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Testing DNDC model for simulating soil respiration and assessing the effects of climate change on the CO_2 gas flux from Irish agriculture

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ABSTRACT

Simulation models can be valuable to investigate potential effects of climate change on greenhouse gas emissions from terrestrial ecosystems. DNDC (the DeNitrification-DeComposition model) was tested against observed soil respiration data from adjacent pasture and arable fields in the Irish midlands. The arable field was converted from grassland approximately 50 years ago and managed since 2003 under two different tillage systems; conventional and reduced tillage. Both fields were located on the same soil type, classified as a free draining sandy loam soil derived from fluvial glacial gravels with low soil moisture holding capacity. Soil respiration measurements were made from January 2003 to August 2005. Three climate scenarios were investigated, a baseline of measured climatic data from a weather station at the field site, and high and low temperature sensitivity scenarios predicted by the Community Climate Change Consortium for Ireland (C4I) based on the Hadley Centre Global Climate Model ($HadCM_3$) and the Intergovernment Panel on Climate Change (IPCC) A1B emission scenario. The aims of this study were to use measured soil respiration rates to validate the DNDC model for estimating CO_2 efflux from these key Irish soils, investigate the effects of future climate change on CO_2 efflux and estimate the efflux uncertainties due to using different future climate projections. The results indicate that the DNDC model can reliably estimate soil respiration from the two fields examined. The model underestimated annual measured CO_2 efflux from the pasture by only13% (model efficiency: ME = 0.6; root mean square error: RMSE = 1.9 and mean absolute error: MAE = 6.3) and that from the arable conventional and reduced tillage by 9% (ME = 0.6; RMSE = 1.6 and MAE = 2.4) and 8% (ME = 0.23; RMSE = 1.8 and MAE = 2.9), respectively. Short-term land use change had no significant effects on CO_2 effluxes from soil. Using the high temperature sensitivity scenario, future C effluxes would increase by 15% for the pasture and 14 and 16% for the arable conventional and reduced tillage systems, respectively. However, under the low temperature sensitivity scenario, lower increases in the C efflux of 6% for the pasture and 5% for the arable field were predicted. The calculated annual CO_2 efflux uncertainties for using the high and low temperature sensitivity scenarios were 9% for the pasture and 8% for the arable field.

1. Introduction

The atmospheric carbon dioxide (CO_2) concentration, since the start of the industrial revolution, has increased by approximately 35% and is predicted to reach 700 ppmv by the end of this century (IPCC, 2001; 2007). In most of European countries, including Ireland, croplands are assumed to lose organic carbon resulting in a net loss of CO_2 to the atmosphere (Janssens et al., 2005; Schulze et al., 2010). This loss may be enhanced by climate warming (Kirschbaum, 1995; Andrews et al., 1999; Cox et al., 2000) and the emitted CO_2 will in turn reinforce climate warming. In this context the most critical issue concerning long-term soil carbon decomposition is increasing temperature. Land use can also substantially alter soil organic carbon (SOC) dynamics (Guo and Gifford, 2002) and in general affect exchanges of greenhouse gases (GHGs) between the soil and atmosphere (Dobbie et al., 1996; Smith et al., 2000; Houghton, 2002).

Soil respiration normally refers to the total soil CO_2 efflux at the soil surface and consists of autotrophic root respiration and heterotrophic respiration associated with decomposition of litter roots and soil organic matter (SOM) (Bernhardt et al., 2006). Soils are the largest carbon pool in terrestrial ecosystems, containing more than two thirds of the total carbon and soil respiration contributes an annual flux of CO_2 to the atmosphere 10 times greater than fossil fuel combustion (Schlesinger, 1997; Folger, 2009). Due to the extent this flux, changes in the rate of soil respiration could have large effects on atmospheric CO_2 concentration. Previous studies have demonstrated that increased rates of soil respiration result from increases in soil temperature (Winkler et al., 1996; Christensen et al., 1997; Jabro et al., 2008) and atmospheric CO_2 (Johnson et al., 1994; Vose et al., 1995; Hungate et al., 1997; Ball and Drake, 1998; Deng et al., 2010). At elevated CO_2, the increase in

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belowground biomass would increase CO_2 efflux from the soil (Edwards and Norby, 1999; Wang et al., 2007) and may enhance carbon release into the rhizosphere by root exudation (Van Ginkel et al., 2000; Allard et al., 2006). Similarly the increase in aboveground biomass would produce more litter-fall, all these factors contributing to higher soil respiration rates (Zak et al., 2000).

The DeNitrification DeComposition (DNDC) model was developed to simulate N_2O, NO, N_2 and CO_2 emissions from agricultural soils (Li et al., 1992, 1994; 2000). The DNDC model was originally developed for USA conditions (Li et al., 1992). It has been used for simulation at a regional scale for the United States (Li et al., 1996), China (Li et al., 2001) and Europe (Dietiker et al., 2010). Advantages of DNDC are that it has been extensively tested and has shown reasonable agreement between measured and modelled results for many different ecosystems such as grassland (Levy et al., 2007; Giltrap et al., 2010), cropland (Cai et al., 2003; Tang et al., 2006; Li et al., 2007) and forest (Lu et al., 2008; Kurbatova et al., 2009). The model has reasonable data requirement and is suitable for simulation at appropriate temporal and spatial scales. The aims of this study were to validate the DNDC model for estimating CO_2 efflux from a representative midlands soil in Ireland, assess the effects of future climate change on CO_2 efflux and estimate the efflux uncertainties due to using different future climate projections.

2. Materials and methods

2.1. Field experimental site

This study is part of an ongoing research to quantify and estimate soil respiration from Irish agriculture (Davis et al., 2010; Jones et al., 2010). The experimental site was located at the Oak Park Research Centre in Carlow 52°86′ N and 6°54′ W, Ireland. The site has an elevation of 56 m (a.s.l), a mean annual rainfall of 824 mm and a mean annual air temperature of 9.4 °C. The adjacent pasture and arable fields are located on the same soil type classified as free draining sandy loam soil derived from fluvial glacial gravels with low soil moisture holding capacity. The arable field was seeded with spring barley at a density of 140 kg ha^{-1} and since 2003 has been managed under two different tillage regimes; conventional tillage where inversion ploughing to a depth of approximately 22 cm was carried out in March 5 weeks prior to planting, and reduced tillage to a depth of approximately15 cm which was carried out in September of the year before planting. Crop straw was cut and left on the ground following harvesting, for the conventional tillage, whilst left standing until ploughed into the soil when carrying the reduced tillage practises in September, for reduced tillage. Nitrogen fertiliser in the form of calcium ammonium nitrate (CAN) was applied at an average rate of 160 kg N ha^{-1} y^{-1} divided into two applications in April (106 kg N ha^{-1}) and May (54 kg N ha^{-1}).

The pasture has been permanent grassland for at least the last 80 years, but was ploughed and reseeded in October 2001 with perennial ryegrass (*Lolium perenne L., cv Cashel*) at a density of 13.5 kg ha^{-1} and white clover (*Trifolium repens L., cv Aran*) at a density of 3.4 kg ha^{-1}. Silage cutting took place once a year in early May and extensive cattle grazing with a stocking rate of 2 cattle ha^{-1} from July to November. CAN was applied at a rate of 200 kg N ha^{-1} y^{-1} in two applications of 128 and 72 kg N ha^{-1} in April and May, respectively.

2.2. Field measurements of soil respiration

Measurements of soil respiration were carried out from January 2003 to August 2005. Measurements were made using a CIRAS gas exchange system (PP systems, UK) fitted with the SRC-1 soil respiration chamber. The soil chamber is cylindrical (height = 150 mm; diameter = 100 mm). The method of measuring soil respiration is that described by Parkinson (1981). The chamber measurement range was 0–9.99 g CO_2 m^{-2} h^{-1}. The patchy grass and spring barley crops were pushed aside before placing the chamber on bare ground and pushed in soil. In order to cover most of the year measurements were made every week from eighteen replicate locations. Previous studies of CO_2 fluxes using CIRAS gas exchange system have sampled at frequencies ranging from weekly to monthly (Bahn et al., 2008). The soil respiration measurements were made between 11:00 am and 13:00 pm which approximately represent daytime averages. Cumulative annual soil respiration for each treatment was estimated by summing the products of weekly mean soil respiration and the number of days between samples (Deng et al., 2010).

2.3. Temperatures and water filled pore space (WFPS)

Soil temperature and volumetric soil moisture measurements were made adjacent to chamber placement at a depth of 0–10 cm using a portable WET sensor (Delta-T devices, UK). Water filled pore space (WFPS in %) was calculated from the equation:

$$WFPS = (SWC \times BD) / (1-(BD / PD)) \tag{1}$$

where, SWC is the volumetric soil water content (g g^{-1}), BD is the bulk density (mg m^{-3}), and PD is the particle density (2.65 mg m^{-3}) Linn and Doran (1984).

Daily minimum and maximum air temperature (°C) and rainfall (mm) were recorded at the adjacent Teagasc Research Centre Weather Station.

2.4. DNDC model

In this study the DNDC model (version 8.9; http://www.dndc.sr.unh.edu/) was applied. DNDC contains four main sub-models (Li et al., 1992; 2000); the soil climate sub-model calculates hourly and daily soil temperature and moisture fluxes in one dimension, the crop growth sub-model simulates crop biomass accumulation and partitioning, the decomposition sub-model calculates decomposition, nitrification, NH_3 volatilisation and CO_2 production, whilst the denitrification sub-model tracks the sequential biochemical reduction from nitrate (NO_3) to NO_2^-, NO, N_2O and N_2 based on soil redox potential and dissolved organic carbon.

Daily measured values of meteorological parameters recorded at the site and land management records were used as input variables to the DNDC model. Details about this input data can be found in Abdalla et al. (2009). Field CO_2 efflux data were used for DNDC model validations by comparing measured and predicted CO_2 efflux. The model accuracies and performance were evaluated by calculating the Mean Absolute Error (MAE), Root Mean Square Error (RMSE) and Model Efficiency (ME; Nash and Sutcliffe, 1970).

$$MAE = \frac{\sum_{i=1}^{n} |P_i - O_i|}{n} \tag{2}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n}} \tag{3}$$

$$ME = 1 - \frac{\sum_{i=1}^{n} (P-O)^2}{\sum_{i=1}^{n} \left(O_i - \bar{O}\right)^2} \tag{4}$$

where O_i are the observed values, P_i are the simulated values, n are the total number of observations and i the current observation.

MAE assesses the size of prediction errors on an individual level. It does not allow for compensation of positive and negative prediction errors. RMSE measures absolute prediction errors, but in a quadratic sense, and is therefore more sensitive to outliers. ME compares the squared sum of the absolute error with the squared sum of the difference between the observations and their mean value. It compares the ability of the model to reproduce the daily data variability with a much simpler model that is based on the arithmetic mean of the measurements. Negative ME value shows a poor performance, a value of 0 indicates that the model does not perform better than using the mean of the observations, and values close to 1 indicate a 'near-perfect' fit (Nash and Sutcliffe, 1970; Huang et al., 2003; Wattenbach et al., 2010).

Annual cumulative CO_2 efflux for model outputs were calculated as the sum of simulated daily fluxes (Cai et al., 2003). The relative deviation (RD) between observed and DNDC outputs was calculated by:

$$RD = (P-O) / O \times 100. \quad (5)$$

2.5. Climate scenarios

The future climate data used in this research were statistically downscaled by the Irish National Meteorological Service Research Group (Met Eireaan) (C4I, 2008) based on the Hadley Centre Global Climate Model ($HadCM_3$) and the emission scenario (A1B) published by the Intergovernmental Panel on Climate Change (Nakicenovic and Swart, 2000; IPCC, 2001). Two different temperature sensitivity scenarios (high and low) were investigated to estimate the uncertainty in future climate (Collins et al., 2006). A regional climate model, known as RCA_3, was applied to the $HadCM_3$ data in a process which is known as dynamic downscaling. RCA_3 is based on a model initially developed by the Rossby Centre and further developed by the C4I project at Met Éireann. The resultant model data has a horizontal resolution of 25 km. A full description is given in the C4I (2008) report.

The baseline scenario was a measured daily climate data set (1961–1990) from a nearby weather station at Oak Park Research Centre. The two future climate scenarios (high and low temperature sensitivity) investigated in this study are of daily data and for a period of 30 years (2061–2090). Weather input data are maximum and minimum air temperature and precipitation. CO_2 concentrations of 370 and 700 ppmv were suggested and used in the models for the baseline and future scenarios, respectively (IPCC, 1995).

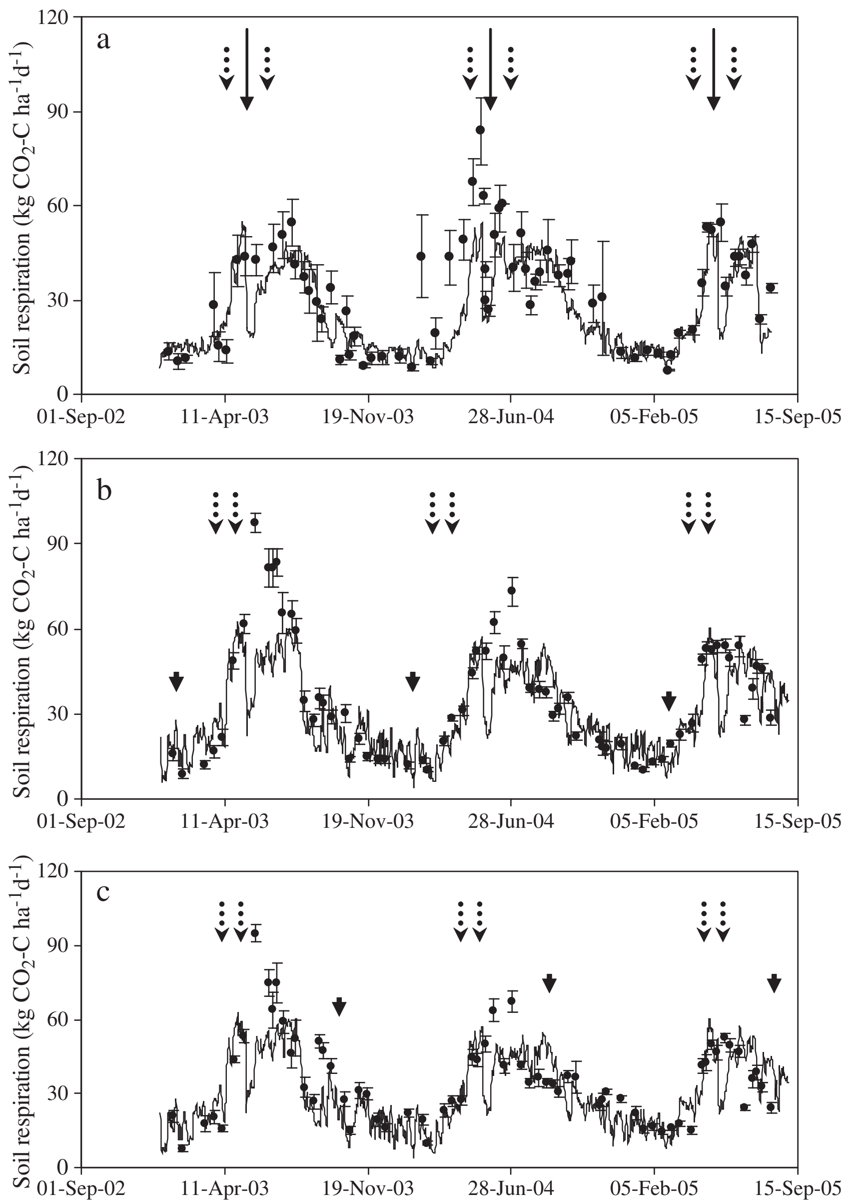

Fig. 1. Comparisons of DNDC model-simulated (lines) and field measured (●) CO_2 efflux from the pasture (a; $r^2 = 0.60$; ME = 0.6; RSME = 1.9 and MAE = 6.3) and the arable conventional (b; $r^2 = 0.60$; ME = 0.58; RSME = 1.6; MAE = 2.37) and reduced (c; $r^2 = 0.52$; ME = 0.23; RSME = 1.8 and MAE = 2.9) tillage. (Error bars for measured values are ± standard error). Long solid arrows show the times of silage cutting, short sick arrows show times of ploughing and dotted arrows show times of fertiliser application.

2.6. Statistical analysis

Statistical analyses were carried out using the PRISM (GraphPad, San Diego, USA) and Data Desk (Data Description Inc., New York, USA) software packages. Both 1-way and 2-way analysis of variance were applied to the CO_2–C efflux data.

3. Results

3.1. Model validation and results under baseline climate

Seasonal patterns of CO_2–C efflux from soils for the observed and DNDC modelled outputs from the pasture and the arable conventional and reduced tillage systems were generally in agreement for most of the measured period (Fig. 1). For the pasture, DNDC predicted a cumulative annual CO_2–C efflux of 9.6 t C ha^{-1} compared with the observed efflux of 11 t C ha^{-1}. Here, both the observed and DNDC predicted CO_2–C effluxes showed significant decline in soil respiration following silage cut in May and animal grazing from July onwards (Fig. 1). The DNDC model underestimated the cumulative annual CO_2–C efflux by 13%. The regressions between observed and modelled effluxes was $y = 0.41x + 0.57$ ($r^2 = 0.6$; ME = 0.6; RMSE = 1.9 and MAE = 6.3). For the arable field, DNDC predicted cumulative annual CO_2–C efflux of 11.3 t C ha^{-1} for both tillage systems, compared with the observed effluxes of 12.4 for conventional and 12.3 t C ha^{-1} for reduced tillage. The DNDC model also underestimated the cumulative annual CO_2–C efflux from the arable field by 9% (conventional tillage) and 8% (reduced tillage). The regressions between observed and modelled effluxes were $y = 0.52x + 15$ ($r^2 = 0.6$; ME = 0.58; RMSE = 1.6 and MAE = 2.37) and $y = 0.58x + 12.8$ ($r^2 = 0.52$; ME = 0.23; RMSE = 1.8 and MAE = 2.9) for the conventional and reduced tillage, respectively. No statistically significant differences ($p > 0.05$) between the daily or cumulative CO_2 effluxes for the two fields or between modelled and observed effluxes were found.

The DNDC predicted values for soil temperature, from both fields agreed well with observed values (Fig. 2). The regressions between observed and modelled effluxes were $y = 0.79x + 1.5$ ($r^2 = 0.81$), $y = 0.71x + 2$ ($r^2 = 0.83$) and $y = 0.69x + 1.9$ ($r^2 = 0.81$) for the pasture and the arable conventional and reduced tillage systems, respectively. Calculated ME, RSME and MAE values of soil temperature

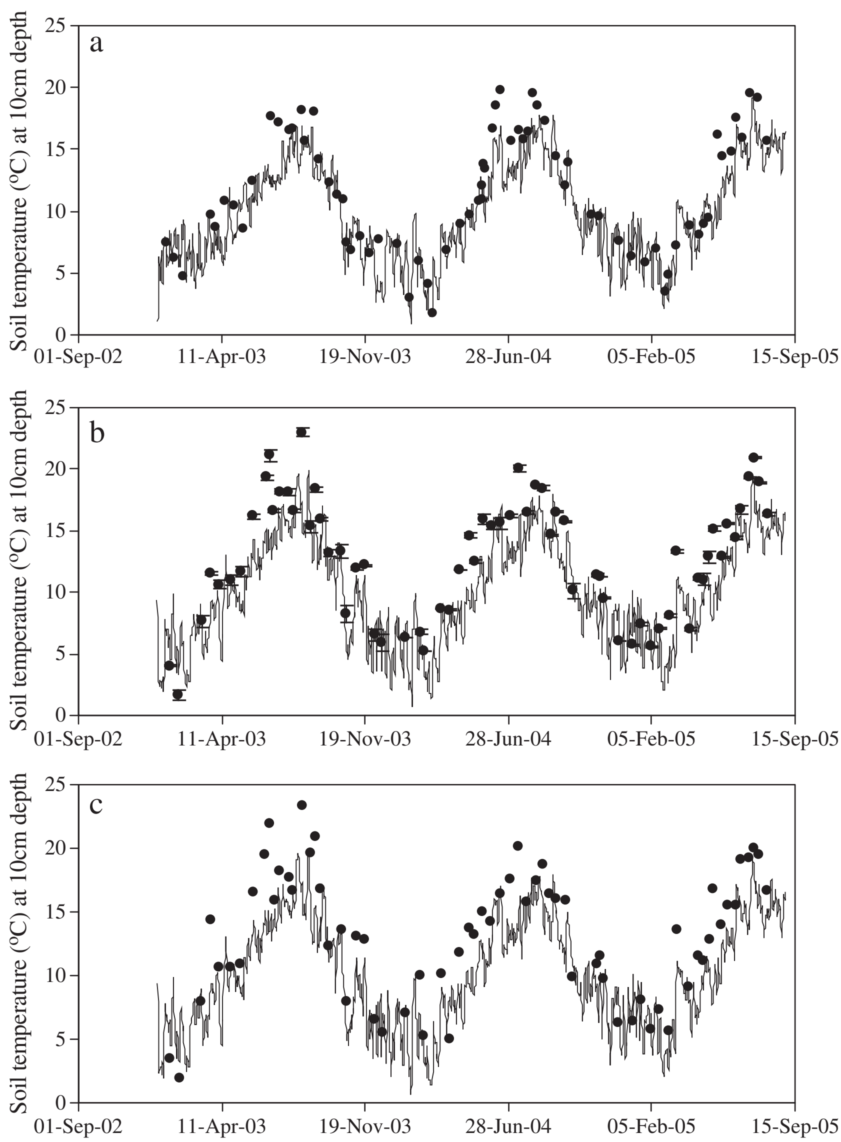

Fig. 2. Comparison between the DNDC simulated (lines) and field measured (●) soil temperature (0–10 cm depth) from the pasture (a; $r^2 = 0.81$; ME = 0.79; RMSE = 0.31 and MAE = 0.95) and arable conventional (b; $r^2 = 0.83$; ME = 0.67; RSME = 0.33 and MAE = 1.78) and reduced (c; $r^2 = 0.81$; ME = 0.38; RSME = 0.47 and MAE = 2.4) tillage systems. (Error bars for measured values are ± standard error).

for the pasture were 0.79 and 0.31 and 0.95 whilst for the arable field were 0.67 and 0.33 and 1.78 (conventional tillage) and 0.38 and 0.47 and 2.4 (reduced tillage), respectively. Although, the model poorly estimated the measured WFPS values (overestimated) for the pasture (r^2 = 0.32; ME = −2; RMSE = 3 and MAE = 15.7) the predicted values for the arable conventional (r^2 = 0.35; ME = 0.12; RMSE = 1.6 and MAE = 2.9) and reduced (r^2 = 0.53; ME = 0.42; RMSE = 1.3 and MAE = 0.73) tillage relatively agreed well with the observed values (Fig. 3). Strong negative relationships were observed between soil moisture and soil temperature. High peaks of CO_2–C effluxes, from both fields, coincided with the high rainfall events and air temperature as illustrated in Fig. 4.

The DNDC model underestimated both the observed annual pasture biomass production by 23% (ME = −0.3; RMSE = 0.15 and MAE = 0.6) (Abdalla et al., 2010) and the observed annual crop biomass of spring barley by 11% for conventional tillage (ME = 0.31; RMSE = 0.77 and MAE = 0.56) and 14% for reduced tillage (ME = 0.23; RMSE = 0.81 and MAE = 0.73). At the baseline climate scenario, DNDC predicted CO_2–C efflux declined following silage cutting whilst for the arable field high CO_2–C peaks, from both tillage systems, were predicted following ploughing (Fig. 5). This post-ploughing efflux peak reached a maximum value of 36 kg CO_2–C ha^{-1} d^{-1} in February for the conventional tillage and up to 90 kg CO_2–C ha^{-1} d^{-1}, in September for reduced tillage (Fig. 5). However, a smaller peak of 29 kg CO_2–C ha^{-1} d^{-1} in September was predicted for conventional tillage.

3.2. Model results under climate change

Under both the low and high temperature sensitivity climate scenarios and for both grassland and arable fields, the pattern of CO_2–C efflux was similar to the baseline climate scenario although, peak heights and cumulative annual effluxes were different (Fig. 5 and Table 1). Under climate change, the highest efflux peak under the high sensitivity scenario for pasture was approximately 57 kg CO_2–C ha^{-1} d^{-1} observed from July to August whilst for the conventional arable field was approximately 55 kg CO_2–C ha^{-1} d^{-1} observed in February and 121 kg CO_2–C ha^{-1} d^{-1} for reduced tillage observed in September. For the high sensitivity scenario, cumulative effluxes were 12.4 and 9.3 and 10 t CO_2–C ha^{-1}y^{-1} whilst for the low sensitivity scenario they were 11.4 and 8.6 and 9.3 t CO_2–C ha^{-1}y^{-1} for the grass and arable conventional and reduced tillage, respectively. Future increases in CO_2–C effluxes, under the high sensitivity scenario, were +15% for the

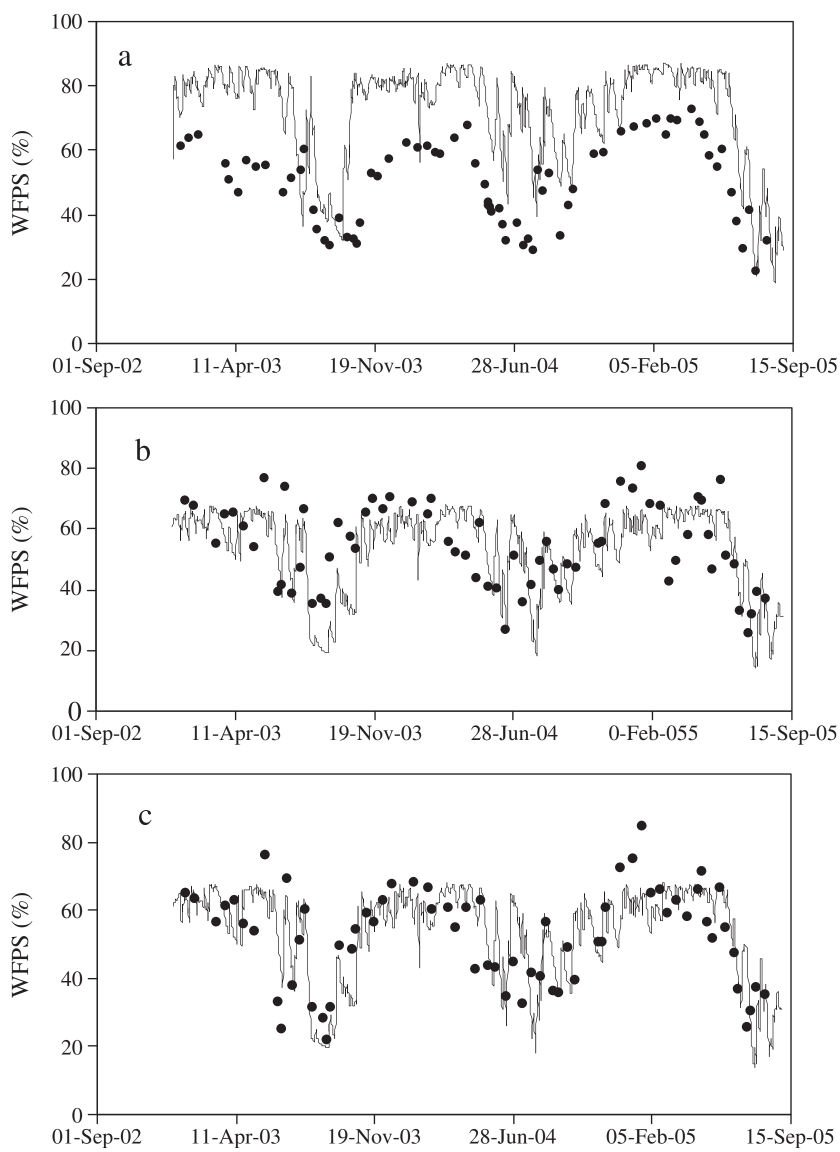

Fig. 3. Comparisons between the DNDC simulated (lines) and field measured (●) WFPS from the pasture (a; r^2 = 0.32; ME = −2; RMSE = 3 and 15.7) and arable conventional (b; r^2 = 0.35; ME = 0.12; RMSE = 1.6 and 2.9) and reduced (c; r^2 = 0.53; ME = 0.42; RSME = 1.3 and 0.73) tillage systems.

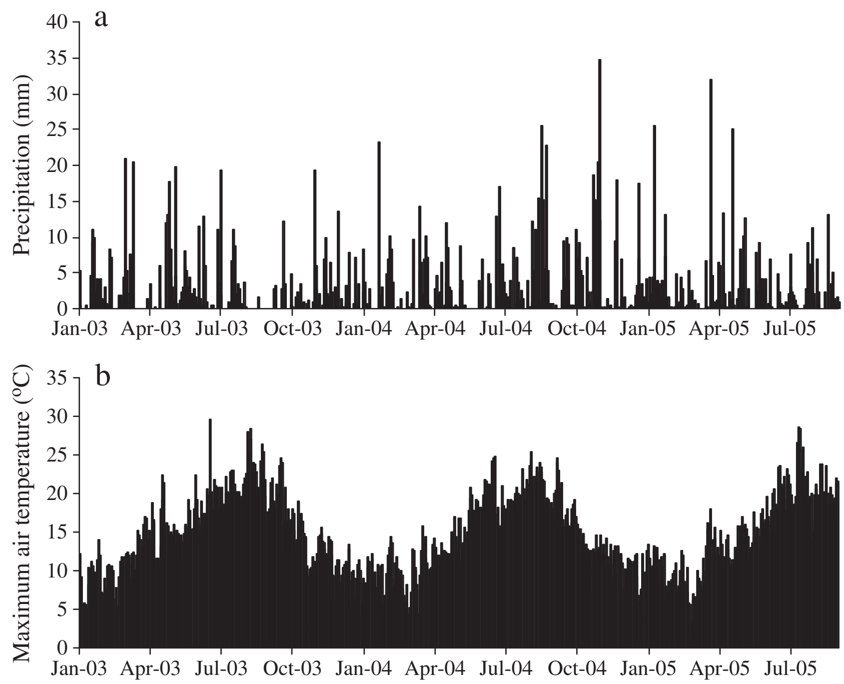

Fig. 4. Precipitation (a) and maximum air temperature (b) during the experimental period (2003–2005).

pasture and +13% for the arable field (Fig. 5 and Table 1). However, under the low temperature sensitivity scenario, reduced increases in CO_2–C efflux of +6% (pasture) and +5% for both arable fields were predicted (Table 1). Statistical analysis showed no significant differences ($p>0.05$) in annual CO_2–C effluxes from the pasture and both tillage treatments, compared with the baseline effluxes (Table 1). The uncertainty between the low and high temperature sensitivity scenarios were 9% for the pasture and 8% for the arable field.

4. Discussion

4.1. Model validation and results under baseline climate

In this study, annual values of field measured soil respiration from the pasture agree with the range of values reported by Bahn et al. (2008) for a range of European grasslands (0.6 to 19.9 t C ha^{-1}) whilst that from the arable lands agree with values measured and modelled from arable soils and range from 4 to 16 t C ha^{-1}(Kutsch and Kappen, 1997; Rees et al., 2005). However, measured soil respiration may be overestimated as all measurements took place during the day light. For the pasture, both the observed and DNDC predicted CO_2–C effluxes showed a significant decline in soil respiration following silage cut in May and animal grazing from July onwards. This negative effect on soil respiration is likely to result from a reduction in plant photosynthetic capability, plant growth and accumulation of litter, which all decrease carbon supply to soil decomposers (Johnson and Matchett, 2001; Sankaran and Augustine, 2004). Cutting and grazing can also reduce root biomass (Fagerness and Yelverton, 2001), a primary contributor to the soil CO_2 pool in grasslands (Raich and Tufekcioglu, 2000), and hence a major factor influencing soil respiration rates. The effect of cutting and grazing would be the dramatic decrease in assimilate delivered to plant roots. Autotrophic soil respiration in late spring and summer months accounted for approximately 50% of measured soil respiration of the grassland and arable soils (data is not shown). Indeed, the dominance of the autotrophic component is apparent for short term (days) and long term (annual) determinations of soil respiration in grassland soils (Janssens et al., 2001; Reichstein et al., 2003; Hibbard et al., 2005 and Bahn et al., 2008; Ruehr et al., 2009). Although, the contribution of root to soil respiration varies widely among different studies, ranging from approximately 15% to 90% (Norman et al., 1992; Dugas et al., 1999; Raich and Tufekcioglu, 2000; Wang et al., 2005; Wang et al., 2007). In relation to this, the underestimation of CO_2 efflux in the grassland soil by DNDC (−13%) may presumably be influenced significantly by an underestimation of predicted above ground biomass of the order of 23% (Abdalla et al., 2010).

For the arable field, no CO_2 efflux peak during the ploughing period, was recorded as chambers had to be removed during this time. However, the baseline DNDC outputs showed a higher CO_2–C peak from both tillage systems following soil ploughing (Fig. 5). Such CO_2 peak following tillage has been reported previously in the literature (Alvaro-Fuentes et al., 2007; Morell et al., 2010). Soil ploughing increases soil disturbance, increases the distribution of crop residues (Vinther and Dahlmann-hansen, 2005; Grigera et al., 2007) increases microclimate (Muller et al., 2009) and therefore, CO_2-evolution (Franzluebbers et al., 1995; Reicosky and Archer, 2007).

Generally, the reduced tillage system increases soil organic carbon content of the surface layer as the results of different interacting factors like less soil disturbing, high soil moisture, increased residue return, reduced surface temperature, proliferation of root growth and biological activity and less soil erosion (Blevins and Frye, 1993). Reduced tillage has the advantage of sequestering C in the soils (Six et al., 2004; Li et al., 2005; Chatskikh and Olesen, 2007). Residue management also has an influence on the availability of organic matter, the quantity of micro-organisms and their activity (Doran et al., 1998; Frank et al., 2006). Although the depth and volume of soil disturbed by tillage usually leads to increased CO_2 evolution rates (Franzluebbers et al., 1995; Reicosky and Archer, 2007), no significant difference was found in soil respiration between conventional and reduced tillage in this study. Furthermore, the model didn't predict any difference here when CO_2 emissions under reduced tillage has been compared with conventional tillage (Kessavalou et al., 1998; Jakson et al., 2003; Chatskikh and Olesen, 2007; Sainju et al., 2008). Higher CO_2 emissions have been observed following conventional tillage operations (Al-Kaisi and Yin, 2005; Omonode et al., 2007; Reicosky and Archer, 2007). In contrast, Franzluebbers et al. (1995) found higher emissions under no-tillage than conventional tillage during overnight measurements using alkali traps. Ball et al. (1999) and Omonode et al.

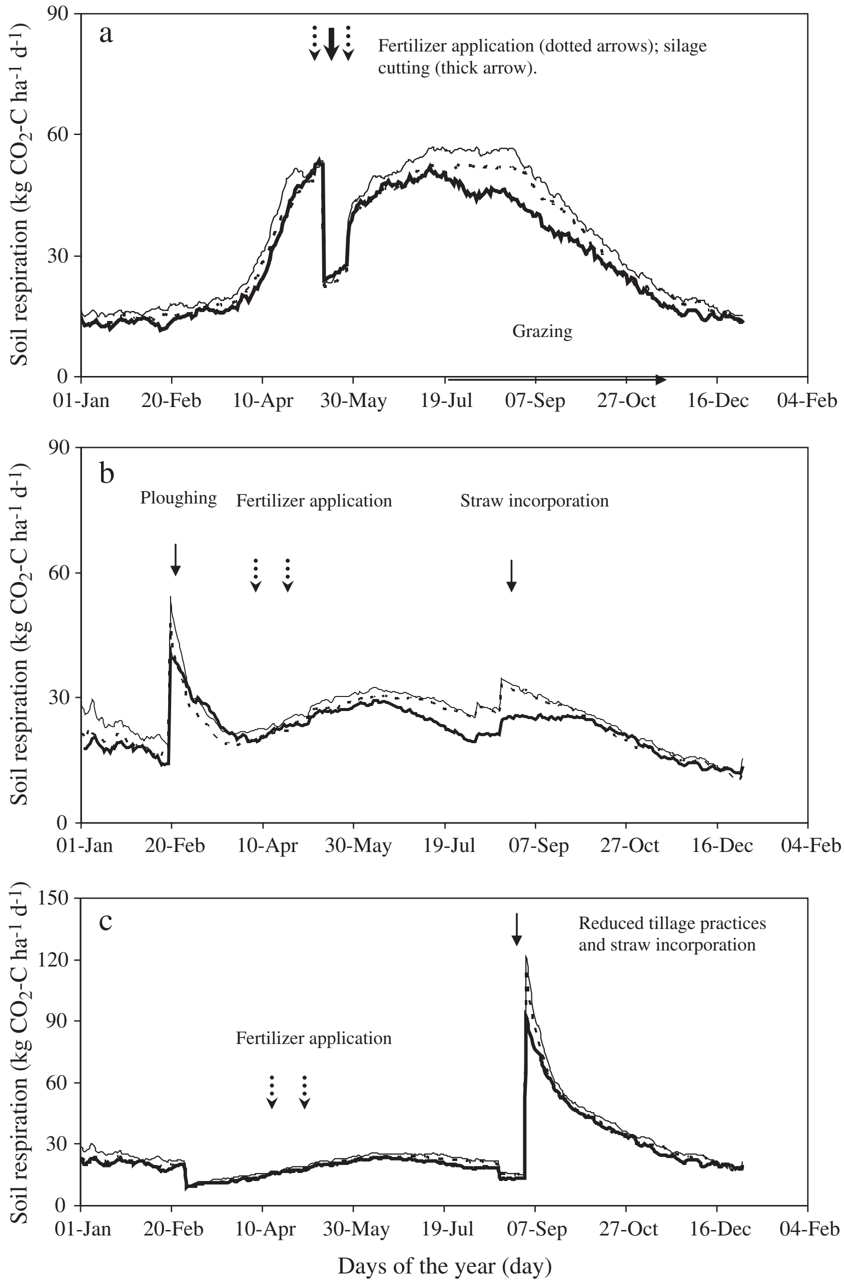

Fig. 5. Effects of climate change on soil respiration from the grass (a) and arable conventional (b) and reduced tillage (c) for the high (light lines) and low (dotted lines) temperature sensitive climate data compared with measured baseline climate (thick lines).

(2007) found no statistical difference in seasonal CO_2 emissions between tillage systems; while different results, varying with year, were found by Mosier et al. (2006) and Fortin et al. (1996). In this study, the short duration reduced tillage applied (3 years) has not yet sequestered CO_2 in soil.

Overall, the DNDC model effectively predicted soil respiration from both the pasture and arable fields although underestimated crop above ground biomass. This is in agreement with other previous studies using DNDC to simulate CO_2 efflux from agriculture (e.g. Li et al., 2006; Tang et al., 2006; Levy et al., 2007; Li et al., 2010). However, the tillage options

Table 1
DNDC modelled CO_2 efflux at baseline and low and high temperature sensitivity scenarios from the pasture and arable conventional and reduced tillage and predicted future percentage change. Differences between different climate scenarios are not significantly different ($p>0.05$).

Cropping system	Baseline ($t\ CO_2$–$C\ ha^{-1}\ y^{-1}$)	Low scenario ($t\ CO_2$–$C\ ha^{-1}\ y^{-1}$)	High scenario ($t\ CO_2$–$C\ ha^{-1}\ y^{-1}$)	% Change	
				low	high
Pasture	10.8	11.4	12.4	6	15
Arable conventional	8.2	8.6	9.3	5	14
Arable reduced	8.9	9.3	10	5	16

provided by DNDC do not allow the reduced tillage used in our study to be fully described and therefore, the model efficiency for simulating CO_2 under reduced tillage (ME = 0.23) was poor compared with that under the conventional tillage (0.6). Both observed and predicted CO_2–C efflux values showed that the seasonality of soil respiration coincided with seasonal climate pattern with high respiration rates in the summer and low rates in the winter (Figs. 2, 3 and 4). Soil temperature and soil moisture are also, a part from assimilate supply, the two most important factors that control soil respiration (Lloyd and Taylor, 1994; Maestre and Cortina, 2003; Saiz and Green, 2006). For instance previous studies found temperature to be a major factor explaining annual variations in CO_2 flux (e.g. Buyanovsky et al., 1986; Duiker and Lal, 2000; Rayment and Jarvis, 2000; Tang et al., 2006; Jabro et al., 2008). Peaks of CO_2 effluxes from both the grassland and arable fields coincided with high rainfall events (Fig. 3). This is in agreement with previous studies reported by Fierer and Schimel (2003) and Morell et al. (2010). Higher daily observed CO_2 efflux compared with the DNDC output, for both the grass and arable fields, appeared during the crop vegetation period due to DNDC underestimating crop above ground biomass production. Differences in CO_2 fluxes between the pasture and arable fields, are not significant ($p > 0.05$). The reason here may be the huge amounts of CO_2 which might released to the atmosphere from the pasture following the ploughing and reseeding in 2001. The DNDC overestimation of measured WFPS values especially for the grasslands ($r^2 = 0.32$; ME = −2; RMSE = 3 and MAE = 15.7) was mainly due to the model poor prediction of biomass production (−23%) and therefore, producing a low transpiration. Both WFPS and crop biomass are important parameters affecting CO_2 emissions from soils (Jabro et al., 2008; Deng et al., 2010). Other problems with the hydrological component in DNDC, especially regarding the simulation of water filled pore space in the soil were also reported (Tonitto et al., 2007a, b; Wattenbach et al., 2010).The model complexity for this part has a profound impact on the uncertainties associated with the CO_2 simulations which also increases the chance of poorer model fit to filed measurements (Wattenbach et al., 2010).

4.2. Model results under climate change

Rising atmospheric CO_2 concentration is expected to increase soil temperature, which may stimulate the flux of carbon dioxide from soils, causing a positive feedback effect (Ise and Moorcroft, 2006). However simulating future CO_2 efflux using different future weather scenarios can give uncertain results. For both the grassland and arable fields, the higher predicted peaks of CO_2 efflux under the high temperature sensitivity scenario were attributed to increasing soil temperature and precipitation compared with the baseline climate scenario. Predicted higher future above ground biomass (Abdalla et al., 2010) will also lead to higher CO_2 from the soil. Previous studies indicate that simulation and prediction of soil respiration in response to climate change should consider changes in biotic factors i.e. plant growth and substrate supply and abiotic factors i.e. temperature and moisture (Wang et al., 2007; Xia et al., 2009). As discussed earlier, temperature is one of the main driving factors affecting CO_2–C efflux from soils (e.g. Buyanovsky et al., 1986; Duiker and Lal, 2000; Rayment and Jarvis, 2000; Tang et al., 2006; Jabro et al., 2008). In the case of the pasture and as a result of higher future above ground biomass production (Abdalla et al., 2010) the CO_2 efflux will increase. The increase in aboveground biomass would produce more litter-fall and contributing to higher soil respiration (Zak et al., 2000; Deng et al., 2010). Here, both soil organic matter decomposition and microbial response to other perturbations, such as fertilisation, temperature and rainfall, can increase (Bramley and White, 1990; Antonopoulos, 1999; Wennman and Katterer, 2006). Future higher CO_2 concentration also stimulates soil respiration (Craine et al., 2001; Wan et al., 2007). High CO_2 concentration can increase plant photosynthesis, growth, below ground C input and substrate leading to greater root and microbial activities and respiration (Edwards and Norby, 1999; Zak et al., 2000; Anderson et al., 2001). In addition, higher soil moisture content resulting from reduced stomatal conductance and transpiration of plant under high CO_2 concentration will enhance root and microbial activities and respiration (Morgan et al., 2004). However, contradicting findings about the effects of soil moisture are reported in the literature. Jabro et al. (2008) found strong correlation between moisture and soil respiration although many other researchers e.g. Bajracharya et al. (2000), Mielnick and Dugas (2000), Merino et al. (2004) and Ding et al. (2007) have reported weak correlations. In this study, predicted higher rainfall events during winter time (C4I, 2008), due to climate change, will positively influence CO_2 effluxes from soils (Laporte et al., 2002). For the arable field, the future post-tillage CO_2–C efflux peak would increase and represent 11 and 50% of the annual efflux for conventional and reduced tillage, respectively. The faster maturation of crops, under climate change, may give farmers an opportunity to cultivate an additional crop, if other resources are not limited, during the main vegetation period (Dietiker et al., 2010) which will allow more CO_2 uptake. However, if water availability is decreasing due to global warming, this could have an impact on crop productivity and reduce the ecosystem ability to store carbon.

5. Conclusions

Our results indicate that the DNDC model can estimate effectively soil respiration from grass and arable lands as free draining soils typical of midlands of Ireland. The model underestimated annual measured CO_2 efflux from the pasture by only 13% (ME = 0.6; RMSE = 1.9 and MAE = 6.3) and from the arable conventional and reduced tillage systems by 9% (ME = 0.58; RMSE = 1.6 and MAE = 2.4) and 8% (ME = 0.23; RMSE = 1.8 and MAE = 2.9), respectively. However, the model underestimated the annual above ground biomass production of the pasture by 23% (ME = −3; RMSE = 0.15 and 0.6) and that of spring barley by 11% (ME = 0.31; RMSE = 0.77 and MAE = 0.56) under conventional tillage and 14% (ME = 0.23; RMSE = 0.81 and MAE = 0.73) under reduced tillage. Predicted soil temperatures for both fields agreed well with the observed temperature values. Calculated ME, RMSE and MAE values of soil temperature were 0.79 and 0.31 and 0.95 for the pasture, 0.67 and 0.33 and 1.78 for conventional tillage and 0.38 and 0.47 and 2.4 for reduced tillage, respectively. Although, the model overestimated measured WFPS values for the pasture, it relatively predicted well the observed WFPS values for the arable conventional and reduced tillage systems. Short-term land use change had no significant effects on CO_2 effluxes from soil. Using the high temperature sensitivity scenario, future CO_2–C effluxes would increase by 15% for the pasture and 13-16% for the arable field. However, under the low temperature sensitivity scenario, increases in the CO_2–C efflux were 6% for the pasture and 5% for both arable tillage treatments. The calculated annual CO_2 efflux uncertainties for using the high and low temperature sensitive scenarios were 9% for the pasture and 8% for the arable field.

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