (39)	330	336 (39)
Wheat	10.2	4.2	−102	49 (18)	289	236 (18)
Barley	8.3	4.1	−102	154 (45)	417	469 (45)
Mustard	0	0	−102	89 (21)	35	22 (21)
Rotation			−136	133 (34)	357	354 (36)
RAFIDIN						
Rape N1	4.3	0	−732	35 (9)	359	−338 (9)
Wheat	7.3	0	−732	40 (6)	470	−222 (6)
Barley	7.1	0	−732	33 (6)	397	−302 (6)
Rotation N1			−732	36 (7)	409	−287 (7)
Rape N2	4.8	0	−750	44 (10)	506	−199 (10)
Wheat	7.3	0	−750	41 (7)	470	−239 (7)
Barley	7.1	0	−750	34 (7)	397	−319 (7)
Rotation N2			−750	40 (8)	460	−253 (8)

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Fig. 1. Simulated (lines) and measured (symbols, ± sd) data for **(a)** shoots, roots and aerial catch crop dry matter; **(b)** Leaf Area Index (LAI); **(c)** net ecosystem production (NEP) and **(d)** comparison between simulated and observed NEP for the experiments on the maize crop at Grignon in 2005 (France).
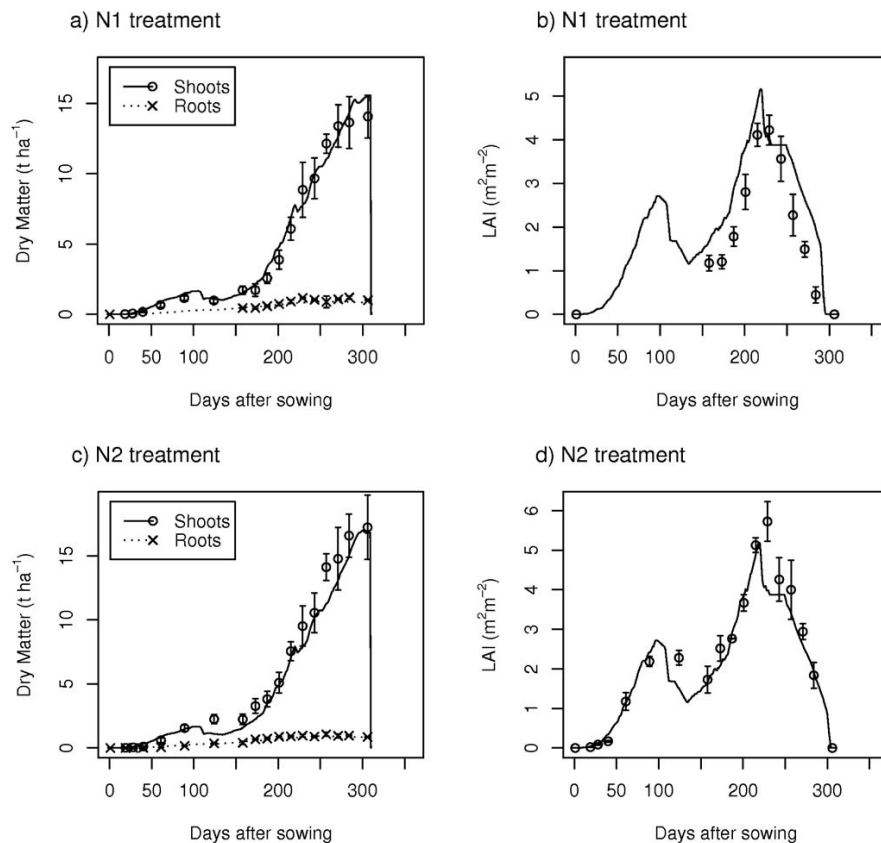
Fig. 2. Simulated (lines) and measured (symbols, ±sd) data for **(a)** shoots and roots dry matter for N1 treatment; **(b)** Leaf Area Index (LAI) for N1 treatment; **(c)** shoots and roots dry matter for N2 treatment and **(d)** Leaf Area Index (LAI) for N2 treatment, in 1995 at Rafidin (France).
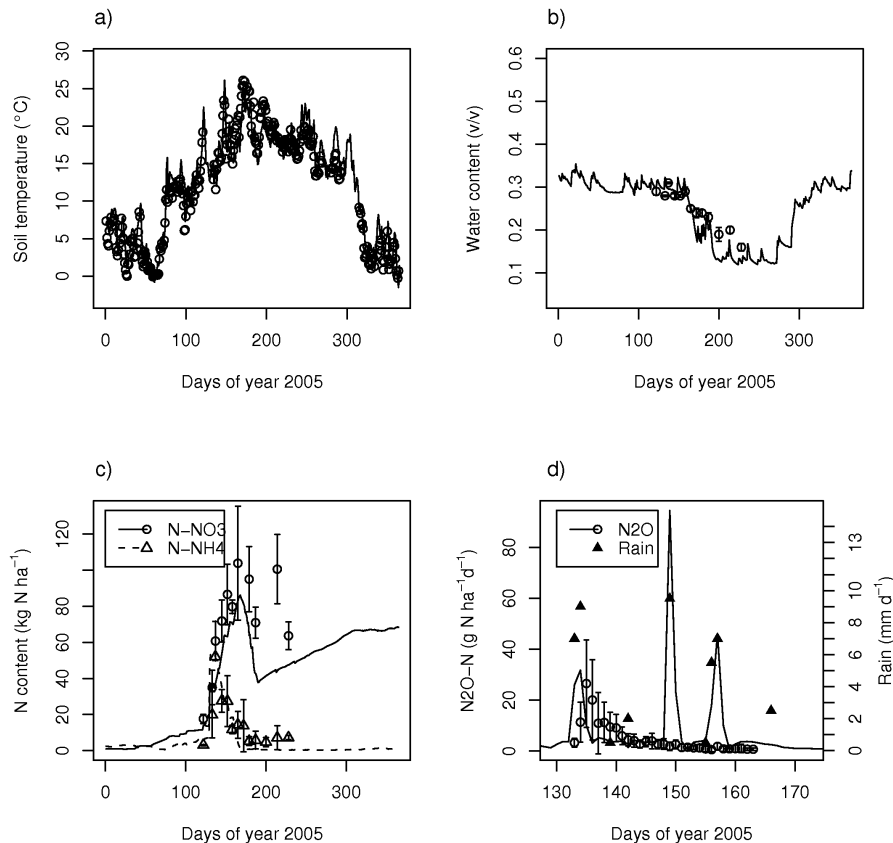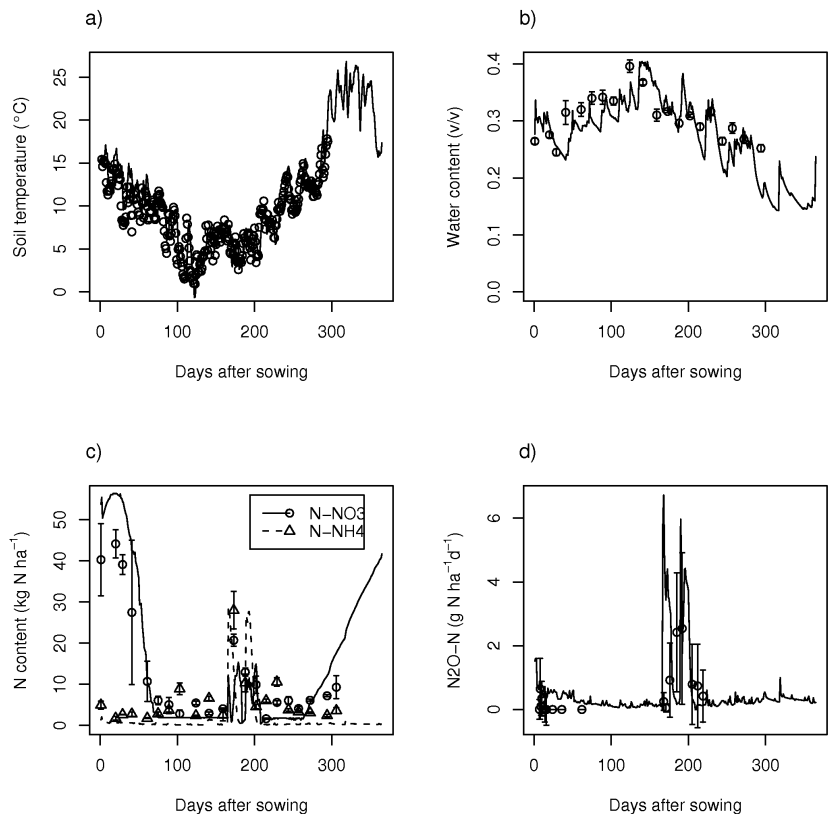
Fig. 3. Simulated (lines) and measured (symbols, ±sd, when available) topsoil (0-30 cm) data for **(a)** soil temperature; **(b)** soil water content; **(c)** soil NO_3-N and NH_4-N contents and **(d)** N_2O emissions and rainfall for the maize experiments at Grignon. The error bars for the N_2O observations correspond to the variability (sd) between the three chambers of measurement.

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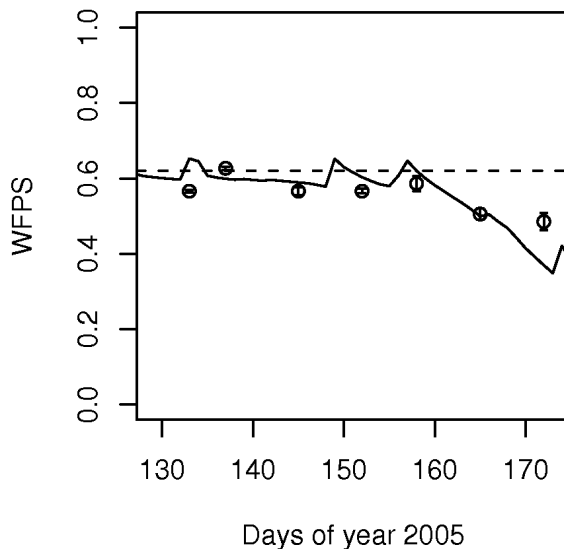
Fig. 4. Simulated (line) and observed (symbols, ±(sd) water-filled pore space (WFPS), and 0.62 threshold for the WFPS function in the N_2O sub-model (dashed line; Grignon, 2005).

Fig. 5. Simulated (lines) and measured (symbols, ±sd when available) topsoil (0-30 cm) data for **(a)** soil temperature; **(b)** soil water content; **(c)** soil NO_3-N and NH_4-N contents and **(d)** N_2O emissions for the rapeseed N1 experiment at Rafidin. The error bars for the N_2O observations correspond to the variability (sd) between the 8 measurement replicates.
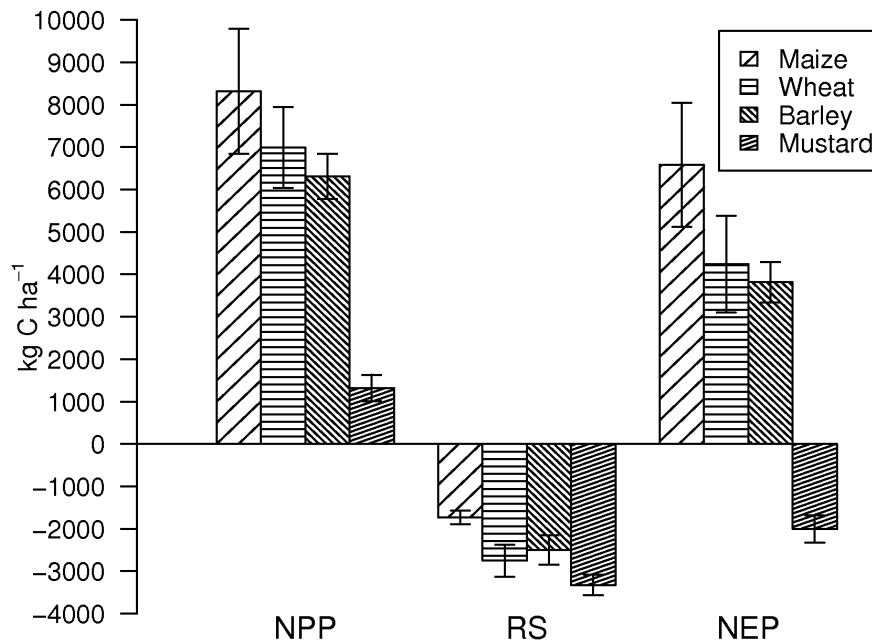
Fig. 6. Breakdown of net ecosystem production (NEP) into net primary production (NPP) and soil respiration (Rs) for the four crops of the rotation (Maize, Wheat, Barley and Mustard) at the Grignon site.
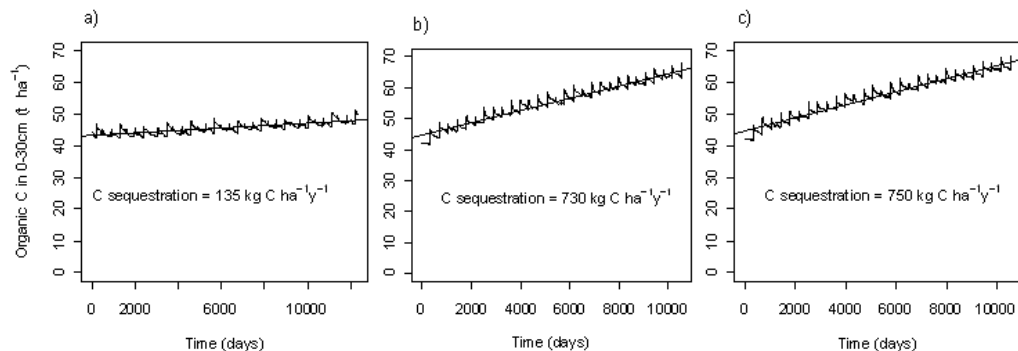
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Fig. 7. Simulated changes of C stock ($t\,C\,ha^{-1}$) in the topsoil (0–30 cm), from 1972 to 2005, for the Maize-Wheat-Barley-Mustard rotation in Grignon **(a)**, and from 1973 to 2002 for the N1 Rapeseed-Wheat-Barley **(b)** and the N2-Wheat-Barley rotations in Rafidin **(c)**.
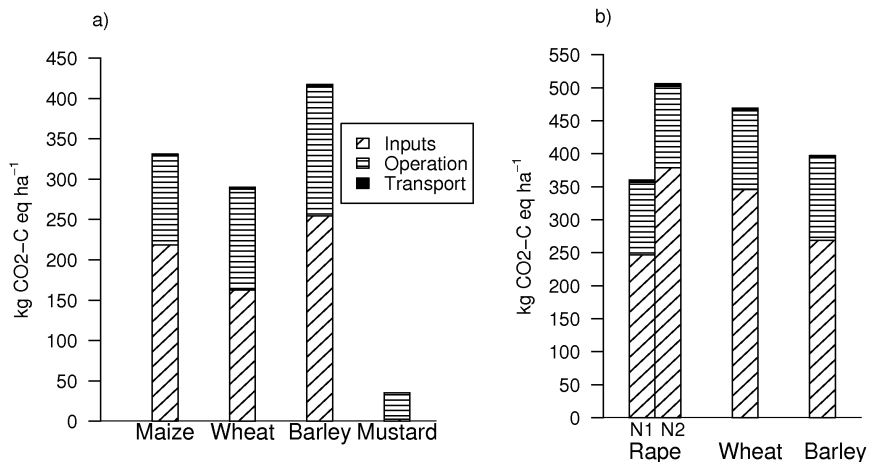
Fig. 8. Greenhouse gas cost of agricultural inputs and cropping operations for crop production (indirect emissions) for the Grignon **(a)** and Rafidin **(b)** cropping systems. The emissions are broken down into the input production, agricultural operations and transports steps.

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