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ORIGINAL ARTICLE

Estimating the effect of nitrogen fertilizer on the greenhouse gas balance of soils in Wales under current and future climate

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Abstract The Welsh Government is committed to reduce greenhouse gas (GHG) emissions from agricultural systems and combat the effects of future climate change. In this study, the ECOSSE model was applied spatially to estimate GHG and soil organic carbon (SOC) fluxes from three major land uses (grass, arable and forest) in Wales. The aims of the simulations were: (1) to estimate the annual net GHG balance for Wales; (2) to investigate the efficiency of the reduced nitrogen (N) fertilizer goal of the sustainable land management scheme (Glastir), through which the Welsh Government offers financial support to farmers and land managers on GHG flux reduction; and (3) to investigate the effects of future climate change on the emissions of GHG and plant net primary production (NPP). Three climate scenarios were studied: baseline (1961–1990) and low and high emission climate scenarios (2015–2050). Results reveal that grassland and cropland are the major nitrous oxide (N_2O) emitters and consequently emit more GHG to the atmosphere than forests. The overall average simulated annual net GHG balance for Wales under baseline climate (1961–1990) is equivalent to 0.2 t CO_2e ha^{-1} y^{-1} which gives an estimate of total annual net flux for Wales of 0.34 Mt CO_2e y^{-1}. Reducing N fertilizer by 20 and 40 % could reduce annual net GHG fluxes by 7 and 25 %, respectively. If the current N fertilizer application rate continues, predicted climate change by the year 2050 would not significantly affect GHG emissions or NPP from soils in Wales.

Keywords ECOSSE · Soil greenhouse gas balance · Net primary productivity · Climate change · Wales · Nitrogen fertilizer

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Introduction

Land use is an important factor for carbon (C) and nitrogen (N) dynamics of ecosystems and can have a great effect on greenhouse gas (GHG) emissions from soils (Forster et al. 2007). In the UK, agriculture represents the second largest source of GHG emissions accounting for 9 % of the UK's total emissions (Defra 2013) and emits 79 % of the total anthropogenic emission of nitrous oxide (N_2O) (Thomas et al. 2011). This is due to field management practices such as application of synthetic N fertilizer (Bouwman et al. 2002), crop type and cover crop (Bell et al. 2012; Abdalla et al. 2014) and manure management and grazing (Forster et al. 2007) which influence nutrient inputs and hydrological and physical conditions of the soil. Forests and woodlands compose a great stock of C in trees, vegetation and in soils by removing a substantial amount of C from the atmosphere. They are a key component in developing climate change mitigation strategies for GHG emissions (Morison et al. 2012).

Nitrous oxide is a potent GHG that contributes about 6 % to the anthropogenic greenhouse effect (IPCC 2013). Emissions of N_2O tend to occur in short-lived bursts following the application of N fertilizers (Leahy et al. 2004; Skiba et al. 2012).The availability of soil mineral N has a direct effect on N_2O production by providing N for both nitrification and denitrification (Baggs and Blum 2004). On a mass basis, N_2O has a global warming potential of 298 times that of CO_2, over a 100-year timescale (IPCC 2013). Methane is produced when organic materials decompose under anaerobic condition in soils (Regina et al. 2006) with high emissions from histosols areas (Mosier et al. 1998). However, generally, cropland soils are often CH_4 sinks (Abdalla et al. 2014). Soils are also a source of CO_2 emission which is associated with disturbance and land use transitions (Janzen 2004) and decomposition of litter roots and soil organic matter (SOM) (Bernhardt et al. 2006).

Application of well-tested process models provides a robust way to estimate GHG emissions from soils to evaluate potential mitigation options and allow the investigation of a variety of climate change-land use scenarios (Giltrap et al. 2010). ECOSSE is an example of such a process-based model (Smith et al. 2010a). ECOSSE was developed to simulate C and N cycling and GHG production in mineral, organo-mineral and organic soils, using concepts originally developed for mineral soils in the two parent models, RothC (Coleman and Jenkinson 1996) and SUNDIAL (Smith and Glendining 1996). Building on these established models, ECOSSE uses a pool approach, describing SOM as pools of inert organic matter, humus, biomass, resistant plant material (RPM) and decomposable plant material (DPM) (Smith et al. 2010a, b).

Climate change is expected to increase surface air temperature and evaporation leading to higher levels of atmospheric water vapour. As a result, the frequency and extent of rainfall is likely to be highly variable (Kattenberg et al. 1995). Such changes in temperature (Fiscus et al. 1997) and precipitation (Mearns 2003) would be expected to influence mineralization and denitrification, and thereby GHG production in the soil, but could also increase plant productivity (Anwar et al. 2007).

The Welsh Government is committed to reducing GHG emissions from agriculture, protecting the environment and combating the effects of future climate change. To achieve these objectives, the Glastir programme is in force, in which farmers are financially supported to adopt a range of on-farm measures to protect soil C, reduce GHG emissions, improve water quality and enhance biodiversity. The main aims of this simulation study were: (1) to estimate the annual net GHG balance for Wales; (2) to investigate the efficiency of the reduced nitrogen (N) fertilizer goal of the sustainable land management scheme (Glastir), through which the Welsh Government offers financial support to farmers and land managers on GHG flux reduction; and (3) to investigate the effects of future climate change on the emissions of GHG and plant net primary production (NPP).

Materials and Methods

ECOSSE model

In this study, we applied the latest version of the ECOSSE (Estimation of Carbon in Organic Soils-Sequestration and Emissions; v. 5.0.1) model to estimate GHG and SOC fluxes for Wales. The ECOSSE model includes all of the major processes of C and N turnover in the soil using well-established equations driven by readily available input variables (Smith et al. 2010a). ECOSSE can be used to carry out site-specific simulations with detailed input data (e.g. Bell et al. 2012; Dondini et al. 2015), or spatial simulations using the limited data typically available at larger scales (e.g. Smith et al. 2010b). Data describing initial SOC, soil water, plant inputs, nutrient applications and timing of management operations are used to run the model.

The water module in ECOSSE is based on SUNDIAL (Smith and Glendining 1996), where water passes through soil layers as 'piston flow'. Precipitation fills the uppermost soil layer with water until it reaches field capacity. Any remaining precipitation then fills the next layer to field capacity. This process is repeated until no precipitation remains or the bottom of the profile is reached. Water remaining after filling all layers to field capacity is partitioned between drainage (water leaving the soil profile), and excess, which fills layers to saturation from the bottom of the profile upwards. The ECOSSE model uses the observed depth of the water table (where available), the available water at saturation and weather data to calculate the restriction to drainage (i.e. the partitioning between drainage and excess), that is required to achieve the observed water table depth. Addition or loss of C and N from different vegetation types is estimated using the C and N fractions in different parts of the plant, and harvest index for crops. Potential evapotranspiration is calculated using the Thornthwaite equation (1948). Total SOC and the proportions of the total C that is inert are added as inputs. The amount of inert organic matter has been estimated in these calculations using an equation derived by Falloon et al. (1998). The ECOSSE model then estimates the amount of organic matter input from plant material by adjusting plant inputs until the simulated SOC at steady state matches the measured values (Wong et al. 2013). Plant material is divided into resistant and decomposable material, based on vegetation-specific ratios (as used in the RothC model; Coleman and Jenkinson 1996).

The ECOSSE model can simulate the soil profile up a depth of three metres, the soil being divided into 5-cm layers to facilitate the accurate simulation of processes to depth. During the decomposition process, material is exchanged between the SOM pools according to first-order rate equations, characterized by a specific rate constant for each pool. The rate constant of each pool is modified depending on the temperature, water content, plant cover and pH of the soil. The N content of the soil follows the decomposition of the SOM, with a stable C/N ratio defined for each SOM pool at a given pH, and N being either mineralized or immobilized to maintain that ratio. Nitrogen is released from decomposing SOM as ammonium (NH_4^+) and nitrified to nitrate (NO_3^-). Carbon and N may be lost from the soil by leaching of NO_3^-, dissolved organic C, and dissolved organic N, denitrification to nitric oxide (NO) and N_2O, volatilization of NH_4^+ or off-take of NH_4^+ and NO_3^- in the plant. Carbon and N may be returned to the soil by plant inputs, inorganic fertilizers, atmospheric deposition or organic amendments (e.g. manure, crop residues). Figure 1 shows the structure of C (a) and N (b) components in ECOSSE model and emissions of the different gases, i.e. CO_2, CH_4, N_2O, NH_3 and N_2. More details about the ECOSSE approach are found in Smith et al. (2010a).

Spatial simulations

Application of the ECOSSE model for spatial simulation of GHG and SOC fluxes was carried out for the whole of Wales on a 1 km^2 soil grid basis. Grid simulations represent the five dominant soil types in each grid cell to capture soil heterogeneity at the sub-grid cell level. Each grid cell value in the model output represents the area-weighted mean of the simulations carried out for each soil type in the grid cell. Land cover was obtained from the Land Cover Map (LCM2007; Morton et al. 2011) simulating three main land uses (arable, grassland and forest). The land use is not linked to the data from the crop yields as such; rather, it is used to calculate the spatial average of emissions per unit area in each grid cell. Rotational grassland is included in arable land use, as the grass ley phase forms part of an arable crop rotation (Richards et al.; unpublished).

As is common practice for soils models (Coleman and Jenkinson 1996; Smith et al. 2010a), ECOSSE was initialized before running each simulation, based on the assumption that the SOC in the soil column was in steady state under the initial land use at the start of the simulation. The equilibrium assumption is used to initialize many biogeochemical models and is used to ensure reasonable distribution of soil C among the various pools in the model. Alternative methods have been proposed (e.g. Hashimoto et al. 2011), but when compared with different methods, the equilibrium run has been shown to be the most robust

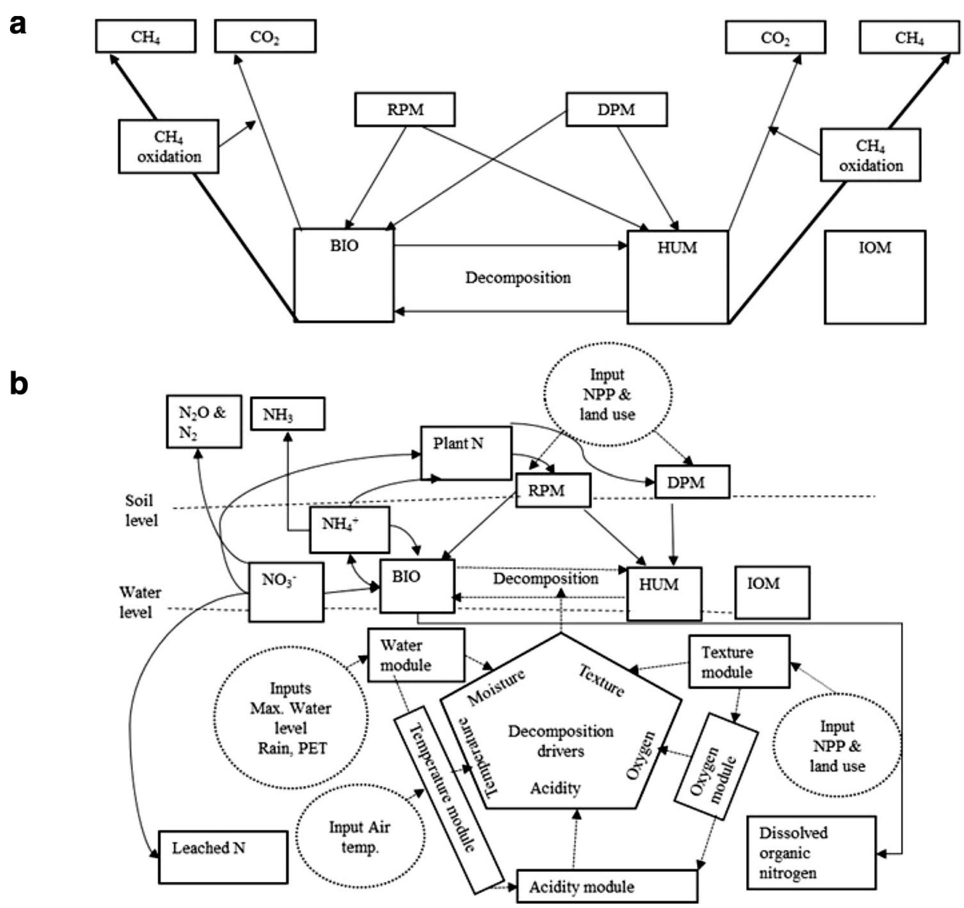

Fig. 1 Structure of C (**a**) and N (**b**) components in ECOSSE model showing emissions of the different gases, i.e. CO_2, CH_4, N_2O, NH_3 and N_2. *BIO* biomass, *HUM* humus, *RPM* resistant plant material, *DPM* decomposable plant material, *IOM* inert organic matter, *NPP* net primary production, *DON* dissolve organic N and *LU* land use. Adapted from Smith et al. (2010a)

(e.g. Senapati et al. 2013). So whist many soils are unlikely to be in equilibrium in reality, the equilibrium assumption provides the most robust initialization procedure, and post-initialization outputs from the model are relatively insensitive to the validity of the assumption (e.g. Senapati et al. 2013). Physical disturbance of SOM during cultivation is simulated by homogenizing the vertical distribution of the SOM pools down to the cultivation depth. For all land uses, the changes in GHG and SOC fluxes are calculated for the top metre of the soil profile. Only the top metre is considered, because this is the depth to which soil parameters are provided by the soil database. Results of GHG and SOC emissions were all reported in terms of CO_2-equivalent values (CO_2e) using the IPCC 100-year global warming potentials (GWPs) (IPCC 2001). The recent IPCC Fifth Assessment Report (2013) provided updated GWPs, but for consistency and compliance with IPCC National GHG Inventories, we have used the IPCC 2001 GWP values, where N_2O has a GWP of 296 and CH_4 has a GWP of 23. The net GHG balance represents the combined impact of changes in N_2O, CH_4 and CO_2 from SOC change (all expressed as CO_2e) and calculated as the sum of N_2O and CH_4 fluxes, minus the change in SOC. A positive net GHG balance is harmful (i.e. emissions to the atmosphere), and a negative net GHG balance is beneficial (i.e. removals from the atmosphere), discounting all other factors.

In ECOSSE, emissions of N due to denitrification and partial nitrification are simulated. The emissions are then partitioned into N_2, N_2O and NO according to the water and nitrate content of the soil. From the fully nitrified N, only 2 % is lost as gas, with 40 % of this gas as NO and 60 % as N_2O. From the partially nitrified N, 2 % is assumed to be lost as gas at field capacity with a linear decrease in this loss as water content declines. The amount of N_2O release due to nitrification can be calculated by Eq. 1 below:

$$N_{n,N_2O} = \left(\left(n_f \times \frac{\psi_c}{\psi_c} \right) + \left(n_{gas} \times (1 - n_{NO}) \right) \right) \times N_n \quad (1)$$

where $N_{n,N2O}$ is the amount of N_2O during nitrification (kg N ha^{-1}), ψ_c is the amount of water held above the permanent wilting point in a soil layer (mm $layer^{-1}$), ψ_f is the amount of water held between field capacity and the permanent wilting point (mm $layer^{-1}$), n_f 0.2 is the proportion of N_2O produced due to partial nitrification at field capacity, $n_{gas} = 0.02$ is the proportion of full nitrification lost as gas, $n_{NO} = 0.01$ is the proportion of the full nitrification gaseous lost as NO and N_n is the amount of N nitrified (kg N ha^{-1}).

The amount N lost by denitrification is partitioned into N_2 and N_2O. The calculation of N_2O gas lost is given in Eq. 2 below:

$$N_{d,N_2O} = \left(1 - \left(\rho_w \times \rho_{NO_3}\right)\right) \times N_d \quad (2)$$

where $N_{d,N2O}$ is the amount of N_2O during denitrification (kg N ha^{-1}), N_d is the amount of N denitrified (kg N ha^{-1}) and ρ_w and ρ_{NO3} are the proportions of denitrification into N according to water and nitrate contents of the soil, respectively. Further details can be found in Smith et al. (2010a).

ECOSSE simulates CH_4 emissions using a process-based but simple approach, as the difference between CH_4 production and CH_4 oxidation, the oxidation process adding to emissions of carbon dioxide. The production of CH_4 is then given by Eq. 3 below:

$$CH_4 = (1 - \alpha - \beta) \quad (3)$$

where α is the proportion of decomposing materials partitioned to biomass, and β is the proportion partitioned to humus. Further details can be found in Smith et al. (2010a).

Soil data

The soil data were derived from the national soil map of Wales and are the product of 60 years of soil survey as described by Falloon et al. (1998). This database provides soil data to a depth of 1 m at a resolution of 1 km, for the dominant soil types under each of the three land use types (arable, grass, forest) in each grid cell. Data for organic C content, bulk density, sand, silt and clay faction from the database were used to drive ECOSSE. Data on the water-holding capacities of soils are not included in the database so these were estimated using pedotransfer functions. For non-peat soils, the British Soil Survey pedotransfer functions were used (Hutson and Cass 1987), which performed well in evaluations (Givi et al. 2004). The soil database also provides the percentage cover of each soil type in each grid cell. The model is run for each dominant soil type in each grid cell and the output area-weighted by the percentage cover in each grid cell to calculate the mean soil responses.

Climate data

Spatial ECOSSE simulations require monthly precipitation and air temperature to drive the soil water model and to determine temperature and moisture rate modifiers for the soil processes. The meteorological data were taken from the UKCP09 Spatially Coherent Projections (Murphy et al. 2009). UKCP09 provides, for high and low emissions scenarios, average monthly temperature and precipitation for Wales on a 25-km UKCP09 rotated pole grid for overlapping 30-year periods centred upon decades ranging from the 2020s to the 2080s. The data were re-projected to the British National Grid for compatibility with other data used in this application of ECOSSE.

To investigate the effects of climate change on GHG and SOC fluxes, two climate scenarios (high and low emission scenarios) for a 35-year period running from 2015 to 2050 were used and compared to the baseline climate (1961–1990). The mean monthly precipitation is relatively unaffected by future climate; however, the mean monthly temperature increases fairly uniformly by around 2 °C. The UKCP09 low and high emission climate scenarios correspond to the B1 and A1F1 emission scenarios of the Forster et al. (2007), respectively.

Yield data

The ECOSSE model can use yield data for each land use type to adjust the plant inputs calculated at steady state (Smith et al. 2010a). Yield data for the different arable crops were obtained from EUROSTAT (2014), whilst biomass data for other land uses were estimated using the Miami model (Lieth 1975). Miami is an empirical NPP model that estimates annual NPP from mean annual temperature and precipitation. Yield estimates for grass and forest are obtained using NPP estimates from Miami, which are then linearly rescaled according to observed peak yields (Living Countryside, 2013) to reflect differences in grass and forest productivity. The model equations are:

$$\mathrm{NPP} = \min(\mathrm{NPPT}; \mathrm{NPPP}) \tag{4}$$

$$\text{with } \mathrm{NPP}_T = 3000\,(1 + \exp(1.315 - 0.119\,T))^{-1} \tag{5}$$

$$\mathrm{NPP}p = 3000\,(1 - \exp(-0.000664 - 0.119\,P)) \tag{6}$$

where T is mean annual temperature (C) and P is total annual precipitation (mm). The Miami estimate of NPP was calculated for each decade in each grid cell using the same meteorological data as used in ECOSSE and was used to modify the steady state plant inputs to the soil using the ratio of calculated NPP to the NPP at steady state.

Fertilizer application

Nitrogen fertilizer was applied in the form of inorganic fertilizer (ammonium nitrate) which is the main form of N fertilizer uses in the UK (British Survey of Fertilizer Practices 2013) and at a rate equal to the annual crop N demand. Crop N demand is a function of plant yield and the C/N ratio of the plant. Full fertilizer application rate (100 %) meets 100 % of the annual crop N demand, whilst 80 and 60 % fertilizer application rate meets only 80 and 60 % of the annual crop N demand, respectively. Arable and grasslands are assumed to be fertilized, whist forest is assumed to remain unfertilized.

Results

Estimated present greenhouse gas fluxes in Wales

Figure 2 shows the predicted mean annual net GHG fluxes under baseline climate (1961–1990) for Wales. Fluxes of GHGs were variable, depending on the land use investigated. These variations in GHG fluxes resulted in variations in the amount of net GHG balance between the different land uses as shown in Table 1 (positive means GHG balance is detrimental and negative means GHG balance is beneficial). The highest emitting land uses are grass and arable, with an effective net GHG balance of 0.405 and 0.191 t CO_2e ha^{-1} y^{-1}, respectively, accounting for the available land cover. The net fluxes from the forest land use of 0.033 t CO_2e ha^{-1} y^{-1} are relatively small compared with that from the grass and arable land uses. For all land uses, N_2O fluxes were the highest contributor to the net GHG balance, especially for the grass and arable land uses, where N fertilizer was applied. However, fluxes of N_2O from the forest land use were low and contributed less to the net GHG balance (Table 1). For all land uses, fluxes of CH_4 were very low and represent a small sink for atmospheric C. The overall annual average uptake of CH_4 is 0.008 t CO_2e ha^{-1} y^{-1} (Table 1). Likewise, the fluxes of SOC were a minor sink with an overall average C uptake of 0.013 t CO_2e ha^{-1} y^{-1} (Table 1). The overall average net GHG balance, from the three investigated land uses across Wales, combining all gas fluxes is equivalent to 0.2 t CO_2e ha^{-1} y^{-1}. Considering the Welsh land use area of 1,857,690 ha (Office for National Statistics 2005), where agriculture (grass and arable) accounts for 75 % and forestry accounts for 13 %, the calculated total annual GHG fluxes from the three investigated land uses in Wales under the baseline climate (1961–1990) suggest a total flux of 0.34 Mt CO_2e y^{-1}.

Effects of the Glastir measure of reducing nitrogen fertilizer application rates on GHG and SOC fluxes in Wales

Application of lower N fertilization rates compared with the baseline resulted in lower N_2O fluxes and thereby lower net GHG fluxes from soils (Table 2). Here, N_2O decreased from 0.230 t CO_2e ha^{-1} y^{-1} (at baseline) to 0.197 t CO_2e ha^{-1} y^{-1} (at 80 % crop N demand) and 0.172 t CO_2e ha^{-1} y^{-1} (at 60 crop N demand). Figure 3 shows the predicted changes in annual net GHG fluxes from the grass and arable land uses at baseline (100 % crop N demand) compared to the 40 %reduced fertilizer application rate scenario (60 % crop N demand) for Wales.

The CH_4 and SOC fluxes were not affected by reducing N fertilizer application rate (Table 2). The amounts of CH_4

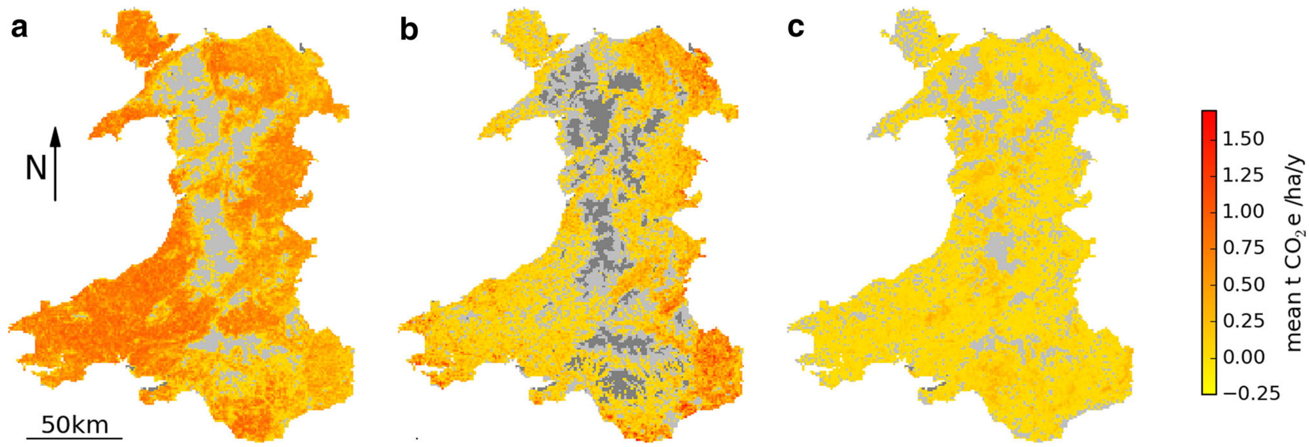

Fig. 2 Simulated mean annual net GHG fluxes (effective t CO_2-e ha^{-1} y^{-1}) from Welsh fertilized grassland (**a**), fertilized arable land (**b**) and forest (**c**), at baseline climate (1961–1990). Results are for emissions per hectare of the specified land cover in each grid cell, which are rescaled by the fraction of the land cover within each grid cell, thus giving the effective emissions per hectare across each grid cell. *Light grey* areas show zero flux; *dark grey* areas show zero land cover

and SOC fluxes, at all fertilization scenarios, represented small sinks of 0.008 and 0.013 t CO_2e ha^{-1} y^{-1}, respectively (Table 2). Reducing applied N fertilizer by 20 % reduced annual N_2O fluxes from 0.44 to 0.37 t CO_2e ha^{-1} (−15 %) and from 0.20 to 0.17 t CO_2e ha^{-1} (−17 %) for the grass and arable lands, respectively (Table 3). Reducing applied N fertilizer by 40 % resulted in reducing annual N_2O fluxes from 0.44 to 0.32 t CO_2e ha^{-1} (−25 %) for the grassland and from 0.20 to 0.14 t CO_2e ha^{-1} (−32 %) for the arable land (Table 3). The overall annual N_2O fluxes, from all land uses, reduced from 0.23 to 0.20 (−15 %) and 0.17 (−25 %) t CO_2e ha^{-1} for 20 % and 40 % N fertilizer reductions, respectively. Consequently, the annual net GHG balance reduced from 0.209 to 0.202 (for 20 % reduction) and 0.177 (for 40 % N reduction) t CO_2e ha^{-1} y^{-1} (Table 2). This is equivalent to annual reductions in C loss of 7 and 25 t CO_2e ha^{-1} for the 20 and 40 % N fertilizer reductions, respectively, compared to the baseline (application of 100 % crop N demand).

Table 1 ECOSSE-estimated mean annual GHG (N_2O and CH_4), SOC fluxes and net GHG balance (effective t CO_2e ha^{-1} y^{-1}; i.e. fluxes rescaled according to available land cover) at baseline climate 1961–1990, for Wales

Ecosystem	N_2O	CH_4	SOC	Net GHG balance
Grassland	0.441	−0.014	−0.022	0.405
Arable land	0.200	−0.002	−0.007	0.191
Forest	0.050	−0.007	−0.010	0.033
Average	0.230	−0.008	−0.013	0.209

Effects of climate change on GHG and SOC fluxes and net primary production for Wales

The ECOSSE model was applied to assess the effects of climate change on GHG and SOC fluxes and NPP in Wales. Two future climate scenarios (low and high; 2015–2050) were compared with the baseline climate (1961–1990). Under climate change, N_2O and SOC fluxes, for all land uses and both climate scenarios, were increased, whilst CH_4 fluxes were decreased (Table 4). However, N_2O dominated the flux change. The CH_4 fluxes remain a small C sink, whilst SOC fluxes became a small C source. The annual net GHG fluxes increased from 0.209 t CO_2e ha^{-1} y^{-1} at the baseline climate scenario, to 0.215 and 0.229 t CO_2e ha^{-1} y^{-1} at the low and high emission climate scenarios, respectively (Table 5). Figure 4 shows the predicted changes in the net annual GHG flux (t CO_2e ha^{-1} y^{-1}) for the different land uses between the baseline and high emission climate change scenario. The NPP values under the low and high warming climate scenarios were increased by 8 % and 10 % compared to that at baseline, respectively (Table 5). The difference between the two climate scenarios is, however, small (about ± 2 %).

Table 2 ECOSSE estimated changes in net annual GHG (N_2O and CH_4), SOC fluxes and net GHG balance (effective t CO_2e/ha) due to reduced N fertilization rate in Wales

Scenario	N_2O	CH_4	SOC	The net GHG balance	% change in net GHG
Baseline	0.230	−0.008	−0.013	0.209	–
20 % fertilizer N reduction	0.197	−0.008	−0.013	0.202	7
40 % fertilizer N reduction	0.172	−0.008	−0.013	0.177	25

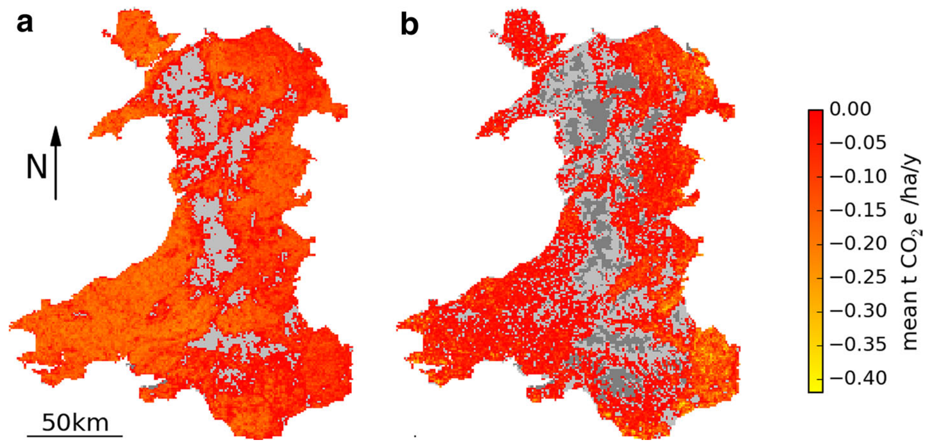

Fig. 3 Simulated change in annual GHG flux (effective t CO_2e ha^{-1} y^{-1}) from Welsh fertilized grassland (**a**) and fertilized arable land (**b**) between the baseline and 60 % N fertilizer application rates. *Light grey* areas show zero change; *dark grey* areas show zero land cover

Table 3 ECOSSE-estimated mean annual N_2O (t CO_2e ha^{-1}) at baseline and two reduced N fertilization rates (−20 and −40 %) at baseline climate, 1961–1990

Ecosystem	Baseline N_2O	20 % fertilizer N reduction	40 % fertilizer N reduction	% change	
				−20%	−40%
Grassland	0.44	0.37	0.32	−15 %	−25
Arable land	0.20	0.17	0.14	−17 %	−32
Forest	0.05	n/a	n/a	n/a	n/a

Table 4 ECOSSE-simulated mean annual N_2O, CH_4 and SOC fluxes and net GHG balance (effective t CO_2e ha^{-1} y^{-1}) at baseline climate and the low and high climate scenarios to 2050, for Wales

Gas flux	Baseline	Low climate scenario	High climate scenario
N_2O	0.230	0.238	0.243
CH_4	−0.008	−0.010	−0.011
SOC	−0.013	0.013	0.003
Net GHG balance	0.209	0.241	0.235

Table 5 ECOSSE-simulated mean annual net GHG fluxes (t CO_2e ha^{-1}) and plant NPP (kt ha^{-1}) at baseline climate and the low and high climate scenarios and percentage change by 2050, for Wales

Climate scenario	GHG (t CO_2e ha^{-1})	% change	NPP (kt ha^{-1})	% change
Baseline	0.209	n/a	230	n/a
Low scenario	0.215	+2	250	+08
High scenario	0.229	+3	254	+10

Discussion

Estimated GHG and SOC fluxes at baseline climate

In this study, the ECOSSE model was used to estimate GHG and SOC fluxes from three main land uses (grass, arable and forest) in Wales. The overall annual net GHG fluxes of 0.2 t CO_2e ha^{-1} y^{-1}, at baseline climate, shows that Wales has a positive net GWP. The calculated total annual net GHG fluxes from the three investigated land uses across Wales are estimated at an equivalent GWP of 0.34 Mt CO_2e y^{-1}. ECOSSE was previously validated and tested for Europe (Bell et al. 2012) and Ireland (Khalil et al. 2013) and showed its credibility to predict GHG emissions. The model responded appropriately to changes in air temperature, timing of precipitation events, land use and system management, which have strong impacts on GHG and SOC fluxes. For all land uses, N_2O was the main contributor to the net GHG emissions from Welsh soils, whilst CH_4 and SOC fluxes were minor sinks. Grasslands and croplands are much larger emitters of N_2O compared to forest due to the addition of N fertilizer. Freibauer and Kaltschmitt (2003) reported that the fluxes of N to the atmosphere and to ground water by leaching (Hack-ten Broeke et al. 1999) are greater from the intensively managed grasslands than from croplands due to higher nitrate input. Lee et al. (2006) and Abdalla et al. (2014) observed negative CH_4 fluxes from cropland; however, fluxes from organic soils, which are typically poorly drained in their natural state (not included in this study), could be high (Levy et al. 2012). However, the estimate of an annual net GHG balance of 0.34 Mt CO_2e y^{-1} assumes stability of existing land uses, and any recent historic land use change is a source of uncertainty in the result, e.g. a recent net change from permanent grass/forest to arable would lead to higher fluxes, whereas a net change from arable to forest/grass would lead to a lower net GHG balance (e.g. Guo and Gifford 2002).

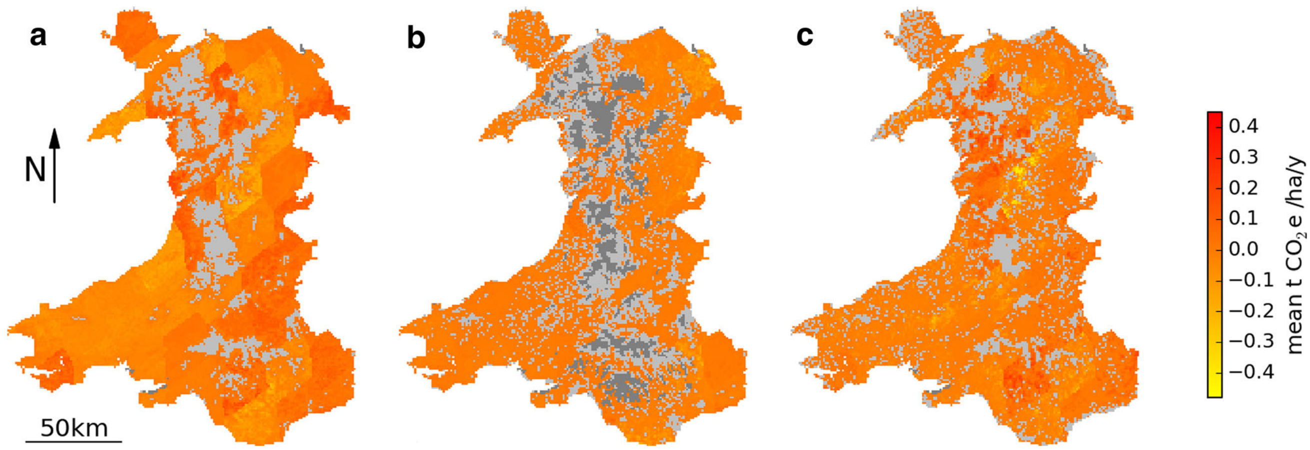

Fig. 4 Simulated change in annual GHG flux (effective t CO_2e ha^{-1} y^{-1}) from Welsh fertilized grassland (**a**), fertilized arable (**b**) and forest (**c**) between baseline and high climate change scenario. *Light grey* areas show zero change; *dark grey* areas show zero land cover

Welsh forests have net annual GHG fluxes of 0.033 t CO_2e ha^{-1} y^{-1} which is low compared with the grass and arable land uses. For many temperate forests, high rates of C uptake have been reported (Aubinet et al. 2001; Berbigier et al. 2001). Land use plays an important role as one of the prime driving forces behind changes in the Earth's climatic system and thereby GHG emissions (Forster et al. 2007). Hayashi et al. (2015) reported that soil–plant interactions strongly affect GHG emissions, in which functions of plant roots influence biogeochemical factors (e.g. availability of oxygen, labile organic C and inorganic N). The N fertilizer application rate estimated by ECOSSE, calculated from the crop N demand, is equivalent to 137 kg N ha^{-1}. Compared with the measured average field N fertilizer application rate for Wales in the period 1974–2012, of 121 kg N ha^{-1} (British Survey of Fertilizer Practices 2013), the ECOSSE estimation is a little higher, but reasonable. This is especially promising considering that the field N fertilizer application rate in Wales has fallen in recent years, and hence the average for the modelled period is likely to be higher than the quoted value (British Survey of Fertilizer Practices 2013). We assumed that arable and grassland were fertilized at a rate required to meet the annual plant N demand, and for simplicity assumed that this was applied as inorganic N rather than manure. According to IPCC default emission factors, the emissions of N_2O from inorganic fertilizer and manures are identical per unit of applied N, so assuming that N was applied in inorganic form would not be expected to greatly affect estimates of N_2O emissions. Further, the absence of manure does not affect modelled CO_2 emissions because the C added though manure would be subsumed into the adjusted plant C inputs required to meet the assumption of equilibrium SOC (Smith et al. 2010a).

Higher net GHG fluxes were observed in coastal areas (Figs. 2) where rainfall was higher and, consequently, soil moisture was high. Both soil moisture and soil N availability are required for high N_2O fluxes. Similar results in field-level studies have been demonstrated in maize (McSwiney and Robertson 2005) and in forest and grassland systems (Maljanen et al. 2002; Abdalla et al. 2010). Soil moisture stimulates denitrification by temporarily lowering oxygen diffusion into the soil (Dobbie and Smith 2001) in addition to increasing the solubility of organic C and NO_3^- (Bowden and Bormann 1986). The strong relationship between N_2O fluxes, and the interaction between soil moisture and soil NO_3^-, suggest that a high rainfall in winter and early spring, together with soil properties such as drainage characteristics, is important in the regulation of N_2O flux from soils. Fluxes of GHG were also increased with increasing air temperature. Here, microbial soil processes such as decomposition, N mineralization, nitrification and nutrient uptake are dependent on temperature (Shaver et al. 2000; Shaw and Harte 2001), and consequently, so are GHG emissions (Abdalla et al. 2009).

Effects of the Glastir measure of reducing nitrogen fertilizer rates on GHG and SOC fluxes for Wales

ECOSSE was applied to assess the efficiency of the Glastir measure of reducing N fertilizer application rate to reduce GHG and SOC fluxes. There are no databases that define application of N fertilizer spatially. ECOSSE therefore estimates the N fertilizer application rate depending on the crop N demand. Under the reduced N fertilizer scenarios, more N is needed by the crop to achieve the full yield. This additional amount of N required by the crop comes from the soil and could lead to more SOC loss to the atmosphere. However, this effect is not accounted for by our model approach which accounts only for the direct effects of reduced N on the flux of N_2O, likely to be the largest impact on net GHG balance due to the high GWP of N_2O.

Heavy utilization of synthetic N fertilizers on grass and arable lands typically results in high N_2O fluxes from soils. However, reducing N fertilizer application rate by 20 and 40 % from the baseline resulted in an overall reduction in net GHG fluxes of 7 and 25 %, thereby lowering climate forcing. Nitrous oxide has a high GWP, thus reducing its emissions would result in beneficial change to net GHG balance (Forster et al. 2007). Availability of mineral N has a direct influence on N_2O production from soils by providing N for both nitrification and denitrification (Baggs and Blum 2004). Reduced N fertilizer inputs lead to slow denitrification rates and a lower proportion of denitrified N emitted as N_2O. Nitrous oxide fluxes from soils occur in short-lived bursts following the application of N fertilizers (Leahy et al. 2004; Skiba et al. 2012). The spatial variability in N_2O fluxes is high (Van den Heuvel et al. 2008) and controlled by interacting abiotic and biotic factors, such as plants, micro-organisms, precipitation and nutrients. Ganesan et al. (2015) reported that N_2O emission seasonal cycles in the UK are due to seasonality in fertilizer application and in environmental drivers such as temperature and rainfall. These factors may vary on an annual basis with a significant effect on the magnitude of the N_2O flux. The flux is also expected to vary on a temporal basis depending on the dominant controlling factor (Mummey et al. 1997). In this study, less reduction in GHG fluxes was observed in coastal areas than in inland areas, due to higher precipitation in coastal areas. Higher precipitation leads to a higher soil water content that in turn leads to a higher denitrification rate. However, although the proportion of denitrified N emitted as N_2O decreases, the net result is an increase in N_2O emissions as soil water content increases. No change was predicted in CH_4 or SOC fluxes due to reducing N fertilizer. This study reveals that the Glastir measure for reducing N fertilizer is an efficient way to reduce N_2O flux and, consequently, GHG emissions from agriculture. However, to further reduce N_2O emissions from agriculture, we recommend matching the supply of mineral N to its spatial and temporal needs by crops and pastures, increasing N use efficiency and using slow-release N or split fertilizer application methods (Abdalla et al. 2010).

Effects of climate change on GHG and SOC fluxes and net primary production for Wales

The effects of climate change on GHG and SOC fluxes and NPP for Wales by the year 2050 were investigated using two climate scenarios, low and high, that correspond to the B1 and A1F1 scenarios of the Forster et al. (2007), respectively. The fluxes of GHG and NPP were not significantly affected by climate change. Under climate change, soil N increases due to increasing mineralization with changing temperature and precipitation (Wennman and Katterer 2006; Abdalla et al. 2010). Soil mineral N and N mineralization are the main sources of N_2O production (Bouwman 1990). Soil characteristics and environmental conditions affect this mineralization (Schoenau and Campbell 1996). The fluxes of N_2O have a threshold response to N, and the amount of N lost to the atmosphere depends on the amount of N taken up by plants (McSwiney and Robertson 2005). Changes in precipitation (Mearns 2003), temperature (Fiscus et al. 1997) and atmospheric CO_2 concentrations could also have positive effects on the productivity of plants (Anwar et al. 2007). Many factors are responsible for CO_2 effects. (1) High CO_2 concentrations directly influence soil C availability by activating photosynthesis and decreasing photorespiration (Akita and Moss 1973). (2) High CO_2 concentrations decrease stomatal conductance (Morison and Gifford 1984) which decreases the transpiration rate per unit leaf area. Low transpiration rates increase the leaf temperature and thereby further increase photosynthesis (Acock 1990). An increase in photosynthesis combined with a decrease in transpiration leads to an increase in the water use efficiency. (3) Higher CO_2 concentrations decrease the crop N concentration (Hocking and Meyer 1991). However, the increase in NPP predicted in this study is small (8–10 %). Nevertheless, the slight increase in N_2O fluxes under climate change, in this study, was likely due to high temperature as precipitation shows little change. Temperature increase soil mineralization and denitrification and consequently N_2O emissions (Abdalla et al. 2010). The SOC fluxes were changed from sinks at baseline climate to small sources under future climate scenarios, with a small difference between the two scenarios (± 2 %). The future increased plant photosynthesis due to high CO_2 concentration increases plant growth, belowground C input and substrate, leading to greater root and microbial activities and respiration (Zak et al. 2000). Previous studies indicate that prediction of soil C fluxes in response to climate change should consider changes in biotic factors, e.g. plant growth and substrate supply, and abiotic factors, e.g. temperature and moisture (Wang et al. 2007; Xia et al. 2009). Temperature is one of the main driving factors affecting C flux from soils (Jabro et al. 2008). The increase in plant growth and aboveground biomass produces more litter fall and may in the short term lead to higher C loss through soil respiration (Zak et al. 2000; Deng et al. 2010), but also to longer-term SOC accumulation. Both soil organic matter decomposition and microbial response to other perturbations, such as fertilization, temperature and rainfall, can increase (Wennman and Katterer 2006).

However, contradicting findings about the effects of rainfall and soil moisture are reported in the literature with increased (Jabro et al. 2008) or unaffected (Ding et al. 2007) C fluxes.

In this study, CH_4 fluxes were low and not significantly affected by climate change. Future overall net GHG balance from Welsh soil will have a positive net GWP, as with baseline climate. Both changes in SOC and plant C inputs (i.e. plant growth) are due to changes in climate, mainly arising through changes in temperature and soil moisture (Smith et al. 2007). This suggests that climate change has little effect on GHG flux and NPP to 2050, and Welsh soils will continue to be a net source of GHG emissions by the year 2050.

Conclusions

In this study, the ECOSSE SOM model was used to estimate the GHG flux of soils in Wales under different climates and fertilizer levels. The GHG fluxes were significantly different between the three investigated land uses. In terms of GWP, the overall average annual net GHG balance at baseline climate (1961–1990) is equivalent to 0.2 t CO_2e ha^{-1} y^{-1}, which makes a total of 0.34 Mt CO_2e y^{-1} for the whole of Wales. The Glastir measure of reducing N fertilizer by 20 and 40 % is effective and could reduce annual net GHG fluxes by 7 and 25 %, respectively, although there is some uncertainty in the resultant effect on yield and soil fertility. If the current N fertilizer application rate continues, climate change up to the year 2050 would not significantly affect net GHG balance or NPP from Welsh soils. The difference in results between the two climate scenarios is small (about $\pm$2 %).

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