The greenhouse gas balance of European grasslands

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Abstract

The greenhouse gas (GHG) balance of European grasslands (EU28 plus Norway and Switzerland), including CO_2, CH_4 and N_2O, is estimated using the new process-based biogeochemical model ORCHIDEE-GM over the period 1961-2010. The model includes: 1) a mechanistic representation of the spatial distribution of management practice; 2) management intensity, going from intensively to extensively managed; 3) gridded simulation of the carbon balance at ecosystem and farm-scale; and 4) gridded simulation of N_2O and CH_4 emissions by fertilized grassland soils and livestock. The external drivers of the model are changing animal numbers, nitrogen fertilization and deposition, land-use change, and variable CO_2 and climate. The carbon balance of European grassland (NBP) is estimated to be a net sink of 15 ± 7 g C m^{-2} yr^{-1} during 1961-2010, equivalent to a 50-year continental cumulative soil-carbon sequestration of 1.0 ± 0.4 Pg C. At the farm-scale, which includes both ecosystem CO_2 fluxes and CO_2 emissions from the digestion of harvested forage, the net C balance is roughly halved, down to a small sink, or nearly neutral flux of 8 g C m^{-2} yr^{-1}. Adding CH_4 and N_2O emissions to net ecosystem exchange to define the ecosystem-scale GHG balance, we found that grasslands remain a net GHG sink of 19 ± 10 g C-CO_2 equiv. m^{-2} yr^{-1}, because the CO_2 sink offsets N_2O and grazing animal CH_4 emissions. However, when considering the farm scale, the GHG balance (NGB) becomes a net GHG source of -50 g C-CO_2 equiv. m^{-2} yr^{-1}. ORCHIDEE-GM simulates an increase of European grassland NBP during the last five decades. This enhanced NBP reflects the combination of a positive trend of net primary production due to CO_2, climate and nitrogen fertilization and the diminishing requirement for grass forage due to the Europe-wide reduction in livestock numbers.

Introduction

Grasslands cover 56.8 million ha (13.2%) of the land area in the EU-27 (Eurostat, 2010). Yet grassland is not the climax natural vegetation for most parts of Europe (except alpine grasslands above the treeline and wetlands), it has been established and managed to feed livestock. Not all pasture is intensively managed. Livestock production involves a variety of cultivation practices and management strategies, which can be classified as intensive or extensive management (Souty *et al.*, 2012). Farmers can graze their animals in fields, harvest grass for forage production, grow fodder crops or buy complementary feed products. The latter is now common for dairy cattle. Different grassland management practices are often combined together in the same farm. Nitrogen-rich mineral and organic fertilizer (manure) are also now commonly applied to European grasslands to maintain the output of animal and dairy products from grass primary productivity. As a result of these interventions the managed semi-natural grasslands of Europe generate a set of CO_2 fluxes exchanged with the atmosphere: the net balance may be a source or a sink. They are also sources of enteric methane (CH_4) emissions by grazing ruminants (and the decomposition of their excrement) and of nitrous oxide (N_2O) emission from fertilized soils.

European grasslands exchange carbon (C) as CO_2 between plants and soils, and the atmosphere by photosynthesis and respiration — fire being negligible. For those grasslands that are regularly mown to produce fodder, harvested biomass is later returned to the atmosphere, often within the same farm, in the form of CO_2 and CH_4 emitted by animal digestion or by manure and slurry decomposition. When grasslands are grazed, biomass ingested by animals contains digestible and non-digestible organic compounds. The non-digestible C fraction (25-40%; the actual range reflects the digestibility of the grazed herbage) of the intake is returned to the field through excreta (faeces and urine). The digestible part is respired as CO_2 shortly after intake. Only a small fraction serves to increase animal mass or to form animal products (e.g., milk and butter) which are exported from the grassland ecosystem (Soussana *et al.*, 2010). Another small part of the digested C is emitted in the form of CH_4 by ruminant enteric fermentation. Soil microbial nitrification and denitrification produce N_2O in soil, processes which depend on temperature, pH, moisture and C availability (Maag & Vinther, 1996; Velthof & Oenema, 1997). The N_2O emissions are enhanced by the nitrogen fertilizer inputs often applied to European grasslands. Given that these fluxes are intimately linked to diverse agricultural practices, the C and greenhouse gas (GHG) balance of managed European grasslands cannot be estimated by using ecological principles or data from natural grasslands. The GHG balance of grassland at local, regional and continental scale is also profoundly impacted by the nature, frequency and intensity of disturbance (e.g., mowing, grazing and manure application, see Soussana *et al.*, 2007).

Several approaches have been used to assessing the C and/or GHG balances of grassland. Eddy-covariance (EC) measurements provide ecosystem-scale CO_2 flux observations at a few European grassland sites (Gilmanov *et al.*, 2007). The C balance and furthermore the GHG balance have been estimated by combining EC observations with data on the lateral input and export of C, as well as CH_4 and N_2O measurements (Allard *et al.*, 2007; Soussana *et al.*, 2007). However, these observation-based estimates usually have limited spatial coverage, and have only been conducted for short periods (e.g., less than a decade). Repeated soil C inventories provide another way to measure the cumulative grassland soil C balance over several years, although they do not measure short-term variability. For example, a national soil inventory has been running since 1978 in England and Wales (Bellamy *et al.*, 2005), but soil bulk density was not measured which increased uncertainties in soil organic carbon (SOC) stock change estimates (Smith et al., 2007). The press by Soussana et al. (2010)

indicated that grassland C sequestration reaches on average 5 ± 30 g C m^{-2} yr^{-1} according to inventories of SOC stocks and 77 g C m^{-2} yr^{-1} for mineral soils according to C flux balance measurements. In addition, empirical approaches were developed to estimate the C and GHG balances. Freibauer (2003) assessed the annual direct biogenic emissions of GHGs of grasslands based on empirical methods and statistics. The simple semi-empirical model CESAR (Vleeshouwers & Verhagen, 2002) was used to infer a C sink in European grasslands at continental scale with large uncertainties (66 ± 90 g C m^{-2} yr^{-1}, Janssens *et al.*, 2003) using only yield census data and land-use change induced soil carbon disturbances.

Process-based models that explicitly represent mechanisms controlling carbon cycling in ecosystems and their water/energy (sometimes nitrogen) interactions are suitable tools to predict long-term C flux responses to external factors such as climate change and management. But these models have many parameters that must first be calibrated for managed grasslands; management processes must also be parameterized. For example, at European scale, Smith *et al.* (2005) predicted either small sources or small sinks of C in grasslands depending on the chosen IPCC-SRES climate and CO_2 scenarios, by using the Roth-C soil organic carbon model (Coleman & Jenkinson, 1996) with net primary productivity (NPP) calculated by the LPJ model (Sitch *et al.*, 2003) and a yield database where management practices were not documented. Levy *et al.* (2007) made a 20-year spatially explicit simulation with the DNDC model to estimate a CO_2 sink in European grasslands, but found a net radiative forcing source when CH_4 and N_2O emissions were accounted for. Management practices were represented in DNDC, but were prescribed from survey data as static drivers for large biogeographical zones. Vuichard *et al.* (2007) assessed the total C sequestration potential, and potential GHG balance using the PaSim process-based grassland model, with an algorithm that defines management practices to maximize the production of livestock from NPP in each grid cell. Although their idea of modelling management as a mechanism in a process model was appealing, it fell short of reproducing actual livestock production and a GHG balance, because net primary production is not the only driver; commercial considerations and policies also determine farmers' management strategies.

This study uses the new process-based biogeochemical model ORCHIDEE-GM version 2.1 with an enhanced representation of grassland management derived from PaSim (Chang *et al.*, 2013, 2015). We tackle the following research questions:

1) What are the carbon and the GHG balance of European grasslands at different scales: ecosystem and farm?

2) How have the carbon and GHG balance evolved during the past 50 years?

3) What factors drove the temporal evolution of the carbon and GHG balances?

Material and methods

Model description

ORCHIDEE is a process-based ecosystem model built for simulating carbon cycling in ecosystems, and water and energy fluxes from site to global scale (Krinner *et al.*, 2005; Ciais *et al.*, 2005; Piao *et al.*, 2007). ORCHIDEE-GM is a recent version that includes the grassland management module from PaSim, a grassland model developed for site applications (Chang *et al.*, 2013). ORCHIDEE-GM version 1 was evaluated at 11 European grassland sites representative of a range of management practices; some of its parameters were calibrated with eddy-covariance net ecosystem exchange (NEE) and biomass measurements. ORCHIDEE-GM proved capable of simulating the dynamics of leaf area index (LAI), biomass and NEE of managed grasslands, although the performance at cut sites was better than at grazed sites (Chang *et al.*, 2013). At continental scale, ORCHIDEE-GM version 2.1 was then applied over Europe on a 25 km grid with 3-hourly climate forcing data to calculate the spatial pattern, long-term evolution and interannual variability of *potential* productivity (Chang *et al.*, 2015). The term *potential* refers here to the productivity that would maximize modelled livestock production in each grid cell using the algorithm of optimal management developed by Vuichard *et al.*, 2007. Chang *et al.* (2015) further added a parameterization to describe the adaptive management strategy of farmers who react to a climate-driven change of the previous years' productivity. At European scale, the grass-fed livestock numbers of each NUTS (Nomenclature des Unités Territoriales Statistique; Eurostat, 2007) region of the Eurostat statistical database is well reproduced by ORCHIDEE-GM (R^2 = 0.76; Chang *et al.*, 2015). Though a full nitrogen cycle is not included in ORCHIDEE-GM version 2.1, the positive effect of nitrogen addition on grass photosynthesis, and thus on the subsequent ecosystem carbon balance, is parameterized with a simple empirical function calibrated from literature estimates (Chang *et al.*, 2015).

Grass-fed livestock numbers in Europe

FAOstat (2013) provides annual country-averaged statistical data for dairy cows, beef cattle, sheep and goats of livestock numbers (with the unit in heads), and meat (carcass weight) or milk yield, as appropriate. Data are available from 1961 till now. Livestock species are converted here to livestock unit (LU) based on the calculation of metabolisable energy requirement, and further feed requirement of each type of animal. In this study, metabolisable energy requirement, the amount of energy (MJ day^{-1}) an animal needs for maintenance and for activities such as lactation, and pregnancy, were calculated following the IPCC Tier 2 algorithms (IPCC, 2006 Vol 4, Chapter 10, Eqns 10.3 to 10.13; see Supporting information for detail). One LU is defined as an average adult dairy cow producing 3000 kg milk annually, with live body weight of 600 kg (Eurostat, 2013; with metabolisable energy requirement of ca. 85 MJ day^{-1}, and with dry matter intake of ca. 18 kg daily calculated in Supporting information Text S1).

Ruminant livestock are not only fed on grass, they also receive feed and residues (from crop products). Thus, each year for each country, the observed number (LU) of *grass-fed* livestock (N_{obs}) was derived by the equation:

$$N_{obs} = N_{beef} \times f_{beef} + N_{dairy} \times f_{dairy} + N_{sheep} \times f_{sheep} + N_{goats} \times f_{goats} \quad (1)$$

where N_{beef}, N_{dairy}, N_{sheep} and N_{goats} are the total LU numbers of beef cattle, dairy cows, sheep, and goats calculated from FAOstat statistics and f_{beef}, f_{dairy}, f_{sheep} and f_{goats} are the grass-fed fraction of each type of animal, taken from Bouwman *et al.* (2005).

ORCHIDEE-GM is designed to simulate gridded *potential* livestock density and its temporal evolution (Chang *et al.*, 2015). Recently, the HIstoric Land Dynamics Assessment, or *HILDA,* data set has been constructed (Fuchs *et al.*, 2013). The data set, which comprises harmonized, high-resolution historic land-change data for Europe covering the period of 1950-2010, is well suited for GHG assessments. The modelled potential livestock density (see Chang *et al.*, 2015 for detail) in every grid cell of the European continent was combined with the actual grassland area in each grid cell from the *HILDA* land-cover map (data from 1961-2010 were used), each year for each country. The potential grass-fed livestock number ($N_{sim\text{-}pot}$) is then given by:

$$N_{sim-pot} = \sum(D_i \times A_i) \tag{2}$$

where for grid-point i, D_i is the potential livestock density and A_i is the grassland area.

Managed grasslands in Europe: intensive vs. extensive

We describe in this section how different types of management are defined in ORCHIDEE-GM version 2.1. Although grasslands in Europe are cultivated to produce livestock, they are not necessarily so intensively managed that they reach their biological potential, i.e., the maximum number of grass-fed animals that can be sustained by NPP. For example, in mountain areas, low productivity grasslands can only be extensively managed i.e. as rough grazing with only occasional mowing and with very little use of synthetic chemicals or treatments. In the second half of the 20th century, widespread abandonment of grasslands was also common in Europe, especially in central European and Baltic countries, driven by inter-related political and socio-economic changes, e.g., as reviewed by Joyce (2014).

The net C balance of a grassland (also named net biome productivity, NBP) is significantly correlated with the total C removed by grazing and mowing (Soussana *et al.*, 2007); this makes knowledge of management intensity (intensive or extensive) crucial for simulating the C and GHG balances. The *extensively managed grassland*, hereafter, represents newly abandoned grasslands with only occasional mowing or rough grazing. We define two simple rules to obtain the proportion of intensively/extensively managed grasslands for driving the ORCHIDEE-GM model, based on total forage requirement by grass-fed livestock numbers, and on the changes of the proportions in response to changes in productivity. These rules are based upon two assumptions: 1) N_{obs} defines the total amount of forage that must be supplied by both types of grassland in each grid cell, and 2) the fraction of grassland that must be intensively managed (as opposed to extensively managed) in each grid cell is used at their carrying capacity (i.e., livestock density corresponding to the biological potential of the grassland (Chang *et al.*, 2015)). Therefore, each year and for each country, the proportion of intensively managed grasslands (f_{int}) is expressed as:

$$f_{int} = {N_{sim-pot}}/{N_{obs}} \tag{3}$$

where $N_{sim\text{-}pot}$ and N_{obs} are the modelled potential and observed grass-fed livestock numbers respectively. The proportion of extensively managed grasslands (f_{ext}) is then calculated as:

$$f_{ext} = 1 - f_{int} \tag{4}$$

These fractions are calculated for every grid cell of each country. For some years in a few countries (Denmark, the Netherlands, Belgium, Luxembourg, Hungary, Italy and Greece), N_{obs} data suggest that grassland actual production exceeds the biological potential from ORCHIDEE-GM ($N_{obs} > N_{sim}$). In that case, all the grasslands are assumed to be managed at their biological potential (i.e., f_{int} = 1). Here we assume that high latitude grassland (over 65^{o}N) has no management applied (i.e., extensive agriculture on natural grassland), and this land is not included in the calculation of N_{sim}. Once the proportion of intensively managed grasslands is defined, the proportion of grazed versus cut grasslands is then calculated each year by the optimization algorithm of Vuichard *et al.* (2007) and the adaptive management response algorithm of Chang *et al.* (2015).

A detailed land management intensity map of European grasslands at 25 km resolution was established using Eqns (3) and (4). The map contains the relative yearly fractions of grassland under different management regimes from 1961 to 2010; it gives the proportions of extensively, as well as of intensively managed (cut and grazed) grasslands. This map incorporated in the *HILDA* land-cover data set defines an enhanced historic land-cover map delineating grassland management intensity. Our study domain covers 30 countries (EU-28 plus Norway and Switzerland), which are further divided into a number of major agricultural regions determined by both environmental and socio-economic factors (Table S1, for a detailed description see Olesen & Bindi *et al.*, 2002).

Simulation set-up

ORCHIDEE-GM is applied on a grid over Europe using the harmonized climate forcing data from the ERA-WATCH reanalysis for the period 1901–2010 and at a spatial resolution of 25' by 25' (Beer *et al.*, 2014). Mean and standard deviation of the ERA-Interim time series (Dee *et al.*, 2011) were adjusted according to the WATCH time series (Weedon *et al.*, 2010; Weedon *et al.*, 2011) by using the overlapping period 1989-2001. The harmonized data set was spatially downscaled to 25' by overlapping CRU CL2.0 (New *et al.*, 2002) monthly means to the spatial anomaly of the harmonized data sets for each single climatic variable. An altitude-based correction was applied for downscaling surface pressure according to a digital elevation map from CRU CL2.0. This resolution (25' by 25') is sufficient to represent regional meteorological regimes accurately in low-lying regions, but not in mountainous areas.

The gridded nitrogen application rate for mineral fertilizer and manure for European grasslands in the European Union (EU27) has been estimated by the CAPRI model (Leip *et al.*, 2011, 2014). Estimates were based on combined information from official and harmonized data sources such as Eurostat, FAOstat and OECD, and spatially dis-aggregated using the methodology described by Leip *et al.* (2008). The data are estimated at a spatial resolution of clusters of 1 km by 1 km and were re-aggregated here to a spatial resolution of 25' by 25'. For French regions, we use data from the French national statistics (AGRESTE statistics, http://agreste.agriculture.gouv.fr). To rebuild the temporal evolution of gridded nitrogen fertilization from 1901 to 2010: 1) organic fertilizer is assumed to have remained constant over time; 2) mineral fertilizers were applied since 1951, with application rates linearly increasing from zero in 1951 to the observed level in 1961; 3) the application rate of mineral fertilizer then followed the total mineral nitrogen fertilizer consumption of the European Union (Tenkorang & Lowenberg-DeBoer, 2008). Besides nitrogen fertilizer application, nitrogen deposition from the atmosphere was considered as nitrogen addition as well. Gridded nitrogen deposition rates for Europe were taken from the European Monitoring & Evaluation Programme (EMEP) data set, a product of EU-PF7 project GHG-Europe (data are available at http://gaia.agraria.unitus.it/ghg-europe/data/others-data): the decadal means were linearly interpolated to annual values.

The effects of land-use change on the terrestrial C cycle were taken into account in ORCHIDEE-GM version 2.1. The fractions of each land-use type are updated annually according to the land-use change maps (in this study, the enhanced historic land-cover map delineating grassland management intensity described previously). The assignment of C into different product pools (with different turnover times) and litter reservoirs, caused by the changes in vegetation (including natural vegetation and crops), is described by Piao *et al.* (2009).

In the simulation of the GHG balance it is assumed that European grasslands were managed from 1901 onwards, and also that the proportions of extensive, cut and grazed grasslands remained identical between 1901 and 1961 in the enhanced historic land-change map. The extensively managed grasslands are simulated as natural grassland in ORCHIDEE-GM because so little management is applied.

The series of simulations is shown in Fig. 1. ORCHIDEE-GM is first run for a spin-up period without management (simulation E1) by recycling the first 10 years of climate forcing (1901-1910) in a loop with CO_2 concentration fixed at the level for 1900 (296 ppm) until an equilibrium is reached for all the carbon pools at each grid point (long-term Net Ecosystem Exchange, NEE = 0 at each grid point). This spin-up usually takes 10,000 years. Starting from soil carbon pools in equilibrium for year 1901 (end of the spin-up) and optimal animal stocking rates (S_{opt}) and fractions of grazed grasslands (F_{opt}) for the reference period (1901-1910) from simulation E2, a second simulation (simulation E3) is then conducted for the period 1901-1960, but with prescribed increasing CO_2, variable climate and nitrogen addition, with the adaptive management change algorithm being activated, and with the enhanced historic land-change map (1901-1960). As a final simulation, ORCHIDEE-GM is run on each grid point during the most recent period 1961-2010 (simulation E4) forced by increasing CO_2, variable climate and nitrogen addition, with the adaptive management change algorithm, and the enhanced land-change map (1961-2010) giving the annual changes in grassland management.

Definition of carbon and full greenhouse gas budgets

Figure 2 shows the C and GHG fluxes from a grassland. In a natural ecosystem, the NEE measured by EC equipment is the C gain or loss by the ecosystem, with a negative NEE value indicating a sink of CO_2 from atmosphere. In managed grasslands, NEE is calculated as:

$$NEE = R_h - NPP + R_{animal} \qquad (5)$$

where R_h is soil heterotrophic respiration, NPP is net primary productivity, and R_{animal} is respiration from grazing livestock (fire disturbance is neglected because in Europe grassland fires are rare). However, the C balance of a managed grassland system (NBP) must account for carbon input and export. The NBP (Schulze & Heimann, 1998; Buchmann & Schulze, 1999; Chapin *et al.*, 2006) is the term applied to the total rate of organic carbon accumulation (or loss) from ecosystems, and can be calculated for grassland (Soussana *et al.*, 2007) as:

$$NBP = -NEE + F_{input} - F_{harvest} - F_{milk/LW} - F_{CH_4} - F_{leach} \qquad (6)$$

where F_{input} is the flux of C entering the grassland ecosystem through manure and slurry application; $F_{harvest}$ is the C lost from the grassland ecosystem through plant biomass export (mowing) and assumed to be later oxidized and released as CO_2 to the atmosphere; $F_{milk/LW}$ is the C lost from the grassland ecosystem though milk production and animal body mass increase; F_{CH4} is the C lost through CH_4 emissions by grazing animals, and F_{leach} is dissolved C, both organic (DOC) and inorganic (DIC) lost through leaching to river headstreams. In this study, F_{input} is determined by a gridded amount nitrogen addition in the form of manure and slurry, taken from the nitrogen fertilization map using a fixed C/N ratio for manure (C/N = 15 based on the range from 11.1 to 20.8 reported by Moral *et al.*, 2005); $F_{harvest}$, and F_{CH4} are simulated explicitly by ORCHIDEE-GM; the calculation of F_{CH4} in ORCHIDEE-GM depends on the amount of digestible fibre in the animal's diet according to the linear regression model of Pinarès-Patino *et al.* (2007), and is derived from PaSim model (Vuichard *et al.*, 2007); $F_{milk/LW}$ and F_{leach} from the grassland ecosystem are not determined and will be neglected in the calculation of NBP. These fluxes will be considered in the Discussion. Positive values of NBP indicate net C accumulation in the ecosystem.

When considering off-site (at farm scale) C fluxes (see Soussana *et al.*, 2010), the harvested biomass is either lost during transportation, or ingested by animals on the farm. Within the ingested part, C in the forage can be exported in various ways: i) respired by ruminants or as labile C in CO_2 fluxes, ii) emitted as CH_4 by enteric fermentation or from manure management, iii) returned to the grassland as fertilizer, iv) exported as animal products (milk and meat), or v) stored on the farm for future use. In the long-term, none of the harvested C is stored on the farm — almost all the C in harvested biomass will be exported from the system (grassland ecosystem plus farm), except for the C returned to the grassland as fertilizer (Fig. 2). As a result, the farm scale net C balance (NCB) including both ecosystem and farm is calculated as NBP minus the C returned to the grassland as manure (F_{return}):

$$NCB = NBP - F_{return} \tag{7}$$

where F_{return} is part of the total manure (and/or slurry) application (F_{input}), that can be calculated as:

$$F_{return} = F_{input} \times R_{grass-fed} \quad (8)$$

where $R_{grass\text{-}fed}$ is the ratio of manure from grass-fed animals to total manure application. Here, we assume that $R_{grass\text{-}fed}$ is the same as the ratio of grass-fed livestock numbers (N_{obs}) to total livestock numbers in each country.

The net GHG exchange of a grassland ecosystem (NGE), as described by Soussana *et al.* (2007), can be calculated by adding CH_4 and N_2O emissions (occurring in the ecosystem) to NEE using the global warming potential (GWP, with inclusion of climate-carbon feedbacks) of each of these gases for a 100-year time horizon (IPCC, 2013):

$$NGE = -(NEE + F_{CH_4-eco} \times GWP_{CH_4} + F_{N_2O-eco} \times GWP_{N_2O}) \quad (9)$$

where GWP_{CH4} = 12.36, as 1 kg C-CH_4 = 12.36 kg C-CO_2; GWP_{N2O} = 127.71, as 1 kg N-N_2O = 127.71 kg C-CO_2; $F_{CH4\text{-}eco}$ is CH_4 emissions by grazing animals; $F_{N2O\text{-}eco}$ is direct and indirect N_2O emission from managed soil (based on IPCC, 2006; the calculation of each component is given in Supporting information Text S2). To be consistent with the signs of the C balance (i.e., a positive NBP indicates a net C sink of ecosystem), in this study, a positive value of NGE indicates the grassland ecosystem is a net GHG sink.

The off-site CO_2, CH_4 and N_2O emissions from the digestion of harvest forage by livestock and manure decomposition contribute to the ecosystem and farm scale net GHG balance (NGB). NGB is then calculated as:

$$NGB = NGE - F_{CO_2-farm} - F_{CH_4-farm} \times GWP_{CH_4} - F_{N_2O-farm} \times GWP_{N_2O} \quad (10)$$

where $F_{CO2\text{-}farm}$ is the proportion of harvested C that is respired by ruminants or released as labile C in CO_2 fluxes; $F_{CH4\text{-}farm}$ is the proportion of ingested C emitted as CH_4 from enteric fermentation or from manure management; $F_{N2O\text{-}farm}$ is direct and indirect N_2O emission from manure management (based on IPCC, 2006; the calculation of each component is given in Supporting information Text S2).

Uncertainties in the NBP and GHG budget estimation

The uncertainties in the predictions from process models may be rather large, a result of: uncertain climate forcing data (e.g., Jung *et al.*, 2007; Zhao *et al.* 2012); parameter value uncertainty (e.g., Zaehle *et al.*, 2005); as well as uncertainty related to the model structure (e.g., Kramer *et al.*, 2002; Morales *et al.*, 2005; Moorcroft, 2006). At the large geographical scale of Europe, a comprehensive assessment of uncertainty can be made using a method such as factorial design (e.g., White *et al.*, 2000) or the Monte Carlo-type stratified sampling approach (McKay *et al.*, 1979), but the many model runs required rule out their use with complex models such as ORCHIDEE-GM, that have a large number of parameters, a half-hourly time step and thus a high computational demand (Campolongo *et al.*, 2000). In this study, we have identified four model inputs and parameters that likely substantially contribute to uncertainties in C and GHG flux simulations (White *et al.*, 2000; Knorr & Heimann, 2001; Knorr & Kattge, 2005; Zaehle *et al.*, 2005; Jung *et al.*, 2007; Kattge *et al.*, 2009). These four sources of uncertainty, define 16 combinations given minimum and maximum values that define a range (± 20% approximately) around the standard values used in the control simulation. The uncertain settings that are tested by systematic sensitivity simulations are: (1) the proportions of managed grasslands (f_{int}, which affects the cultivation map of European grasslands); (2) the response of photosynthetic capacity to nitrogen addition (parameter $Nadd_{max}$, Chang *et al.*, 2015); (3) the maximum rate of Rubisco carboxylase activity ($Vcmax_{opt}$) and the maximum rate of photosynthetic electron transport ($Jmax_{opt}$); and (4) the prescribed maximum specific leaf area (SLA_{max}, Chang *et al.*, 2013). Simulations with the 16 factor combinations at the full geographical scale of this study (9237 grid points) would still require a prohibitively large amount of computational time. We therefore based the uncertainty analysis on a sub-sample of 195 grid cells evenly spaced over our study area. These give a good representation of the spatial distribution, magnitude and interannual variability of grasslands' NBP and NGE (see Supporting information Text S3 for detail). Complete simulations (as described in Fig. 1) were conducted at these grid points with these factor combinations (with minimum and/or maximum values for each factor; Table 1). The standard deviation (SD) of the simulated NBP and NGE results was then used to characterize and assess the uncertainties of the C balance and GHG budget.

Results

The NBP and the GHG budget of European grasslands

Over 1961-2010, the average modelled NPP over the 1.3×10^6 km^2 of European grassland is 559 ± 122 g C m^{-2} yr^{-1}: 86% of it is respired back into the atmosphere by heterotrophic processes in soil and 4% by grazing livestock. Thus, European grassland ecosystems act as a sink, extracting CO_2 from the atmosphere (NEE) at the rate of -57 ± 21 g C-CO_2 m^{-2} yr^{-1}. Exports of harvested forage and CH_4 emission account for 95%, and 3% of NEE, respectively. Accounting for C from manure and slurry application (15 g C m^{-2} yr^{-1}), the average NBP of European grassland is 15 ± 7 g C m^{-2} yr^{-1} over the period 1961-2010, that is a cumulative C storage of 1.0 ± 0.4 Pg C at continental scale over 50 years. When considering off-site (farm) C fluxes, the net C balance (NCB) at ecosystem+farm scale is quasi-neutral, with an average value of around 8 g C m^{-2} yr^{-1}, given the fact that ca. 50% of the manure and slurry application (ca. 7 g C m^{-2} yr^{-1}) is from grass-fed animals.

We calculated CH_4 emission from enteric fermentation by grazing livestock to amount to 1.87 ± 0.79 g C-CH_4 m^{-2} yr^{-1} during 1961-2010. Direct and indirect N_2O emissions from fertilized grassland soils were 0.12 ± 0.04 g N-N_2O m^{-2} yr^{-1} during 1961-2010, given the distribution of nitrogen additions from the gridded nitrogen fertilizer application map and our model (see Supporting information Text S2 for details), as well as the parameters and emission factors from guidelines (IPCC, 2006). In terms of net radiative forcing fluxes expressed in CO_2 equivalents, CH_4 and N_2O emissions reached 23 ± 9 g C-CO_2 equiv. m^{-2} yr^{-1} and 15 ± 6 g C-CO_2 equiv. m^{-2} yr^{-1}, i.e. offsetting 41% and 26% of the average NEE (CO_2 sink) respectively. Altogether, the net GHG exchange (NGE) of European grassland is 19 ± 10 g C-CO_2 equiv.

m^{-2} yr^{-1}, indicating a net GHG sink (P < 0.01, Student's t-test) during the period 1961-2010. The uncertainty of NBP, NGE and their components comes from 1-sigma standard deviation of the 16 sensitivity tests.

Lastly, we calculated the NGB of grassland by adding GHG fluxes exchanged outside the ecosystem boundaries (see Fig. 2). We estimate that 85% of the harvested forage (46 g C-CO_2 m^{-2} yr^{-1}) is lost off-site and returned to the atmosphere as CO_2 emitted by decomposed forage grass, livestock respiration, and decomposed labile C in manure produced at-barn. Enteric fermentation and manure anaerobic decomposition produce 1.6 g C-CH_4 m^{-2} yr^{-1}. N_2O emission from manure management emits 0.02 g N-N_2O m^{-2} yr^{-1} to the atmosphere Therefore, contrary to the ecosystem scale NGE, the ecosystem and farm scale NGB is net a GHG source of -50 g C-CO_2 equiv. m^{-2} yr^{-1} (P < 0.01, Student's t-test).

Temporal evolution of the NBP and NGE of European grassland

We obtain an increase of European grassland NBP over the last five decades (NBP linear trend of 0.25 ± 0.08 g C m^{-2} yr^{-2}, P = 0.26) (Fig. 3a). The increase occurs after 1990 (1.83 ± 0.30 g C m^{-2} yr^{-2}, P = 0.07), with no trend of NBP being simulated before that date (-0.25 ± 0.15 g C m^{-2} yr^{-2}, P = 0.55). An enhancement of the GHG sink (NGE) in European grassland (sink trend of 0.49 ± 0.13 g C-CO_2 m^{-2} yr^{-2}, P = 0.05; Fig. 3b) is found, which is induced by the enhanced sink of CO_2 from the atmosphere (NEE, sink trend of 0.56 ± 0.14 g C-CO_2 m^{-2} yr^{-2}, P = 0.04) as well as by the changes of CH_4 emissions by animals (0.0016 ± 0.0011 g C-CH_4 m^{-2} yr^{-2}, P = 0.58; here positive trend indicates a decreasing CH_4 emission) and of N_2O emissions from soil (0.0003 ± 0.0001 g N-N_2O m^{-2} yr^{-2}, P = 0.08; here positive trend indicates a decreasing N_2O emission). The uncertainty of the trends above comes from 1-sigma standard deviation of the trends from the 16 sensitivity tests.

Regional NBP and GHG budget of grasslands and their trends

Figure 4 shows the NBP and NGE and their component fluxes for eight major agricultural regions of Europe, as the average for each decade. On average C exported from the ecosystem as harvested forage and released at the farm-level offsets most of the C sequestrated from the atmosphere into grassland soils (NEE). Thus the NBP of European grasslands is mainly determined by the differences between those two terms, except for Western Europe where high organic C (usually manure and/or slurry) input plays another major role in increasing NBP (Fig. 4). During the last five decades, almost all grassland regions in Europe were simulated to be a net C sink (positive NBP; Fig. 4) except for some C lost in Southeastern (1980s) and Eastern regions (1980s). Obvious NBP increases between 1961 and 2010 are found in Alpine and all eastern regions.

The spatial distribution of NGE over European grassland regions generally follows the pattern of NEE (Fig. 4), given the less variable components of CH_4 and N_2O emissions determined by livestock numbers and nitrogen-fertilization amounts. Exceptions are Northeastern, Southeastern and Eastern Europe, where CH_4 and N_2O emissions were substantially reduced after 1990, due to decreasing livestock numbers. The largest net GHG sink by grassland is found in the British Isles. This sink is explained by the high grassland productivity causing soil C sequestration, which offsets non-CO_2 gas emissions (Chang *et al.*, 2015).

Discussion

NBP uncertainties from model inputs and parameters

The errors in the key model inputs and parameters considered for uncertainty assessment cause an uncertainty of NBP (on average 1-sigma error) of ± 7 g C m^{-2} yr^{-1}. Within this total uncertainty, the uncertainties caused by management parameters, such as the fraction of intensively managed grassland in each grid cell (f_{int}) and the response of grass photosynthesis to nitrogen addition ($Nadd_{max}$) make a smaller contribution (± 4.4 g C m^{-2} yr^{-1} and ± 3.2 g C m^{-2} yr^{-1} respectively) than the uncertainties coming from parameters representing photosynthetic and morphological plant traits ($Vcmax_{opt}$ / $Jmax_{opt}$, and SLA_{max}), which contribute an NBP uncertainty of 4.8 g C m^{-2} yr^{-1} and 5.8 g C m^{-2} yr^{-1} respectively. The uncertain values of these parameters could be one of the sources for model-data disagreement when simulating C fluxes at measurement sites (Chang *et al.*, 2013). However, these PFT-specific average plant functional traits in ORCHIDEE, in reality, are highly site-specific, although on average they fall within a narrow range of variation. To reduce the uncertainty in the trait-related parameters, improved observation data sets are required on both mean value at community level (rather than species level) and on spatial distribution. Meanwhile, these traits are tightly correlated with leaf nitrogen concentrations (Ordoñez *et al.*, 2009) suggesting a possible way to reduce the uncertainty by fully coupling nitrogen and C cycles in terrestrial ecosystem models (e.g., Zaehle & Friend, 2010).

The uncertainty in model management-related parameter, f_{int}, plays only a small role in the uncertainty of NBP estimated by ORCHIDEE-GM. It implies that the absolute value of f_{int}, tested with ± 20% range from the standard value across the period 1901-2010, has very limit effect on the NBP estimate. This small uncertainty could be explained by the combination of two factors: first, one of our assumptions for grassland management prescribed that the proportions of extensive, cut and grazed grasslands remained identical between 1901 and 1961, thus no changes in grassland management intensity happened during this period in our simulation; and second, the legacy effects of grassland management intensity change (e.g., conversion from extensively managed grasslands to intensively managed grasslands) on soil C levels would be weak after 60 years continual management (Fig. S1). This non-linear (declining) rate of change in SOC has been implied in some researches (e.g., Post & Kwon, 2000; Soussana *et al.*, 2010) and supported by long-term observations (conversion from cropland (very intensively managed) to grassland (less intensively managed compared to cropland) at Rothamsted, UK; Johnson *et al.*, 2009), though the curve was reversed in our simulation due to the different initial changes in land use/management.

Furthermore, NBP can be significantly affected by the recent historic change of grassland usage. For example, an NBP increase (Fig. 4) follows the large decreases in the fraction of intensively managed grassland in all eastern regions during the period 1991-2010 (Fig. 5c), which were caused by the reduction of livestock numbers (Fig. S2). However, the grassland management intensity map, as an input in the model, carries three sources of uncertainty: 1) The grass composition in livestock's diet is only known with sub-continental resolution (Western Europe, Eastern Europe and former USSR, Bouwman *et al.*, 2005) and as a static value without temporal evolution, which could be different depending on region and time period; 2) in reality, European grassland is mostly cultivated by mowing and grazing of the same areas, whereas we split the cut and grazed grasslands with the assumption that the intensively managed grasslands are cultivated up to their biological potential; 3) management was more often applied in productive grasslands. Meanwhile abandonment happened first in infertile regions. However, in this study, the proportion of intensively managed grasslands

(f_{int}) was equally applied to every grid cell of the country. Although many sources of uncertainty exist, the grassland management intensity map for Europe established in this study is to our knowledge the first attempt to split managed and abandoned grassland over a wide area, to help us gain a better understanding the C and GHG budgets.

Comparison with previous estimates

Our assessment shows a positive NBP, i.e., a net carbon sink in biomass and soils (15 ± 7 g C m^{-2} yr^{-1}, averaged for 1961-2010). This is equivalent to a net C sink of about 20 Tg C yr^{-1} over 1.3×10^6 km^2 of European grassland soils, without accounting for C lost through leaching as DOC and DIC. C lost through DOC could reach 5.3 ± 2.0 g C m^{-2} yr^{-1} (data averaged for observations from four grassland sites; Kindler *et al.*, 2011), and leaching of DIC is mostly biogenic DIC from respiratory CO_2 in soil (about 80% and 100% of total DIC leaching from calcareous soils and from carbonate-free soils respectively; Kindler *et al.*, 2011); but this source has already been included in the model as heterotrophic respiration. Nevertheless, non-biogenic (lithogenic) DIC leaching from calcareous soils could reach about 11 g C m^{-2} yr^{-1} and thus be significant (Kindler *et al.*, 2011; data extracted from two grassland sites with calcareous soils and assuming 20% of DIC is non-biogenic). In addition, the C export through milk products and liveweight gain was not determined in our simulation, and was not accounted for in the calculation of NBP. According to the calculation based on animal products from statistics (see Supporting information Text S2 for detail), it will be less than 1.3 g C m^{-2} yr^{-1} for all European grassland. However, it has only marginal effect on the NBP calculation because this small C export, if it is not exported as the form of animal products, will be either respired by animal or turned to manure and later decomposed too, and this has been accounted for in NEE.

ORCHIDEE-GM estimates a higher NBP (27 ± 8 g C m^{-2} yr^{-1}) in the most recent decade compared to the period 1961-2000 (12 ± 6 g C m^{-2} yr^{-1}). This estimate is comparable to the grassland C sequestration according to the C flux balance from 12 EC grassland measurement sites (23 ± 187 g C m^{-2} yr^{-1} accounting for NEE, $F_{harvest}$, and F_{input}; see Table 1A of Soussana *et al.*, 2010 for detail) but larger than that derived from limited inventories of SOC stocks (5 ± 30 g C m^{-2} yr^{-1}) from a literature search (Soussana *et al.*, 2010). The difference can be explained by sampling gaps in SOC inventories and/or by the fact that our estimate does not include soil C losses from DOC leaching and by erosion (two processes that reduce the inventory value compared to our process-model based estimate). However, our NBP estimate is lower than the average from nine site observations (104 ± 73 g C m^{-2} yr^{-1}, Soussana *et al.*, 2007) and from previous results obtained with simpler models (66 ± 90 g C m^{-2} yr^{-1}, Janssens *et al.*, 2003; 36 ± 18 g C m^{-2} yr^{-1}, Smith *et al.*, 2005) or from both (74 ± 10 g C m^{-2} yr^{-1}, Ciais *et al.*, 2010). Meanwhile, the uncertainty induced by model input parameters (± 7 g C m^{-2} yr^{-1}, NBP on average of 50 years from 1-sigma standard deviation of the 16 sensitivity tests) and the climate induced variability (± 22 g C m^{-2} yr^{-1} interannual or ± 8 g C m^{-2} yr^{-1} decadal over the last five decades NBP variation) in our estimate reminds us that soil C sequestration remains sensitive to management, functional traits of grass species, and climate variability (Soussana *et al.*, 2010).

The N_2O emission from European grassland soils (15 ± 6 g C-CO_2 equiv. m^{-2} yr^{-1}) is close to the value derived from site observations (14 ± 4.7 g C-CO_2 equiv. m^{-2} yr^{-1}, Soussana *et al.*, 2007) and to the model estimates made using process-based mechanisms (DNDC: 13 g CO_2-C equiv. m^{-2} yr^{-1}, Levy *et al.*, 2007; and PaSim: 17 g CO_2-C equiv. m^{-2} yr^{-1}, Vuichard *et al.*, 2007). The CH_4 emission from enteric fermentation by grazing livestock (23 ± 9 g C-CO_2

equiv. m^{-2} yr^{-1}) is lower than the value derived from site observations (54 g C-CO_2 equiv. m^{-2} yr^{-1}, Soussana *et al.*, 2007) due to the fact that observations only account for emissions per grazed grassland area while our estimate is an average per total grassland area of all types (i.e., extensively managed, cut and grazed grasslands). As a result, our estimate of grassland ecosystem-scale GHG balance is a net CO_2 equivalent sink (NGE, 19 ± 10 g C-CO_2 equiv. m^{-2} yr^{-1}), smaller than the mean value derived from site observations (54 g C-CO_2 equiv. m^{-2} yr^{-1}, Soussana *et al.*, 2010). Furthermore, after taking into account off-site GHG emissions, a small source of GHG (-50 g C-CO_2 equiv. m^{-2} yr^{-1} during 1961-2010, and -30 g C-CO_2 equiv. m^{-2} yr^{-1} in the most recent decade) gives the first estimate for European grassland, which is a larger source than previous estimates made for a few farms (an insignificant sink of 23 ± 21 g C-CO_2 equiv. m^{-2} yr^{-1}, Soussana *et al.*, 2007).

The major causes of changing NBP and GHG balance

In a typical agricultural system, NBP is usually smaller than the magnitude of NEE because of the permanent export of a fraction of NPP exceeding the input of organic C from manure (Eq. 6; Soussana *et al.*, 2007). The change in NBP over European grasslands during the most recent five decades is attributed to two major processes: the changing sink-strength for atmospheric CO_2 (see NEE, green bars in Fig. 4); and the varying C export (red bars in Fig. 4).

NEE represents the fluxes of CO_2 exchanged between grassland ecosystems and the atmosphere; it is determined by the difference between NPP by plants and R_h from soil (Eq. 5; we have shown that R_{animal} is less than 5% of R_h for European grasslands). Within the two components of NEE, the increasing productivity (NPP, Fig. 5a and d) is simulated by

ORCHIDEE-GM over all European grasslands — except for the Mediterranean region. This trend in NPP is supported by multiple evidence from experimental studies (e.g., Walker & Steffen, 1997; Campbell *et al.*, 2000; Shaw *et al.*, 2002; Ainsworth & Long, 2005) and trends in satellite vegetation indices (e.g., Hicke *et al.*, 2002; Piao *et al.*, 2006; Seaquist *et al.*, 2007). The NPP increase could be induced by climate change and elevated CO_2 concentration (Ainsworth & Long, 2005), as well as nitrogen addition (Le Bauer & Treseder, 2008; Xia & Wan, 2008) and other management changes (e.g., re-sowing with improved varieties of grass). The NPP increase in extensively managed grasslands (e.g., British Isles, Western Europe, Alpine, Fig. 5d), where nitrogen fertilizer is not applied, can be mainly attributed in the model to climate change and increasing CO_2 concentration. For the intensively managed grasslands, the NPP increase is also induced by the intensified nitrogen addition during the period of 1961-1990 (Fig. 5b), due to the very simple parameterization of nitrogen-effects on photosynthesis (Chang et al., 2015).

Given the widespread positive trends of NPP, the different patterns of NEE evolution in different regions are mainly characterized by the trends of R_h which is controlled by climate, by organic C availability and the micro-environment (soil physical and chemical properties). Compared to increasing NPP, the relatively slower increase of R_h could lead to enhanced NEE (e.g., the British Isles and Alpine; Fig. 5a and 5d). Meanwhile, the R_h of the extensively managed grassland is usually larger than that of the intensively managed grassland (Fig. 5d), because most of the NPP in the extensively managed grassland remains in the grassland ecosystem to increase organic C availability instead of being exported (as it is for the intensively managed grasslands). Thus reduction of grass-fed livestock numbers (causing the conversion from intensively managed grassland to extensively managed grassland; Fig. 5c) is the major factor determining the evolution of R_h during the transition periods of some regions (e.g., in all eastern regions during the period 1991-2010).

The Europe-wide reduction of livestock numbers (more than 18% during the period 1991-2010 based on total metabolisable energy requirement calculated in Supporting information Text S1 with original data from FAOstat; Fig. S2) reduced the need for grass forage (with respect to grassland C balance, forage is a C export thus it lowers NBP). With the constraint that the total forage requirement by grass-fed livestock numbers must be met from grass NPP, our simulation takes into account the NBP response to the less intensive grassland management induced by the decreasing livestock numbers. As a result, the reduction of grass-fed livestock numbers causes enhanced sequestration of C in soil (NBP increase). The reduction in livestock numbers, which means the reduction of C export and the abandonment of grasslands (converted to extensively managed grasslands), decreased the CH_4 emissions from enteric fermentation directly, and reduced N_2O emissions because less nitrogen fertilizer (include mineral nitrogen and organic manure) is applied. Thus the causes of the increased NBP of European grassland (i.e., the reduction of livestock numbers) have at the same time contributed to GHG mitigation.

ORCHIDEE-GM accounts for land-use change (e.g., forest or cropland converted to grassland), allowing the net land-use change C flux of the newly established grasslands to be taken into account in this study. For example, with conversion of cropland to grassland, substantial gains in SOC (positive NBP) are found by meta-analysis (Post & Kwon, 2000; Conant *et al.*, 2001; Guo & Gifford, 2002); conversion of native forest to grassland can also result in SOC increase (Post & Kwon, 2000; Conant *et al.*, 2001; Guo & Gifford, 2002), however, the NBP (C balance of the ecosystem) would decrease because the large amount of biomass C loss (Conant *et al.*, 2001). The area of grassland in Europe has declined since the 1960s (ca. 7%) but has slowly increased again since the early 1990s (ca. 3%; *HILDA* historic land-cover change data set). In another simulation without land-cover change from or to grassland during 1991-2010 (grassland area was kept at the 1991 level), ORCHIDEE-GM estimated an NBP of 15 g C m^{-2} yr^{-1}, a little lower than the estimate with grassland change included (19 g C m^{-2} yr^{-1}). In other words, the recent land-cover change was simulated to make a limited contribution to grassland NBP in this study over 1991-2010 (a small sink of 4 g C m^{-2} yr^{-1}).

A large increase of European grassland NBP over the last two decades (1.83 ± 0.30 g C m^{-2} yr^{-2}, P = 0.07; Fig. 3a) is obtained in this study. As discussed in this section, it can be caused by several drivers including climate change, CO_2 trends, nitrogen addition, land cover and management intensity changes. To better understand their role in the changing NBP, quantification of their effects will be presented in a companion paper (Part 2).

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Supporting Information Legends

Text S1. Calculation of livestock numbers in Europe.

Text S2. Components of the GHG budget.

Text S3. Grid point selection for NBP uncertainty analysis.

Table S1. Major agricultural regions in Europe (Olesen & Bindi, 2002).

Table S2. Grids chosen by the selection processes with different latitude / longitude intervals.

Figure S1. Changes in relative soil organic carbon (SOC) of intensively managed grasslands during the period 1901-1960 simulated by ORCHIDEE-GM.

Figure S2. Ruminant livestock numbers in each of major agricultural regions of Europe and their evolution during the period 1961-2010.

Figure S3. The spatial distribution of the selected grid points (Group 6: with a latitude / longitude interval of 1.5°).

Figure S4. The differences in average NBP and the correlation coefficient between NBP time series from all grid cells (control group) and from each group of grid cells.

Tables

Table 1. Key model inputs and parameters for C balance and GHG budget simulations and their ranges[ab]

Model Input or Parameter	unit	standard value	minimum	maximum	description
f_{int}	percent	f	f × 80%	f × 120%	proportion of intensively managed grassland
N_{addmax}	percent	60%	40%	80%	the saturate status of nitrogen addition effect on photosynthetic capacity
$Vcmax_{opt}$ / $Jmax_{opt}$	µmol m^{-2} s^{-1}	55 / 110	44 / 88	66 / 132	$Vcmax_{opt}$: the maximum rate of Rubisco carboxylase activity $Jmax_{opt}$: the maximum rate of photosynthetic electron transport
SLA_{max}	m^2 g C^{-1}	0.048	0.0384	0.0576	the prescribed maximum specific leaf area

[a] Factors are modified by ±20% of standard value (except for N_{addmax}, which was modified by ± 20% of absolute value).

[b] For each combination, minimum or maximum value of each factor is used, which forms 2^4 = 16 factor combinations.

Figure legends

Figure 1. Illustration of the simulation protocol, forcing data and initial state for various simulations. Enhanced historic LC map indicates the enhanced historic land-change map delineating grassland management intensity.

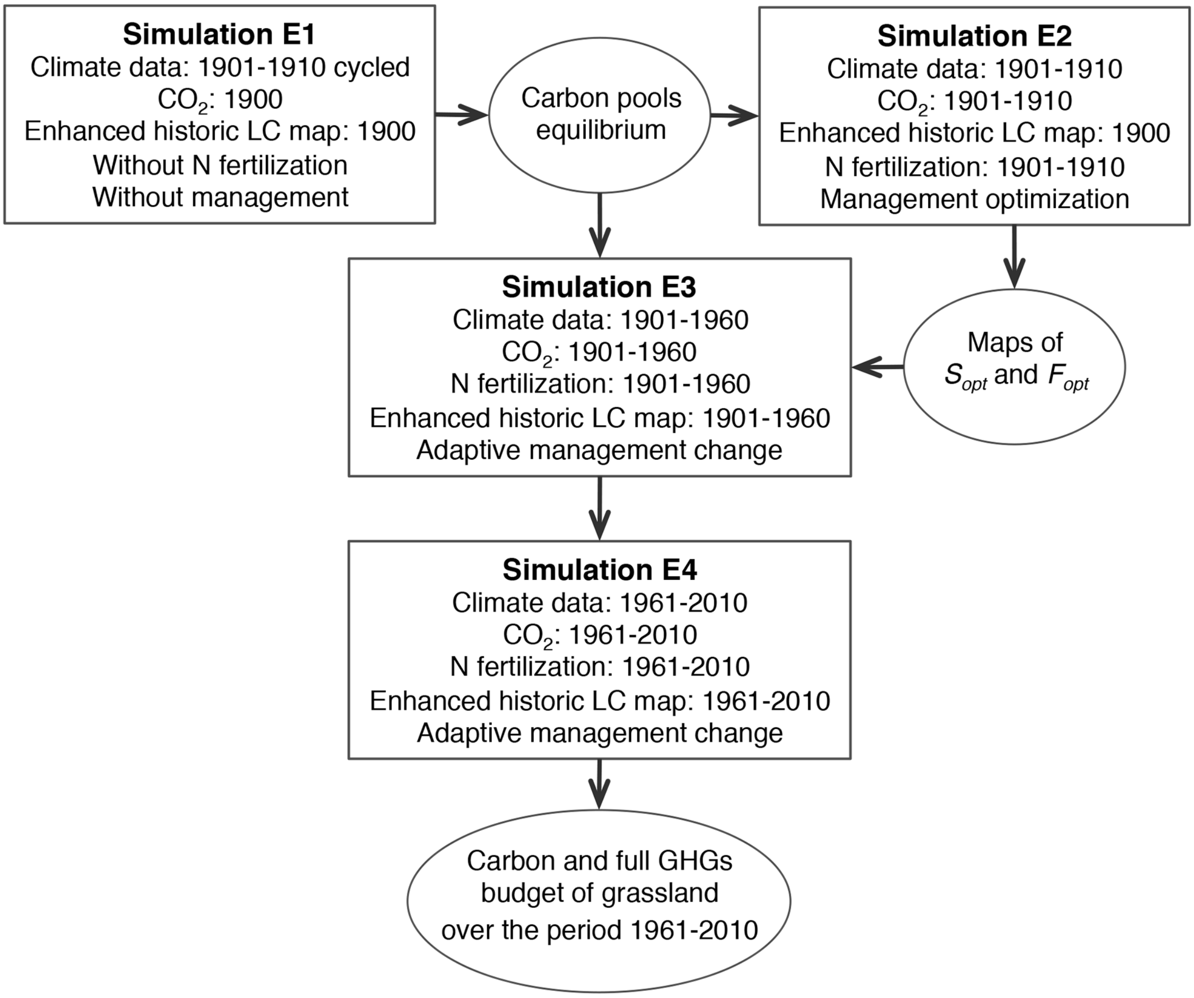
Figure 2. Carbon and GHG (CO_2, CH_4 and N_2O) fluxes in European grasslands at ecosystem and farm scale. Red arrows represent CO_2 fluxes (g C-CO_2 equiv. m^{-2} yr^{-1}); green arrows represent CH_4 fluxes (g C-CH_4 equiv. m^{-2} yr^{-1}); Blue arrows represent N_2O fluxes (g N-N_2O equiv. m^{-2} yr^{-1}); and orange arrows represent carbon fluxes other than in the form of CO_2 (g C m^{-2} yr^{-1}). NGE: the net GHG exchange of grasslands. NGB: the ecosystem and farm scale net GHG balance.

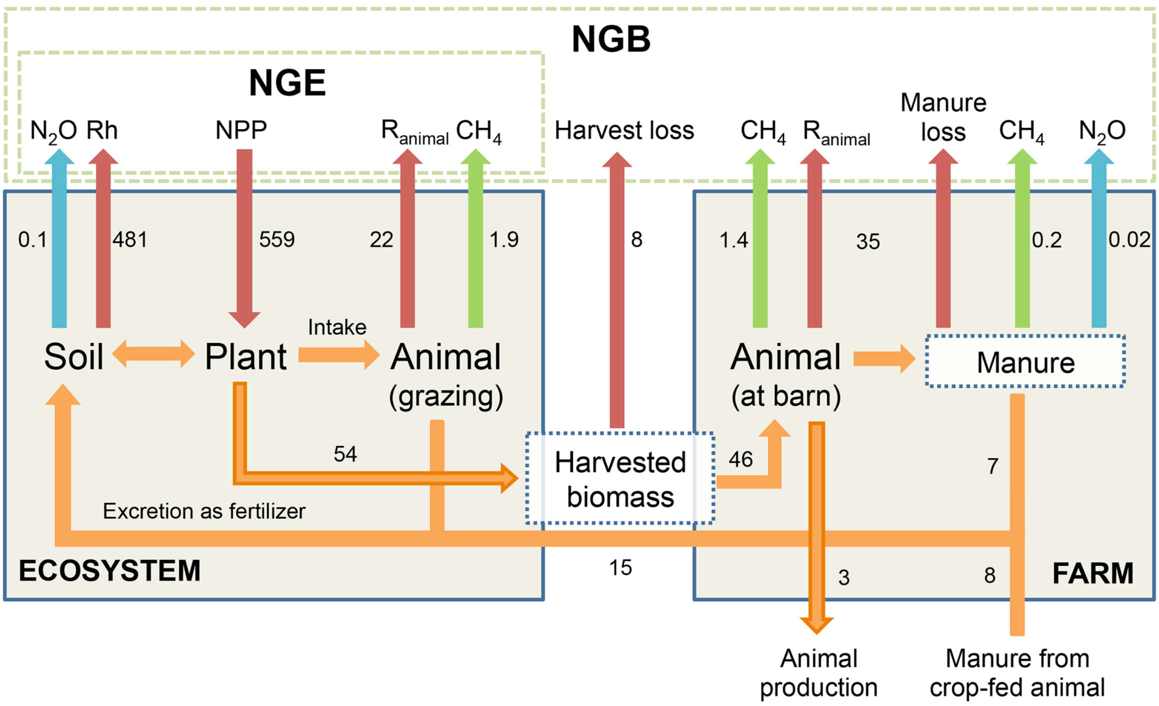
Figure 3. NBP (a) and GHG budget (b) of European grassland ecosystems predicted by ORCHIDEE-GM. A positive value of NBP indicates the grassland ecosystem is a net C sink. A positive value of the GHG fluxes indicates the grassland ecosystem is a net GHG sink. The negative values of the CH_4 and N_2O fluxes indicate the grassland ecosystem is a CH_4 and N_2O source. All GHG fluxes are expressed as global warming potential (g C-CO_2 equiv. m^{-2} yr^{-1}).

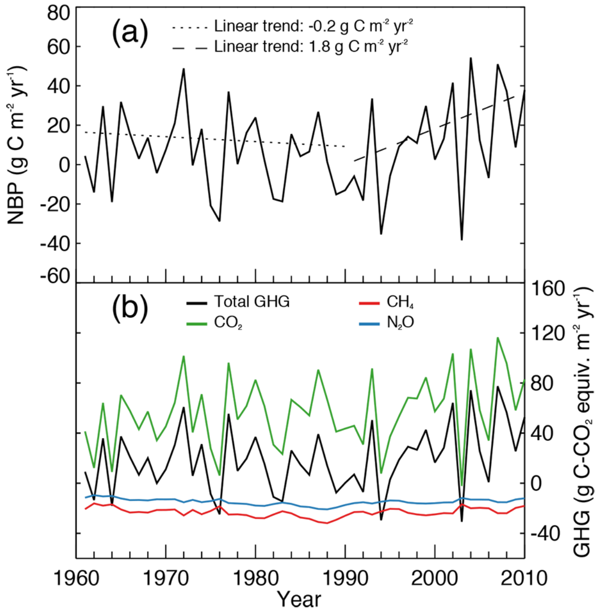
Figure 4. The NBP (far left, black), NGE (far right, light green), and their components divided into a number of major agricultural regions for the most recent five decades. The major agricultural regions are determined by both environmental and socio-economic factors and shown in Table S1 (for a detailed description see Olesen & Bindi *et al.*, 2002). The five values of each component are 10-year averages for (from left to right) 1961-1970, 1971-1980, 1981-1990, 1991-2000, and 2001-2010. NBP: the C balance of grassland ecosystem (g C m^{-2} yr^{-1}); C_{input} (blue): the C entering the system through manure and slurry application (g C m^{-2} yr^{-1}); C_{export} (red): the C lost from the system through harvested biomass, and CH_4 emission by grazing animals (g C m^{-2} yr^{-1}); NGE: the net GHG exchange of grassland ecosystem expressed as global warming potential (g C-CO_2 equiv. m^{-2} yr^{-1}), including CO_2 (dark green),

CH_4 (orange) and N_2O (purple) fluxes. Positive NBP and NGE indicate net C and GHG sinks respectively. The negative values of the CH_4 and N_2O fluxes indicate the grassland ecosystem is a CH_4 and N_2O source.

Figure 5. (a) NEE components (NPP and heterotrophic respiration (R_h)); (b) annual total nitrogen fertilizer application (including organic and mineral fertilizer); (c) fraction between intensively managed (int.) and extensively managed (ext.) grassland; and (d) NEE components of intensively managed (int.) and extensively managed (ext.) grassland divided into major agricultural regions for the most recent five decades. The major agricultural regions are determined by both environmental and socio-economic factors and shown in Table S1 (for a detailed description see Olesen & Bindi *et al.*, 2002). The five values of each component are 10-year averages for, from left to right, 1961-1970, 1971-1980, 1981-1990, 1991-2000, and 2001-2010.

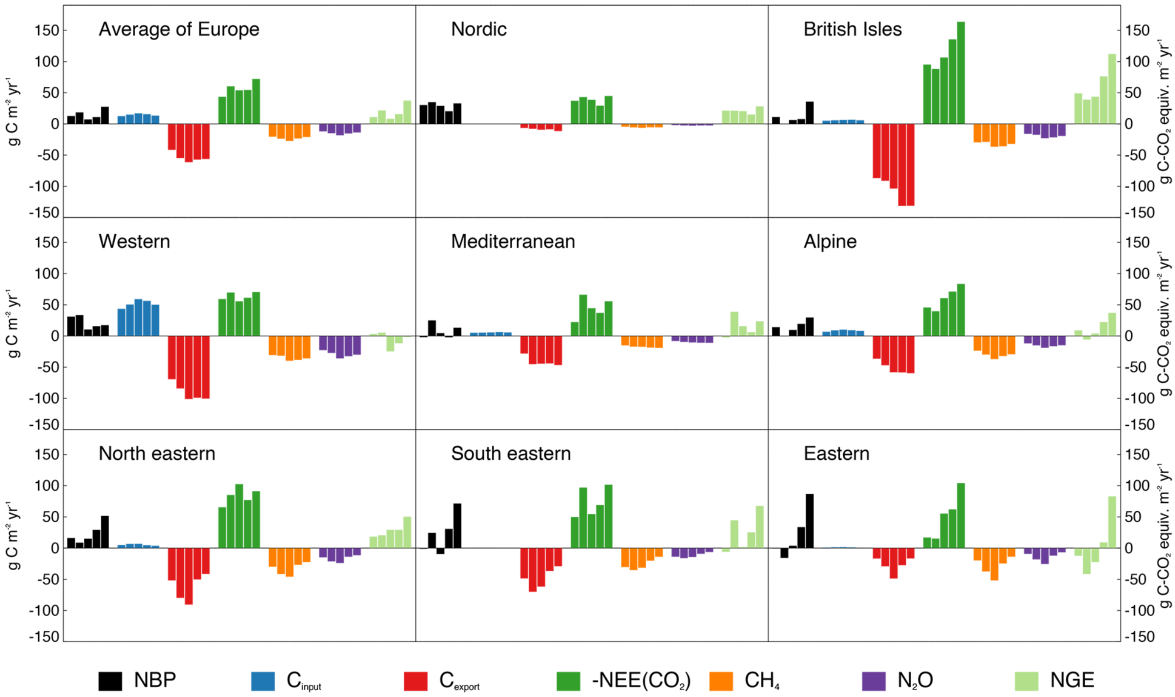

Simulation E1
Climate data: 1901-1910 cycled
CO_2: 1900
Enhanced historic LC map: 1900
Without N fertilization
Without management
Carbon pools equilibrium
Simulation E2
Climate data: 1901-1910
CO_2: 1901-1910
Enhanced historic LC map: 1900
N fertilization: 1901-1910
Management optimization
Simulation E3
Climate data: 1901-1960
CO_2: 1901-1960
N fertilization: 1901-1960
Enhanced historic LC map: 1901-1960
Adaptive management change
Maps of S_{opt} and F_{opt}
Simulation E4
Climate data: 1961-2010
CO_2: 1961-2010
N fertilization: 1961-2010
Enhanced historic LC map: 1961-2010
Adaptive management change
Carbon and full GHGs budget of grassland over the period 1961-2010


NGB
NGE
N_2O Rh
NPP
R_{animal} CH_4
Harvest loss
CH_4 R_{animal}
Manure loss
CH_4
N_2O
0.1
481
559
22
1.9
8
1.4
35
0.2
0.02
Soil
Plant
Intake
Animal (grazing)
Animal (at barn)
Manure
54
Harvested biomass
46
7
Excretion as fertilizer
ECOSYSTEM
15
3
8
FARM
Animal production
Manure from crop-fed animal



(a)
Linear trend: -0.2 g C m⁻² yr⁻²
Linear trend: 1.8 g C m⁻² yr⁻²
NBP (g C m⁻² yr⁻¹)
(b)
Total GHG
CO_2
CH_4
N_2O
GHG (g C-CO_2 equiv. m⁻² yr⁻¹)
Year

924



Average of Europe
Nordic
British Isles
Western
Mediterranean
Alpine
North eastern
South eastern
Eastern
g C m⁻² yr⁻¹
g C-CO_2 equiv. m⁻² yr⁻¹
NBP
C_{input}
C_{export}
-NEE(CO_2)
CH_4
N_2O
NGE

925


(a)
Rh
- NEE = NPP - Rh
g C m⁻² yr⁻¹
0
200
400
600
800
1000
(b)
Amount of nitrogen fertilizer application
g N m⁻² yr⁻¹
0
4
8
12
16
20
(c)
Intensively managed
Extensively managed
Percent (%)
0
20
40
60
80
100
(d)
Rh (int.)
- NEE (int.)
Rh (ext.)
- NEE (ext.)
g C m⁻² yr⁻¹
0
200
400
600
800
1000
Europe
Nordic
British Isles
Western
Mediterranean
Alpine
North eastern
South eastern
Eastern

926