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Simulation of soil carbon efflux from an arable soil using the ECOSSE model: Need for an improved model evaluation framework?

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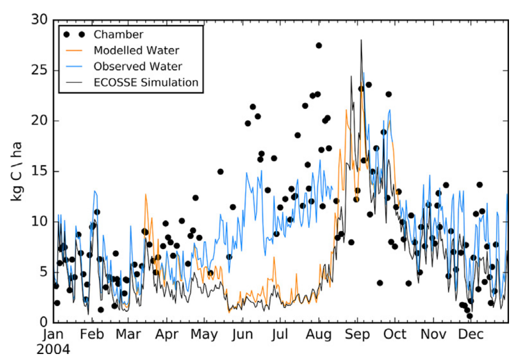
HIGHLIGHTS

- Soil carbon modelling is essential for quantification of GHG flux.
- Commonly used soil C model was evaluated and discrepancies were found.
- Deconstruction of model rate modifiers shows deficiency in water component.
- r^2 Values improve significantly using observed soil water content instead of modelled.
- We recommend stronger evaluation of biogeochemical models.

GRAPHICAL ABSTRACT



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ABSTRACT

Globally, it is estimated that ~1500 Pg C of organic carbon is stored in the top meter of terrestrial soils. This represents the largest terrestrial pool of carbon. Appropriate management of soils, to maintain or increase the soil carbon pool, represents a significant climate change mitigation opportunity. To achieve this, appropriate tools and models are required in order to more accurately estimate soil carbon fluxes with a view to informing and developing more effective land use management strategies. Central to this is the evaluation of models currently in use to estimate soil carbon emissions. In the present study, we evaluate the ECOSSE (Estimating Carbon in Organic Soils – Sequestration and Emissions) model which has its origins in both SUNDIAL and RothC and has been widely used globally to model soil CO_2 fluxes across different locations and land-use types on both organic and mineral soils. In contrast to previous studies, the model was found to poorly represent observed soil respiration at the study site, an arable cropland on mineral soil located in south-east Ireland. To isolate potential sources of error, the model was decomposed into its component rate equations or modifiers. This investigation highlighted a deficiency in the model simulated soil water, resulting in significant inhibition of the model simulated CO_2 flux relative to the observed data. When measured values of soil water at the site were employed, the model simulated soil respiration improved significantly (r^2 of 0.775 vs 0.154). This highlighted model deficiency remains to be evaluated at other sites; however, the research highlights the need for a more comprehensive evaluation of soil carbon models prior to their use in informing policy, particularly models which are employed at larger scales and for climate change projections.

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1. Introduction

Carbon emissions associated with land use, land use change and forestry (LULUCF) contribute the second largest source of carbon emissions to the atmosphere (Bond-Lamberty and Thomson, 2010; Scharlemann et al., 2014), with an estimated contribution of approximately 33% of total anthropogenic emissions, or ~150 petagrams carbon (Pg C; 10^{15} g), over the period 1850–2000 (Houghton, 2003). While the relative contribution has declined over recent decades (contributed ~12.5% of total anthropogenic emissions between 1990 and 2010 – Houghton et al., 2012), largely attributed to an increase in fossil fuel emissions, increasing attention is being focused on simulating terrestrial carbon stocks and emissions, as terrestrial soils may present a significant climate change mitigation opportunity if managed appropriately.

Globally, it is estimated that approximately 1500 Pg C of organic carbon is stored in uppermost meter of terrestrial soils (Scharlemann et al., 2014; Oertel et al., 2016). This represents the largest terrestrial carbon pool, roughly equivalent in sum to both the atmospheric (816 Pg C) and terrestrial phytomass (469.6 Pg C) pools (Scharlemann et al., 2014). Although estimates of SOC stocks in, and emissions from, terrestrial soils remain highly uncertain (Houghton et al., 2012; Scharlemann et al., 2014; Oertel et al., 2016), there remains a pressing need to improve our understanding of soil carbon management in order to minimise soil carbon losses and increase the carbon sequestration potential of soils (Scharlemann et al., 2014).

Soil CO_2 efflux, or soil respiration (R_S), is comprised of both heterotrophic (R_h) (anaerobic and aerobic microbial decomposition) and autotrophic (R_a) (plant root) respiration of CO_2 from the soil to the atmosphere. While fine roots of woody plants can host heterotrophs (e.g. ectomycorrhizal fungi), the received nutrients are derived from photosynthesis and therefore generally considered in the autotrophic component (Högberg et al., 2005). The contribution of root respiration to total soil respiration is however highly variable, with published estimates ranging from 10% to >90% depending on vegetation cover and season (Hanson et al., 2000), but on average is estimated to contribute up to ~50% of total soil respiration (Oertel et al., 2016). This partitioning varies between perennial and cropland systems as root growth commonly contributes an increased proportion to R_s during the growing season (Hanson et al., 2000).

Ecosystem respiration (R_{eco}), which includes both soil and aboveground plant respiration, also fluctuates seasonally with the growth cycle. The difference between carbon uptake by plants during photosynthesis and ecosystem respiration is referred to as the net ecosystem exchange (NEE). When the NEE is positive, the ecosystem represents a source of CO_2 to the atmosphere and a CO_2 sink when negative. As direct measurements of R_{eco} and R_h are difficult to obtain; R_h is typically estimated from R_{eco} which is in turn derived from NEE and GPP which are measured, or estimated from measured values, based on observations obtained at eddy covariance flux tower sites.

Soil respiration rates have been found to vary significantly with vegetation/plant type (Raich and Tufekciogul, 2000; Oertel et al., 2016). In general, a positive correlation is associated on an annual basis between soil respiration and above ground litter production (Raich and Schlesinger, 1992). Increasing vegetation cover also impacts on the soil microclimate, primarily associated with decreased soil temperatures due to increased leaf area and resultant shading effect (Oertel et al., 2016). A meta-analysis by Raich and Tufekciogul (2000) found on average that cropped fields displayed increased rates of soil respiration (~20%) relative to surrounding fields in fallow, however, this difference was not significant. Kessavalou et al. (1998) also found increased CO_2 emissions during spring and summer, based on inter-row chamber measurements over arable cover (e.g wheat).

Belowground biomass, soil microbial activity and decomposition rates are highly dependent on soil temperature, soil water content, nutrient availability and soil pH (e.g. Singh and Gupta, 1977; Carlyle and Than, 1988; Raich and Schlesinger, 1992; Cook and Orchard, 2008; Guntiñas et al., 2013). As a result, soil respiration rates are predominantly influenced by meteorological, climatological and land management factors (e.g. land cover, land cover change, nutrient application etc. - Oertel et al., 2016). Process-based models, which seek to simulate soil carbon dynamics and/or soil respiration, therefore typically require these factors as input variables or parameters. For example, RothC (Rothamsted Carbon Model - Coleman and Jenkinson, 1996), requires information on soil type (e.g. proportion of clay) and inputs of meteorological variables (e.g. temperature, rainfall and potential evapotranspiration), plant residues and nutrient applications to simulate the turnover of organic carbon in topsoils. Similarly, ECOSSE (Estimating Carbon in Organic Soils – Sequestration and Emissions; Smith et al., 2010a), which has its origins in SUNDIAL (Simulation of Nitrogen Dynamics in Arable Land - Bradbury et al., 1993) and RothC (Coleman and Jenkinson, 1996), requires the specification of parameters such as soil pH, bulk density, sand and silt content and soil depth, in addition to those parameters required by RothC, to simulate the soil fluxes of greenhouse gases (e.g. CO_2, N_2O, CH_4) from organic soils. These models employ a common approach by partitioning soil organic matter (SOM) into 'pools' of inert organic matter (IOM), humus (HUM), biomass (BIO), resistant plant material (RPM) and decomposable plant material (DPM); processes and turnover rates of C and N are then simulated using simple equations driven by common input variables such as soil characteristics and meteorological/climatological data. The decomposition process is described by first order rate equations (with specific rates for each pool) which are modified according to external factors such as temperature, moisture, crop cover and soil pH (Dondini et al., 2017).

The aim of this study was to evaluate the most recent version of the ECOSSE model (v6.2), in simulating observed soil respiration rates for croplands on a free-draining mineral soil. The study site used in this research was chosen as it contributed to FLUXNET, a network of regional networks of flux measurement sites; these sites record detailed information on the site characteristics (e.g. soil, meteorology etc.) necessary to run the model and, importantly, also had independent supplementary observations (NEE, soil chamber observations) which could be used to evaluate the model. The ECOSSE model was chosen for a number of reasons, (1) it has previously been applied at the study site to assess fluxes of greenhouse gases and SOC stock changes (Khalil et al., 2013) and was found to outperform other similar process-based models (e.g. DNDC, DailyDayCent) when estimating N_2O fluxes (Khalil et al., 2016); (2) ECOSSE was developed from concepts initially implemented in SUNDIAL (Bradbury et al., 1993) and RothC (Coleman and Jenkinson, 1996) models which have been widely reported in the literature; (3) it has been applied widely in a variety of environments for different land-use types including European cropland (Smith et al., 2010b; Bell et al., 2011; Khalil et al., 2013; Dondini et al., 2017), peatland (Abdalla et al., 2014), land under Miscanthus and Willow (Dondini et al., 2016a) and bioenergy cover crops (Dondini et al., 2016b); and (4) ECOSSE can be scaled to derive national estimates of soil C with limited inputs, therefore the model could be employed to inform national inventories and policies. ECOSSE has also been coupled with JULES (Joint UK Land Environment Simulator), a community land surface model employed in the latest version of the UK Met Office Unified Model (Ostle et al., 2009).

Prior to undertaking the evaluation, the ECOSSE model was initialized using available measurements, or parameters and variables derived from observed values. Following this, the model was initially evaluated against R_h, derived as a proportion of R_{eco}. However, due to concerns over the methods used to estimate R_{eco}, the model was subsequently evaluated against data obtained from a separate soil chamber experiment, results from which overlapped in time with the model simulations. Following this evaluation, soil respiration was then simulated using an alternative approach, which considered the individual contributions of the dominant external drivers of soil respiration, namely, temperature, moisture, crop cover and soil pH, employing different formulations.

The present research seeks to contribute to the existing, growing, literature on the evaluation of ECOSSE, but highlights a potential area for model improvement.

2. Materials and methods

2.1. Soil respiration simulation

The ECOSSE model and input requirements have been extensively described elsewhere (see Smith et al., 2010a; Dondini et al., 2016b; Dondini et al., 2017); only those details considered important for the current study are included here. Although ECOSSE was originally developed for organic soils, it has been widely applied and evaluated on mineral soils (Bell et al., 2011; Khalil et al., 2013; Dondini et al., 2016a; Dondini et al., 2016b; Dondini et al., 2017). In common with a number of similar models, ECOSSE describes the decomposition process using first order rate equations based on temperature, moisture, crop cover and soil pH (Dondini et al., 2017). These are outlined below; additional empirical formulations which relate the relevant variables to soil respiration are also outlined as they are subsequently employed.

2.1.1. Soil temperature

In the absence of soil moisture limitations, the relationship between soil respiration and temperature is generally considered to be positive, with colder soils inhibiting microbial activity and CO_2 generation (Raich and Schlesinger, 1992; Lloyd and Taylor, 1994). However, the determination of the exact relationship remains challenging (Lloyd and Taylor, 1994). Consequently, a number of empirically based formulations, which relate soil respiration to either soil or air temperature, have been proposed. In this study a number of selected temperature modifiers (outlined below) were applied to the observed data to investigate the relevant ECOSSE modifier.

Based on analysis of data from a range of different ecosystems and soil temperatures, Lloyd and Taylor (1994) derived a simplified expression (Arrhenius type expression) for soil respiration rate based on temperature, at a standardized temperature of 10 °C as follows,

$$R_S = R_{10}\ \exp\left(308.56\left(\frac{1}{56.02}-\frac{1}{T-T_0}\right)\right) \tag{1}$$

where, R_{10} is the respiration rate at 10 °C, T is air temperature and T_0 is a temperature between T and 0 K. Lloyd and Taylor (1994) suggest a value for T_0 of 227.13 K, which provided an optimized fit to the observational data employed in their analysis. Jacobs et al. (2007) provide an alternative formulation, originally developed for grasslands, again derived from a simple Arrhenius type expression and includes a correction to modify soil respiration for conditions of soil water stress, as follows,

$$R_S = R_{10}(1-f(w))\ \exp\left[\left(\frac{E_0}{283.15R^*}\right)\left(1-\frac{283.15}{T_{soil}+273.15}\right)\right] \tag{2}$$

Where, $f(w) = C\frac{w_{max}}{w_{soil}+w_{min}}$ where E_0 is the activation energy (kJ $kmol^{-1}$), R^* (kJ $kmol^{-1}$ K^{-1}) is the universal gas constant and T_{soil} is temperature in the first soil layer, and f(w) is a function to modify soil respiration under conditions of soil water stress, w_{max} and w_{min} are reference soil water content values of 0.55 and 0.005, respectively.

The temperature function in ECOSSE is described as a first order process, following from SUNDIAL and RothC, for both anaerobic and aerobic decomposition, with m_t the temperature rate modifier, specified as follows,

$$m_t = \frac{47.9}{1+\ exp\left(\frac{106}{T_{air}+18.27}\right)} \tag{3}$$

where, T_{air} is the mean daily air temperature (°C). ECOSSE assumes a Q_{10} constant (measure of the rate of change of a system as a consequence of 10 °C temperature increase) of 2.0.

2.1.2. Soil water

There is a complex relationship between soil moisture and microbial respiration within soil (Reichstein and Beer, 2008); major factors affecting the rate of respiration include soil water content, substrate availability and time (Cook and Orchard, 2008) all of which vary with soil water content. Models typically simplify these interactions by using rate modifying factors. For example, the RothC model (Coleman and Jenkinson, 1996) which ECOSSE inherits some characteristics from, employs a modifying factor (b) for soil respiration due to soil moisture based on estimated soil moisture deficits (SMD), derived from rainfall and potential evapotranspiration (PE) data (Coleman and Jenkinson, 2014):

$$If\ \ accumulated\ (acc)\ SMD{<}0.444\ \ \max SMD,$$

$$\mathrm{b} = 1$$

Otherwise,

$$b = 0.2 + (1.0-0.2) * \frac{maxSMD-acc\ SMD}{maxSMD-0.444\ maxSMD} \tag{4}$$

Once a soil dries beyond a soil moisture deficit threshold, respiration becomes increasingly inhibited until wilting point, after which the modifier is set to 0.2. The ECOSSE water modifier has its origins in the SUNDIAL model (Bradbury et al., 1993; Smith et al., 1996) and assumes aerobic decomposition proceeds at maximum rate as the soil dries from field capacity to the amount of water held at −100 kPa, decomposition is then increasingly inhibited until the soil reaches its permanent wilting point,

$$m_w = 1-\frac{((1-m_{w0})\ x\ (\Psi_{f-}\Psi_{c-}\Psi_i))}{\Psi_{f-}\ \Psi_i}\ \ ;(\text{if } (\Psi_{f-}\Psi_c){<}\Psi_\mathrm{i}, m_w = 1) \tag{5}$$

where, m_{w0} is the rate modifier at permanent wilting point (0.2), Ψ_c is the water held above permanent wilting point, Ψ_i is the water held between field capacity and −100 kPa, and Ψ_f is the water held between field capacity and permanent wilting point (all units in mm/$layer^{-1}$). This is calculated for each 5 cm soil layer to the specified depth in ECOSSE; leaching between layers is by simple piston flow. Saturated conditions are also known to inhibit aerobic respiration (Reichstein and Beer, 2008) and ECOSSE includes a modifier for soil water conditions between field capacity and saturation. However, agricultural soils are considered to be free draining and as such, soil water rarely, if ever, exceeds field capacity.

2.1.3. Vegetation cover

The modifying effect of vegetation cover on soil respiration is simulated in ECOSSE using a crop modifier, originally derived from RothC. While the selection of the threshold is somewhat arbitrary, it is based on findings from a number of studies (e.g. Sommers et al., 1981; Sparling et al., 1982). The crop modifier (m_{crop}) is set as.

$$\mathrm{m_{crop}} = 1 \text{ if the soil is bare (no effect), and}$$

$$\mathrm{m_{crop}} = 0.6 \text{ if the soil is vegetated}$$

The effect of which reduces soil respiration during the growing season by 40%.

2.1.4. Soil pH

The pH modifier in ECOSSE was introduced for organic soils where pH is more variable. The pH modifier is as follows,

$$m_{pH} = m_{pH,\ min} + (1 - m_{pH,\ min}) \left(\frac{pH - pH_{min}}{pH_{max} - pH_{min}} \right) \quad (6)$$

where aerobic decomposition proceeds at an optimum rate ($m_{pH} = 1$) until the pH falls below a critical threshold (pH_{max}) and the minimum rate of decomposition is set as,

$$m_{\text{pH, min}} = 0.2,\ \ pH_{\text{min}} = 2, pH_{\text{max}} = 4.5$$

2.2. Site description

The experimental site used in this study is an arable field located at the Teagasc Oak Park Research Centre, Co. Carlow, Ireland (Fig. 1), for further details see (Davis et al., 2010).

The site has been under cropland for over 50 years with sugar beet, spring barley, maize and oil seed rape planted in rotation until 2000. Since 2000 the site has been cropped continuously with spring barley. This study initially focuses on the years 2004–2006 due to the availability of suitable data. Full details of the site and soil characteristics are listed in Table 1. Land management details for the period are outlined in Table 2.

The site hosted an eddy covariance flux tower over the study period providing access to net ecosystem exchange measurements that were utilized in the study (Davis et al., 2010). Data available from the flux tower included meteorology, volumetric soil water content and NEE, from which R_{eco} was derived.

2.2.1. Meteorological data

Daily meteorological data were obtained from two sources: the Irish meteorological service, Met Éireann, who provided data from the nearby weather station located on the grounds of the Teagasc Oak Park Research Centre and the nearest synoptic station located in Kilkenny approximately 30 km away (1), and the flux tower stationed in the experimental field, covering the period from 2004 to 2006 (2). As ~7% of the data from 2004 to 2006 were missing from the Oak Park meteorological station, gaps were subsequently infilled using either the flux tower or Kilkenny synoptic station data, in that order. As long-term data were not available from Oak Park, data from the nearby Kilkenny synoptic station were obtained to derive the 30-year averages used for model spin-up (in which soil C is brought to equilibrium). Meteorological and climatological information utilized for the study is shown in Fig. 2.

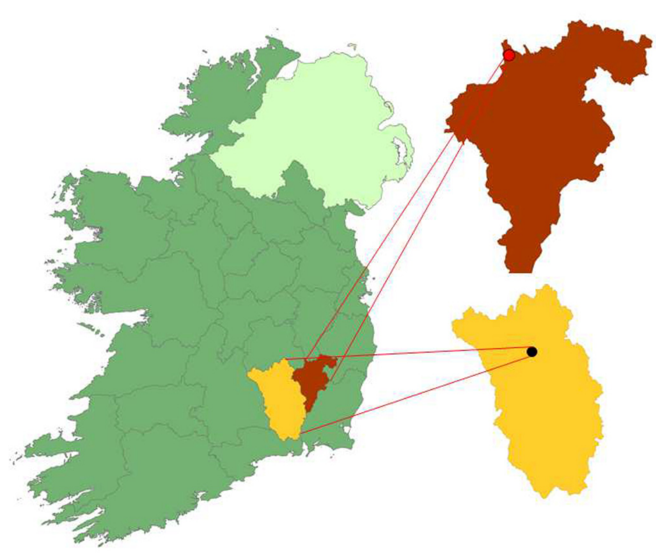

Fig. 1. Republic of Ireland showing Kilkenny (yellow) and Carlow (brown) with Kilkenny synoptic station (black point) and case study location Oak Park (red point).

Potential evapotranspiration (PE) values were unavailable for the Oak Park site for the years 2004–2006. Consequently, daily values for PE for the period of interest were initially estimated using the Hargreaves method (Hargreaves and Samani, 1985). Since 2008 when the weather station was upgraded, Met Éireann have derived estimates of PE using the FAO-56 Penman-Monteith method, facilitating an evaluation of the Hargreaves method over the period 2008 to 2016. This evaluation indicated a significant overestimation of PE values derived using the Hargreaves approach when compared to the Met Éireann calculated values. A linear calibration was derived from the 2008 to 2016 period and subsequently applied to the Hargreaves estimated values for the 2004 to 2006 period, resulting in modified PE values which were used as input to the model. Fig. 3 illustrates the cumulative sums for the years 2008 to 2010 based on the original Hargreaves method, the modified Hargreaves estimates and the Met Éireann derived PE values. A difference in annual accumulations of ~100 mm is evident between the pre- and post- modified Hargreaves values.

2.2.2. Soil respiration

As R_{eco} represents the combined soil auto- and hetero- trophic respiration, the daily R_{eco} values was subsequently partitioned between the gross autotrophic and heterotrophic components. This was achieved by running DNDC (DeNitrification-DeComposition; (Giltrap et al., 2010)), using the same inputs and weather data outlined previously, to derive ratios of R_h to R_{eco}, following the method of Khalil et al. (2013). Alternatively, Hardie et al. (2009) propose that R_h is between 46 and 59% of R_{eco}; Abdalla et al. (2014) split this seasonally so that R_h is assumed to be at its lowest at 46% during summer (JJA), 59% during winter (DJF) with a mean value (52.5%) for the rest of the year. Both these methods produced a similar temporal signal but the cumulative fluxes were found to be higher for the seasonal method (Fig. 4).

Dondini et al. (2017) suggest that since ECOSSE simulates GHG fluxes from the soil layers defined by the user, whereas the flux data represents fluxes from the entire soil profile, model output will fall below the estimated R_h. Due to these complexities in partitioning flux tower data into autotrophic and heterotrophic components, soil respiration measurements using chamber data was ultimately prioritized as more useful for model evaluation. However, soil respiration from the chamber data was only available for 2004, a limiting factor on the present study. Soil chamber measurements of CO_2 fluxes, obtained from Jones et al. (2010), were measured using a CIRAS 2 infra-red gas analyzer coupled to static chambers (SRC-1 soil respiration chamber, PP Systems, Hitchin, Herts, UK). The system allowed automated in-field soil CO_2 flux measurements every 20–90 min. Twelve collars were inserted to a depth of 5 cm into the soil 12 days before measurements began to alleviate the effect of soil disturbance on the fluxes. While it is likely that the measurements from the soil chambers include both components of heterotrophic (R_h) and autotrophic (R_a) respiration, the soil chamber data does provides an upper limit to Rs in which to assess the model.

2.2.3. Soil moisture

Volumetric soil water content (SWC) (%) measurements at the flux tower were also available for the period 2004–2006. The SWC data, obtained from a previous study (Davis et al., 2010), was measured using a CS616 Water Content Reflectometer (Campbell Scientific) to a depth of 20 cm. The measured Soil Water Content (SWC) in the field ranged from 3.92% to 27.14% with a mean of 16.95%, over the period of measurement. As the SWC was measured at a 20 cm depth, for comparison with the ECOSSE model which requires water content to be specified to 25 cm, the SWC volume percentage was estimated to a depth of 25 cm and converted to mm. Field experiments indicate that volumetric water content at relatively shallow depths does not vary greatly, indicating that this

Table 1
Oak Park Site Characteristics (adapted from observed data, (Khalil et al., 2013) and (Abdalla et al., 2009a)).

Site characteristics	
Climate data	
Latitude/longitude (decimal)	52.858/−6.915
Elevation (m)	58.208
Mean annual temperature	10.04
Annual accumulated precipitation	822.7
Land-use history	Heavily cultivated for 40 years with a mix of oil seed rape, cereals and sugar beet, was previously under pasture. Spring barley since 2000.
N concentration in rainfall (mg N l^{-1})	0.001*
Atmospheric CO_2 concentration (ppm)	380*
Annual atmospheric N deposition (kg/ha^{-1}):	11
Soil properties	
Vegetation cover	Spring Barley
Soil type	Euteric Cambisol/Grey Brown Podzolics
Soil texture	Sandy loam
Bulk density (g cm^{-3}): 0–10/0–25 cm	1.42/1.48
Clay (%) 0–10/0–25 cm	15.13/14.73
Silt (%) 0–10/0–25 cm	25.63/33.73
Sand (%) 0–10/0–25 cm	59.24/51.55
Total SOC (kg ha^{-1}): 0–10/0–25 cm	19,912/42,888
Total IOC (kg ha^{-1}): 0–10/0–25 cm	3863/8163
Organic C content at surface (kg C kg^{-1})	0.019
Soil pH 0–10/0–25	7.24/7.35
AW at field capacity (mm): 0–10/0–25 cm	22.69/55.13
Water content at saturation (%): 0–10/0–25 cm	47.21 (AW = 29.51 mm)/45.56 = 133.87 mm (AW = 71.17 mm)
Water content at field capacity (%): 0–10/0–25 cm	40.39 (AW = 22.69 mm)/38.97 = 97.43 mm (AW = 54.73 mm)
Water content at wilting point (%): 0–10/0–25 cm	17.70 (AW = 17.70 mm)/17.08 (AW = 42.7 mm)
NH_4 and NO_3 (kg N ha^{-1}): 0–10/0–25 cm	2.8/6.92 and 9.5/23.17
Harvest	Grain harvest, mulch/till
Tillage	Conventional and reduced
WFPS at field capacity (0–10 cm depth)	0.68
WFPS at wilting point (0–10 cm depth)	0.12
Depth of water retention layer (cm)	100
Depth of impermeable layer (cm)	>150 (drainage class high)

* Default Values.

method is appropriate (Qiu et al., 2001; Quesada et al., 2004; Tromp-van Meerveld and McDonnell, 2006; Martin et al., 2012). The derived SWC ranged in values from 9.8 to 67.85 mm, with an average of 42.25 and median of 45.2 mm over the period.

3. Results & discussion

Fig. 4 illustrates the estimated R_{eco}, derived from measurements taken at the flux tower, R_h partitioned from R_{eco} using the two previously described methods and ECOSSE simulated R_h using the model parameters outlined in Tables 1 and 2. A marked difference is evident between the ECOSSE simulated soil heterotrophic respiration (R_h) values and R_h values derived using the methods outlined above. While not unexpected, largely due to the uncertainties associated with partitioning the net flux R_{eco} between its two gross components (R_a and R_h), the results are in marked contrast to previous studies from the site which employed a similar approach (Khalil et al., 2013; Khalil, 2015).

Liu et al. (2006) previously found a strong correlation between soil CO_2 efflux and the daily variation of photosynthetically active radiation (PAR). On investigation, a temporal offset is evident between the timing of peak radiation and temperature at Oak Park, with leaf area index, here used as a proxy for plant growth, more closely corresponding with radiation (Fig. 5). The seasonality of R_{eco} is dominated by above ground plant respiration (Barr et al., 2004; Matteucci et al., 2015), in turn reflecting the seasonal growth of plants. Hence, any partitioning of R_{eco} to derive R_h will ultimately reflect this seasonality. As R_h variability in ECOSSE is primarily influenced/modified by temperature, an offset in model simulated R_h will result. However, the offset in timing between radiation and temperature at the site is not sufficient to account for the difference between the model simulated and estimated values of R_h.

Subsequently, soil chamber measurements for 2004 were used to compare to the model simulated $R_{h,}$ as chamber measurements are

Table 2
Management timeline of spring barley fertilized with CAN NitroSulphur.

	2003	2004	2005	2006
Crop 1 sow	20/03/2003	26/03/2004	14/03/2005	20/03/2006
Crop 1 harvest	23/08/2003	26/08/2004	08/08/2005	01/08/2006
Fert 1 Date	15/04/2003	27/04/2004	16/04/2005	12/04/2006
Fert 1 (kg N/ha)	137	140	109	89.91
Fert 2 Date	–	–	10/05/2005	11/05/2006
Fert 2 (kg N/ha)	–	–	55	50
Crop 2 type	–	–	Mustard Cover	–
Crop 2 sow	–	–	12/09/2005	–
Crop 2 harvest	–	–	21/02/2006	–

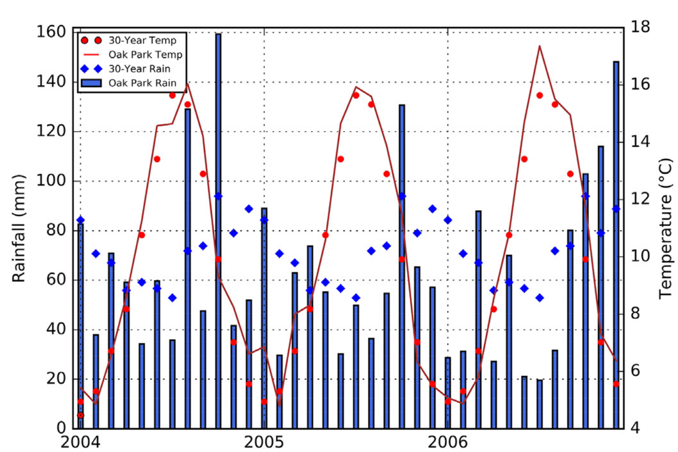

Fig. 2. Meteorology for 2004–2006 for Oak Park and 30 year climatology from 1974 to 2003 from Kilkenny synoptic station (~30 km from Oak Park).

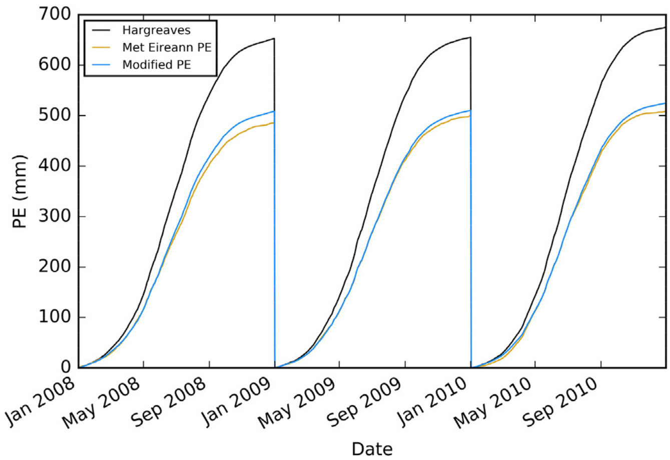

Fig. 3. Cumulative PE illustrating the overestimation derived using the Hargreaves calculation, compared to Met Éireann PE and PE modified, using calibration equation.

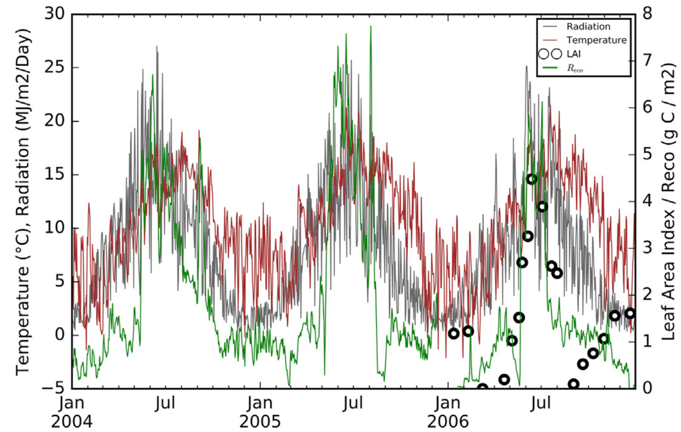

Fig. 5. Radiation, R_{eco}, temperature (2004–2006) and leaf area index (LAI) (2006) measured at the site.

considered more reliable than flux partitioned ecosystem respiration (Dondini et al., 2017) (Fig. 6). The simulated R_h values appear much closer to the CO_2 soil chamber measurements after August, indicating that the model is capturing a component of the measured soil respiration. However, the model simulation does not replicate the measured soil chamber values during the plant growing season, from April to August (crop sowing date: 25 March; crop harvest date: 25 August).

To investigate this, the modifier equations outlined in Section 2.1.1 were applied to the meteorological data at the site to investigate potential sources of error in the timing and magnitude of the ECOSSE simulated values.

3.1. Temperature modifier

For comparison, the comparable component expressions from Eq. (1) (Lloyd and Taylor, 1994) and 2 (Jacobs et al., 2007) were employed along with the ECOSSE temperature modifier (Eq. (3)) (Smith et al., 2010a) to simulate soil respiration at the site. Fig. 7 shows the simulated soil respiration response to temperature based on each of these methods, which all produce results positively correlated with the measured soil chamber data (Spearman's Rho of 0.848 for each, significant at the 0.01 level). Despite the Jacobs et al. (2007) equation being derived for grasslands, the outcome is consistent with both the ECOSSE and Lloyd and Taylor expressions.

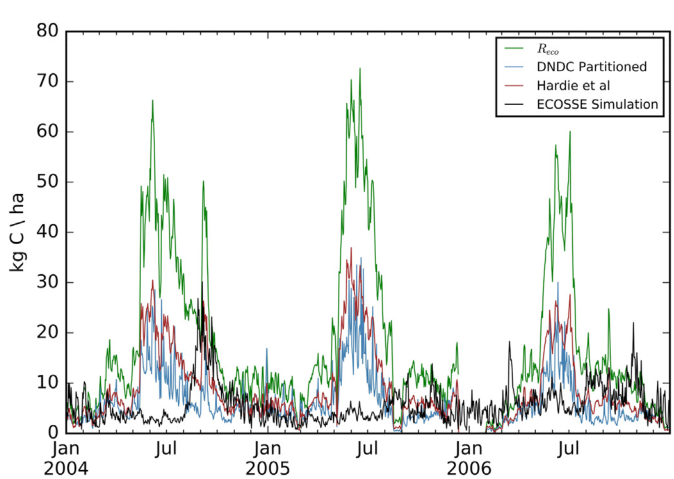

Fig. 4. Comparison between R_{eco}, estimated from measurements at the flux tower, R_h partitioned using relative proportions (R_h/R_{eco}) from DNDC (following Khalil et al., 2013), R_h partitioned using the method of Hardie et al. (2009) and ECOSSE model simulated R_h, over the period 2004–2006.

3.2. Water modifier

The ECOSSE water modifier was then applied (Eq. (5)) to the model simulated available water (AW); available as an output from the model for each 5 cm soil layer. For the purposes of this evaluation, the water modifier was applied to the simulated available water, accumulated over each 5 cm layer to a depth of 25 cm. While the soil depth in the ECOSSE model simulation was set to a depth of 45 cm, the dominant soil efflux typically arises from the upper most layers - SUNDIAL allocates 80% of SOM to the 0-25 cm layers - (Bradbury et al., 1993), and for simplification, only the AW accumulation to 25 cm was used. Also, the selection of this depth allowed for a direct comparison with soil water content derived from measurements. Evident from Fig. 8, the model simulated AW and consequently, the water modifier (m_w) has a significant impact on the simulated CO_2 fluxes; results from applying both the temperature and water modifier closely replicate the ECOSSE model simulated values, indicating the importance of model simulated soil water content.

3.3. Crop and pH modifiers

Finally, the crop (m_{crop}) and pH (m_{pH}) modifiers were applied. The crop modifier follows Jenkinson (1977) and applies a rate of 0.6 when the crop is growing, and 1 when the crop is absent. This acts to further reduce the CO_2 efflux during the growing season; but, in spite of the threshold value applied (i.e. 0.6) its effect is proportionally small due to the previous effect of the water modifier. The modifier of 0.6 is

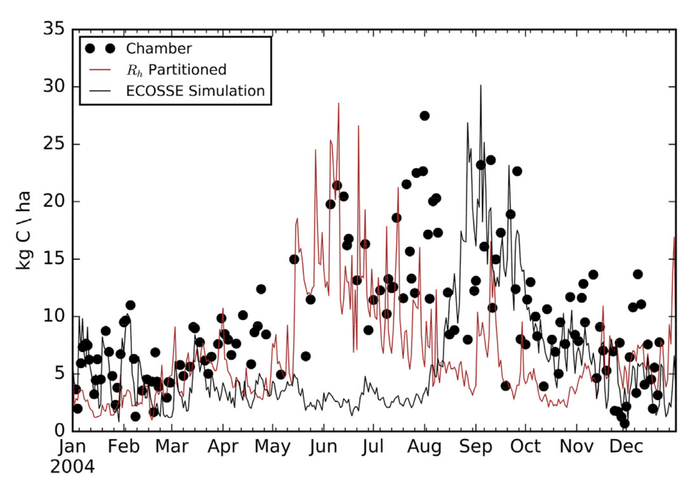

Fig. 6. Comparison between model simulated R_h, R_h partitioned using DNDC and measured soil respiration from the soil chamber experiment for 2004.

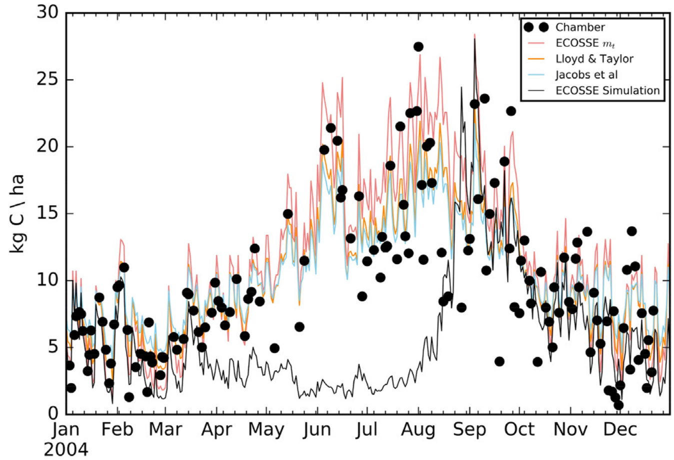

Fig. 7. Temperature modifiers (coloured lines), chamber data (dots) and model output (solid black line) for 2004.

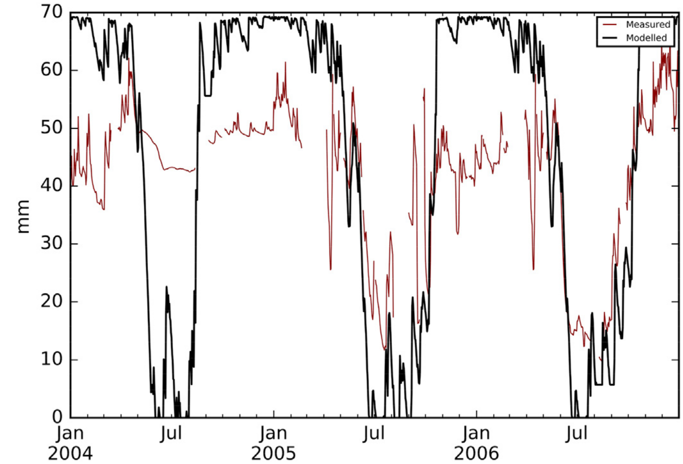

Fig. 9. Soil Water Content derived for a depth to 25 cm, based on measured volumetric soil water content and ECOSSE modelled available water based on an accumulation of each 5 cm layer to a depth of 25 cm.

arguably an arbitrary one, future work could examine the potential for amplified respiration resulting from increased root growth and microbial activity as plants grow.

As soil pH is near neutral (pH ~7.3) at the site, the modifier is assumed to be 1, similar to RothC and SUNDIAL (Coleman and Jenkinson, 1996; Bradbury et al., 1993) for well managed arable soils and thus had no impact on the calculated soil efflux.

3.4. Comparison with measured SWC

As a combination of the ECOSSE simulated AW and water modifier were found to have the largest impact on the simulated soil efflux, the model simulated AW was initially compared to the measured soil water content (volumetric % converted to mm over 25 cm depth) (Fig. 9). While the ECOSSE model appears to capture the timing and duration of soil drying, the model overestimates the magnitude. This is particularly evident in 2004, where the measured SWCs remain high (no water stress), but the model simulated AW indicates complete drying of the soil layers to 25 cm (water stress). During 2005 and 2006, the measured SWCs indicate drying of the soil layers, but the model simulated AW again overestimates the magnitude, with complete drying of the model soil layers for ~10 weeks in 2005 and ~3 weeks in 2006.

As measured SWC values were available, the ECOSSE water modifier was applied to the SWC estimated to 25 cm ($m_w(SWC)$), based on the volumetric SWC measurements, rather than the model simulated AW. The results from this indicate a much lower suppression of soil respiration, relative to the ECOSSE model simulated values (Fig. 10), particularly during the plant growing season. This is evidenced by lower RMSE and MAE values for the empirical model using $m_w(SWC)$ compared to the actual ECOSSE model output; similarly, higher correlations are evident between the empirical model using $m_w(SWC)$ and the chamber measurements (Table 3).

3.5. Model sensitivity to available water model parameter

Inconsistent reporting of available water content and differences in the pattern of soil CO_2 emissions resulting from different available water inputs motivated further research into the impact of different AW model parameter values. In the absence of direct field measurements of soil water tension, field capacity, water content at wilting point and water available at saturation are typically estimated using pedotransfer functions (after Saxton and Rawls, 2006); in order to determine soil water characteristics based on soil parameters at varying tensions. US based literature widely denotes −33 kPa as the tension at field capacity and −1500 kPa the tension at wilting point; AW is then the difference between the two. However, soil tension at field capacity estimates can range from ~ − 10 kPa for sandy soils to −33 kPa for

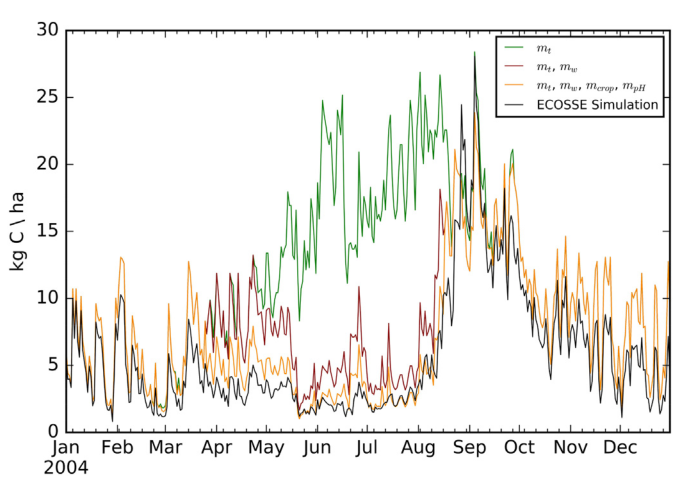

Fig. 8. ECOSSE modifiers applied as follows, temperature (m_t), temperature & water (m_t, m_w), temperature, water, crop and pH (m_t, m_w,m_{crop}, m_{pH}), and ECOSSE model simulated soil respiration.

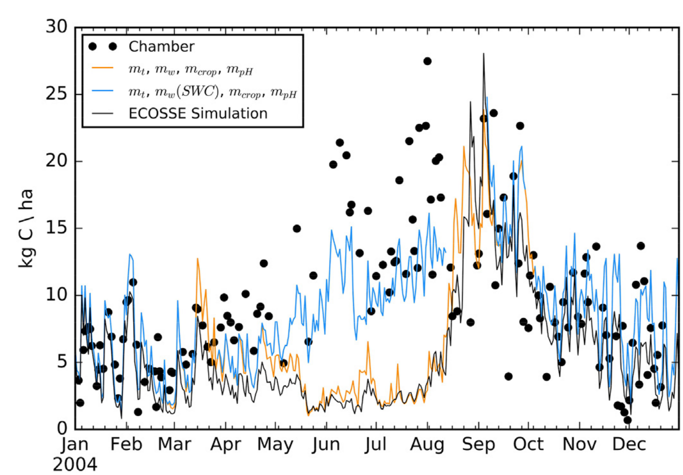

Fig. 10. ECOSSE modifiers (m_t, m_w,m_{crop}, m_{pH}) applied to both model simulated available water (yellow line) and using measured SWC (blue line). Soil chamber measurements are also plotted, along with the ECOSSE model simulated values.

Table 3
Correlation (grey) MAE and RMSE (white) for modelled SWC, observed SWC and model simulated R_h.

	m_t, m_w, m_{crop}, m_{pH}	m_t, $m_w(SWC)$, m_{crop}, m_{pH}	Model
Chamber	0.154	0.775*	0.238*
Model	0.961*	0.515*	1
MAE[a]	4.97	2.81	5.25
RMSE[a]	7.21	3.78	7.38

* Correlation is significant at the 0.01 level.
[a] MAE and RMSE compare the chamber data to R_h derived from the ECOSSE modifiers, modifiers using SWC, and model simulated R_h.

Table 4
Moisture characteristics from pedotransfer functions.

Sandy loam	% Moisture	250 mm
Saturation (0 kPa)	44.6	111.5
Field capacity (10 kPa)	38.2	95.5
Wilting point (1500 kPa)	10.4	26
Available water (FC–WP)	27.8	69.5

loam and clay loam soils (Paul, 2006) with Irish soils being 'commonly near −5 kPa' (Keane, 2004, pg. 85), further increasing the upper range of available water estimates. Using pedotransfer functions at 33 kPa a sandy loam soil has ~12% available water, at −10 kPa the same soil has 29% available water. This gives a potential range of available water from 30 to 72.5 mm/25 cm depending on kPa chosen for field capacity; available water to 25 cm is required as an input parameter to the model.

Table 3 shows the results of pedotransfer equations for the sandy loam soil at Oak Park based on Saxton and Rawls (2006). These values differ from those reported by Abdalla et al. (2009b) who report water filled pore space (WFPS) at field capacity and wilting point, and from Khalil et al. (2013) who report AW at field capacity as 55.13 mm for 0–25 cm.

Changes to the AW input parameter of the model were found to impact the timing, but not the magnitude of CO_2 fluxes, while changes to water available at saturation and water content at wilting point have no apparent impact on simulated CO_2. Fig. 11 illustrates the ECOSSE model output with the range of ten experimental runs using AW values from 20 to 110 mm (wilting point to saturation for this soil – Table 4), and the 5 and 95% confidence intervals around these experiments.

As modifying the available water parameter in the model was found not to influence the resultant CO_2 fluxes, adjustments to clay content were performed to investigate the effects of soil structure on drainage. Sensitivity testing of both clay and sand content in the soil yielded no change in the excessive drainage or CO_2 output of the model, changes to the 'drainage class' of the soil also showed no change. Reducing PE or increasing precipitation did affect soil moisture and CO_2 outputs, but it is difficult to justify artificial irrigation when not based in reality.

4. Conclusion

The development and application of models has a key role to play in improving our understanding of soil carbon science but also in informing and supporting future decisions on appropriate LULUCF management options. However, prior to their use in decision making, such model needs to be widely evaluated.

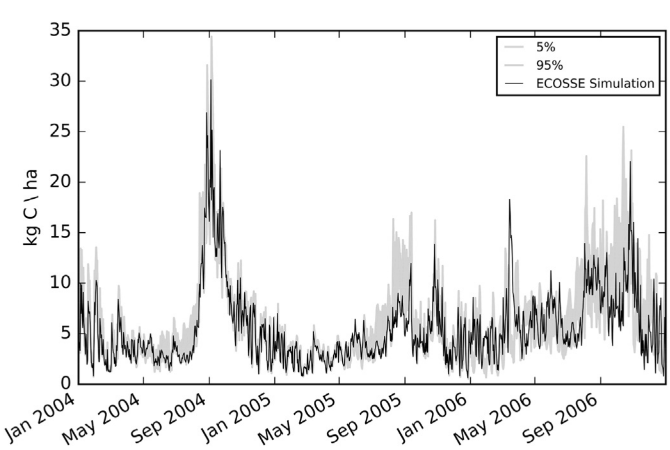

Fig. 11. ECOSSE model sensitivity to available water (AW) with mean values displayed as a solid black line and grey shading indicating the 5 and 95% confidence intervals.

The ECOSSE model has been widely applied on mineral soils previously, principally for grassland systems. The current study evaluated the model under an arable system on a free draining soil and was found it was deficient in simulating available water. Investigating the modifiers applied by the model to input data indicates that the simulation of soil water in site-specific mode provides an inaccurate representation compared to estimates of SWC derived from measurements, and in turn significantly impacts the simulation of soil respiration relative to soil chamber measurements. This may be due to the fact that tillage systems (particularly on free-drained sandy soils) are highly dynamic. The use of observed SWC data as input to the water modifier equation clearly illustrates that excessive drainage of water in the model is suppressing CO_2 fluxes from the soil, a trend not replicated in the observations. Model performance is significantly improved using observed SWC data, which show a much higher correlation with chamber measurements than the ECOSSE modelled respiration (r^2 of 0.775 vs 0.154). This excessive drainage cannot be counteracted by adjusting relevant model parameters indicating a revision of the ECOSSE water component is needed for this model to perform optimally for arable systems on mineral soils. While using ECOSSE for the estimation of soil organic carbon sequestration from cropping systems may prove to be robust as this is often observed on a decadal scale based on cumulative annual fluxes, these findings have implications for the simulation of greenhouse gas emissions (particularly CO_2 respiration and N_2O emissions) for mineral soil-based crop systems.

To generalize the results; 2004 represented a year in which the observed and model soil water displayed the greatest divergence, hence the effects on soil respiration are also likely to be greatest as a consequence. While 2004 may represent an 'anomalous' model year in terms of simulated water, such events provide an opportunity to investigate model response more fully. To what degree are the findings specific to the year and the case study location? At least one other study has highlighted a similar model deficiency in soil water content (Bell et al., 2011). If these models are to provide useful guidance to inform mitigation strategies of future soil emissions, then they need to demonstrate a robust response to a broad range of meteorological conditions that could arise as a consequence of changes in the climate system.

A comprehensive framework for model evaluations is ultimately required; identifying a global network of sites with the requisite model input and evaluation data facilitating a more comprehensive intercomparison of models. The identification of outlier events, such as 2004, for use in evaluations would also provide a focus to where greater research effort could be directed. The ultimate aim of which is to demonstrate the utility of these models and provide confidence in their use for informing policy.

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References

Abdalla, M., Jones, M., Ambus, P., Williams, M., 2009a. Emissions of nitrous oxide from Irish arable soils: effects of tillage and reduced N input. Nutr. Cycl. Agroecosyst. 86: 53–65. https://doi.org/10.1007/s10705-009-9273-8.

Abdalla, M., Wattenbach, M., Smith, P., Ambus, P., Jones, M., Williams, M., 2009b. Application of the DNDC model to predict emissions of N2O from Irish agriculture. Geoderma 151:327–337. https://doi.org/10.1016/j.geoderma.2009.04.021.

Abdalla, M., Hastings, A., Bell, M.J., Smith, J.U., Richards, M., Nilsson, M.B., Peichl, M., Löfvenius, M.O., Lund, M., Helfter, C., Nemitz, E., Sutton, M.A., Aurela, M., Lohila, A., Laurila, T., Dolman, A.J., Belelli-Marchesini, L., Pogson, M., Jones, E., Drewer, J., Drosler, M., Smith, P., 2014. Simulation of CO2 and attribution analysis at six European peatland sites using the ECOSSE model. Water Air Soil Pollut. 225, 2182. https://doi.org/10.1007/s11270-014-2182-8.

Barr, A.G., Black, T.A., Hogg, E.H., Kljun, N., Morgenstern, K., Nesic, Z., 2004. Inter-annual variability in the leaf area index of a boreal aspen-hazelnut forest in relation to net ecosystem production. Agric. For. Meteorol. 126:237–255. https://doi.org/10.1016/j.agrformet.2004.06.011.

Bell, M.J., Jones, E., Smith, J., Smith, P., Yeluripati, J., Augustin, J., Juszczak, R., Olejnik, J., Sommer, M., 2011. Simulation of soil nitrogen, nitrous oxide emissions and mitigation scenarios at 3 European cropland sites using the ECOSSE model. Nutr. Cycl. Agroecosyst. 92:161–181. https://doi.org/10.1007/s10705-011-9479-4.

Bond-Lamberty, B., Thomson, A., 2010. Temperature-associated increases in the global soil respiration record. Nature 464, 579–584.

Bradbury, N.J., Whitmore, A.P., Hart, P.B.S., Jenkinson, D.S., 1993. Modelling the fate of nitrogen in crop and soil in the years following application of 15N-labelled fertilizer to winter wheat. J. Agric. Sci. 121:363–379. https://doi.org/10.1017/S0021859600085567.

Carlyle, J.C., Than, U.B., 1988. Abiotic controls of soil respiration beneath an eighteen-year-old *Pinus radiata* stand in South-Eastern Australia. J. Ecol. UK 76 (3), 654–662 (Forestry S.).

Coleman, K., Jenkinson, D.S., 1996. RothC-26.3 - a Model for the Turnover of Carbon in Soil. Evaluation of Soil Organic Matter Models, NATO ASI Series. Springer, Berlin, Heidelberg:pp. 237–246 https://doi.org/10.1007/978-3-642-61094-3_17.

Coleman, K., Jenkinson, D., 2014. RothC - a Model for the Turnover of Carbon in Soil.

Cook, F.J., Orchard, V.A., 2008. Relationships between soil respiration and soil moisture. Soil Biol. Biochem. 40:1013–1018. https://doi.org/10.1016/j.soilbio.2007.12.012.

Davis, P.A., Brown, J.C., Saunders, M., Lanigan, G., Wright, E., Fortune, T., Burke, J., Connolly, J., Jones, M.B., Osborne, B., 2010. Assessing the effects of agricultural management practices on carbon fluxes: spatial variation and the need for replicated estimates of net ecosystem exchange. Agric. For. Meteorol. 150:564–574. https://doi.org/10.1016/j.agrformet.2010.01.021.

Dondini, M., Richards, M., Pogson, M., Jones, E.O., Rowe, R.L., Keith, A.M., McNamara, N.P., Smith, J.U., Smith, P., 2016a. Evaluation of the ECOSSE model for simulating soil organic carbon under Miscanthus and short rotation coppice-willow crops in Britain. GCB Bioenergy 8:790–804. https://doi.org/10.1111/gcbb.12286.

Dondini, M., Richards, M.I.A., Pogson, M., McCalmont, J., Drewer, J., Marshall, R., Morrison, R., Yamulki, S., Harris, Z.M., Alberti, G., Siebicke, L., Taylor, G., Perks, M., Finch, J., McNamara, N.P., Smith, J.U., Smith, P., 2016b. Simulation of greenhouse gases following land-use change to bioenergy crops using the ECOSSE model: a comparison between site measurements and model predictions. GCB Bioenergy 8:925–940. https://doi.org/10.1111/gcbb.12298.

Dondini, M., Alberti, G., Delle Vedove, G., Ventura, M., Tonon, G., Viger, M., Harris, Z.M., Jenkins, J.R., Richards, M., Pogson, M., Taylor, G., Smith, J.U., Smith, P., 2017. Evaluation of the ECOSSE model to predict heterotrophic soil respiration by direct measurements. Eur. J. Soil Sci. 68:384–393. https://doi.org/10.1111/ejss.12416.

Giltrap, D.L., Li, C., Saggar, S., 2010. DNDC: a process-based model of greenhouse gas fluxes from agricultural soils. Agric. Ecosyst. Environ. 136:292–300 Estimation of nitrous oxide emission from ecosystems and its mitigation technologies. https://doi.org/10.1016/j.agee.2009.06.014.

Guntiñas, M.E., Gil-Sotres, F., Leirós, M.C., Trasar-Cepeda, C., 2013. Sensitivity of soil respiration to moisture and temperature. J. Soil Sci. Plant Nutr. 13, 445–461.

Hanson, P.J., Edwards, N.T., Garten, C.T., Andrews, J.A., 2000. Separating root and soil microbial contributions to soil respiration: a review of methods and observations. Biogeochemistry 48:115–146. https://doi.org/10.1023/A:1006244819642.

Hardie, S.M.L., Garnett, M.H., Fallick, A.E., Ostle, N.J., Rowland, A.P., 2009. Bomb-14C analysis of ecosystem respiration reveals that peatland vegetation facilitates release of old carbon. Geoderma 153:393–401. https://doi.org/10.1016/j.geoderma.2009.09.002.

Hargreaves, Samani, 1985. Reference crop evapotranspiration from temperature. Appl. Eng. Agric. 1:96–99. https://doi.org/10.13031/2013.26773.

Högberg, P., Nordgren, A., Högberg, M.N., Ottosson-Löfvenius, M., Bhupinderpal-Singh, Olsson, P., Linder, S., 2005. Fractional contributions by autotrophic and heterotrophic respiration to soil-surface CO2 efflux in Boreal forests. SEB Exp. Biol. Ser. 251–267.

Houghton, R.A., 2003. Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000. Tellus Ser. B Chem. Phys. Meteorol. 55:378–390. https://doi.org/10.1034/j.1600-0889.2003.01450.x.

Houghton, R.A., House, J.I., Pongratz, J., van der Werf, G.R., DeFries, R.S., Hansen, M.C., Le Quéré, C., Ramankutty, N., 2012. Carbon emissions from land use and land-cover change. Biogeosciences 9:5125–5142. https://doi.org/10.5194/bg-9-5125-2012.

Jacobs, A.F.G., Heusinkveld, B.G., Holtslag, A.A.M., 2007. Seasonal and interannual variability of carbon dioxide and water balances of a grassland. Clim. Chang. 82:163–177. https://doi.org/10.1007/s10584-006-9182-7.

Jenkinson, 1977. The turnover of soil organic matter in some of the Rothamsted classical experiments [Great Britain]. Soil Sci. 123, 298–305.

Jones, M., Osborne, B., Williams, M., Saunders, M., Lanigan, G., Burke, J., Davis, P., Abdalla, M., Clifton-Brown, J., Connolly, J., Kumar, S., Nagy, M., 2010. CLIMATE CHANGE – Accounting for Greenhouse Gas Sources and Sinks in Major Irish Land-Use Categories: Towards the Establishment of a co-Ordinating Centre for FLUX Measurements (CCFLUX) (No. 43), STRIVE. EPA, Dublin.

Keane, Collins, 2004. Climate, Weather and Irish Agriculture. 2nd ed. AGMET.

Kessavalou, A., Mosier, A.R., Doran, J.W., Drijber, R.A., Lyon, D.J., Heinemeyer, O., 1998. Fluxes of carbon dioxide, nitrous oxide, and methane in grass sod and winter wheat-fallow tillage management. J. Environ. Qual. 27:1094–1104. https://doi.org/10.2134/jeq1998.00472425002700050015x.

Khalil, M.I., 2015. Development of Methodologies and Modelling for Accounting Greenhouse Gases and Organic Carbon Stocks in Agricultural Soils (No. 136), STRIVE. EPA, Dublin.

Khalil, M.I., Richards, M., Osborne, B., Williams, M., Müller, C., 2013. Simulation and validation of greenhouse gas emissions and SOC stock changes in arable land using the ECOSSE model. Atmos. Environ. 81:616–624. https://doi.org/10.1016/j.atmosenv.2013.09.038.

Khalil, M.I., Abdalla, M., Lanigan, G., Osborne, B., Müller, C., 2016. Evaluation of parametric limitations in simulating greenhouse gas fluxes from Irish arable soils using three process-based models. Agric. Sci. 07:503–520. https://doi.org/10.4236/as.2016.78051.

Liu, Q., Edwards, N.T., Post, W.M., Gu, L., Ledford, J., Lenhart, S., 2006. Temperature-independent diel variation in soil respiration observed from a temperate deciduous forest. Glob. Chang. Biol. 12:2136–2145. https://doi.org/10.1111/j.1365-2486.2006.01245.x.

Lloyd, J., Taylor, J.A., 1994. On the temperature dependence of soil respiration. Funct. Ecol. 8:315–323. https://doi.org/10.2307/2389824.

Martin, J.G., Phillips, C.L., Schmidt, A., Irvine, J., Law, B.E., 2012. High-frequency analysis of the complex linkage between soil CO(2) fluxes, photosynthesis and environmental variables. Tree Physiol. 32:49–64. https://doi.org/10.1093/treephys/tpr134.

Matteucci, M., Gruening, C., Goded Ballarin, I., Seufert, G., Cescatti, A., 2015. Components, drivers and temporal dynamics of ecosystem respiration in a Mediterranean pine forest. Soil Biol. Biochem. 88:224–235. https://doi.org/10.1016/j.soilbio.2015.05.017.

Oertel, C., Matschullat, J., Zurba, K., Zimmermann, F., Erasmi, S., 2016. Greenhouse gas emissions from soils—a review. Chem. Erde-Geochem. 76:327–352. https://doi.org/10.1016/j.chemer.2016.04.002.

Ostle, N.J., Smith, P., Fisher, R., Ian Woodward, F., Fisher, J.B., Smith, J.U., Galbraith, D., Levy, P., Meir, P., McNamara, N.P., Bardgett, R.D., 2009. Integrating plant–soil interactions into global carbon cycle models. J. Ecol. 97:851–863. https://doi.org/10.1111/j.1365-2745.2009.01547.x.

Paul, E.A., 2006. Soil Microbiology, Ecology and Biochemistry. Academic Press.

Qiu, Y., Fu, B., Wang, J., Chen, L., 2001. Spatial variability of soil moisture content and its relation to environmental indices in a semi-arid gully catchment of the Loess Plateau, China. J. Arid Environ. 49:723–750. https://doi.org/10.1006/jare.2001.0828.

Quesada, C.A., Miranda, A.C., Hodnett, M.G., Santos, A.J.B., Miranda, H.S., Breyer, L.M., 2004. Seasonal and depth variation of soil moisture in a burned open savanna (campo Sujo) in Central Brazil. Ecol. Appl. 14:33–41. https://doi.org/10.1890/01-6017.

Raich, J.W., Schlesinger, W.H., 1992. The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. Tellus Ser. B Chem. Phys. Meteorol. 44: 81–99. https://doi.org/10.1034/j.1600-0889.1992.t01-1-00001.x.

Raich, J.W., Tufekciogul, A., 2000. Vegetation and soil respiration: correlations and controls. Biogeochemistry 48:71–90. https://doi.org/10.1023/A:1006112000616.

Reichstein, M., Beer, C., 2008. Soil respiration across scales: the importance of a model–data integration framework for data interpretation. J. Plant Nutr. Soil Sci. 171: 344–354. https://doi.org/10.1002/jpln.200700075.

Saxton, K.E., Rawls, W.J., 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. Soil Sci. Soc. Am. J. 70 (5), 1569–1578.

Scharlemann, J.P., Tanner, E.V., Hiederer, R., Kapos, V., 2014. Global soil carbon: understanding and managing the largest terrestrial carbon pool. Cardiol. Manag. 5:81–91. https://doi.org/10.4155/cmt.13.77.

Singh, J.S., Gupta, S.R., 1977. Plant decomposition and soil respiration in terrestrial ecosystems. Bot. Rev. 43:449–528. https://doi.org/10.2307/4353928.

Smith, J.U., Bradbury, N.J., Addiscott, T.M., 1996. SUNDIAL: a PC-based system for simulating nitrogen dynamics in arable land. Agron. J. 88:38. https://doi.org/10.2134/agronj1996.00021962008800010008x.

Smith, J., Gottschalk, P., Bellarby, J., Chapman, S., Lilly, A., Towers, W., Bell, J., Coleman, K., Nayak, D., Richards, M., Hillier, J., Flynn, H., Wattenbach, M., Aitkenhead, M., Yeluripati, J., Farmer, J., Milne, R., Thomson, A., Evans, C., Whitmore, A., Falloon, P., Smith, P., 2010a. Estimating changes in Scottish soil carbon stocks using ECOSSE. I. Model description and uncertainties. Clim. Res. 45:179–192. https://doi.org/10.3354/cr00899.

Smith, J., Gottschalk, P., Bellarby, J., Chapman, S., Lilly, A., Towers, W., Bell, J., Coleman, K., Nayak, D., Richards, M., Hillier, J., Flynn, H., Wattenbach, M., Aitkenhead, M., Yeluripati, J., Farmer, J., Milne, R., Thomson, A., Evans, C., Whitmore, A., Falloon, P., Smith, P., 2010b. Estimating changes in Scottish soil carbon stocks using ECOSSE. II. Application. Clim. Res. 45:193–205. https://doi.org/10.3354/cr00902.

Sommers, L.E., Gilmour, C.M., Wildung, R.E., Beck, S.M., 1981. The effect of water potential on decomposition processes in soils. Water Potential Relations in Soil Microbiology. SSSA Specialpubl:pp. 97–117 https://doi.org/10.2136/sssaspecpub9.c3.

Sparling, G.P., Cheshire, M.V., Mundie, C.M., 1982. Effect of barley plants on the decomposition of 14C-labelled soil organic matter. J. Soil Sci. 33:89–100. https://doi.org/10.1111/j.1365-2389.1982.tb01750.x.

Tromp-van Meerveld, H.J., McDonnell, J.J., 2006. On the interrelations between topography, soil depth, soil moisture, transpiration rates and species distribution at the hillslope scale. Adv. Water Resour. 29:293–310 (Experimental Hydrology: A Bright Future). https://doi.org/10.1016/j.advwatres.2005.02.016.