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Testing the ability of the DNDC model to predict CO_2 and water vapour fluxes of a Swiss cropland site

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ABSTRACT

The ability of the DeNitrification DeComposition (DNDC) model to predict CO_2 and water vapour fluxes at the CarboEurope cropland site Oensingen on the Swiss Plateau was tested for the years 2004–2009. DNDC was able to simulate the seasonal trends of CO_2 and water vapour fluxes quite well. Also the cumulative fluxes for winter wheat, winter barley, winter rapeseed, potato and cover crop were mostly well estimated in comparison with direct eddy covariance (EC) flux measurements. However, some specific problems of DNDC were found. (i) Net CO_2 uptake was overestimated during winter, when EC measurements indicated C loss; this was probably due to a strong response of assimilation to temperature. (ii) Net CO_2 uptake was also overestimated for crops sown in autumn; we interpreted these problems as a result of inadequate consideration of the photoperiod of these crops. Being aware of these minor limitations in DNDC, the model was used to predict the net ecosystem exchange (NEE) of CO_2 of 2009 with higher temperature (+2 °C and +4 °C in yearly mean temperature). The model predicted NEE of $-610\,g\,C\,m^{-2}$ in 2009 under current conditions, $-604\,g\,C\,m^{-2}$ for +2 °C and $-458\,g\,C\,m^{-2}$ for +4 °C. This was due to a faster development of the main crop (winter wheat). These tests indicated that DNDC could become a valid tool to predict the consequences of climate change on NEE in cropland agroecosystems.

1. Introduction

Numerical models simplify reality in such a way that it can be described mathematically. For practical reasons (development and computational time, number of unknown parameters and assumptions), simple models are preferred over complex ones as long as they are able to realistically represent the system under investigation. The easiest model we can imagine considers only one factor as a function of a single variable, for example transpiration rate of the canopy as a function of temperature (Jamieson et al., 1995). The more complex the problem and the ecological compartment, the more variables (and interactions between variables) may need to be considered in a model. The De-Nitrification De-Composition (DNDC) model (Li et al., 1992a,b), which was used in this study, is one of the models that show a relatively high level of complexity. This is not surprising for a model that should be able to simulate fluxes of CO_2, H_2O, N_2O, N_2, CH_4 as well as leaf area index (LAI) development, organic matter decomposition rate, nutrient leaching, change in soil organic carbon (SOC) and biomass production.

The need for such models has been growing in agricultural sciences to assess the possible impacts of climatic change on agricultural yields and on the associated greenhouse gas fluxes (Solomon et al., 2007). Croplands typically loose carbon (Jenkinson, 1991; Jones, 1973) and contribute to the observed atmospheric CO_2 increases (Schulze et al., 2009). Janssens et al. (2003) estimated emissions from European croplands to be $300\,Tg\,C\,year^{-1}$, thus of the same order of magnitude as European forest carbon sinks ($377\,Tg\,C\,year^{-1}$). Additionally, climatic change (in particular higher CO_2 concentration, global warming and decreasing water availability) could have an important impact on plants productivity, i.e. yield, and eventually on the ecosystem's ability to store carbon. Numerical models, like DNDC, may help predicting the consequences of climatic change on agriculture, but first they have to be able to correctly simulate current conditions. Validation tests therefore play a very important role to assess the model skill.

Several papers have reviewed the suitability of DNDC to model greenhouse gas fluxes (e.g. Qiu et al., 2005; Tonitto et al., 2007; Kurbatova et al., 2009), in particular CH_4 and N_2 (e.g. Babu et al., 2006; Beheydt et al., 2007; Pathak et al., 2005) and for spatial scales ranging from single fields to entire regions. Moreover, uncertainty analysis of the DNDC model have been performed (Tonitto et al., 2007; Hastings et al., 2010). Irrespective of the trace gas under consideration, validation tests are considered useful to either demonstrate the flexibility of the model to predict greenhouse gas fluxes under varying conditions or to reveal weaknesses and flaws in particular situations. Our objectives were thus (i) to investigate the suitability of DNDC to predict the CO_2 and evapotranspiration fluxes measured by eddy covariance over a set of representative

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Table 1
Soil parameters for the Oensingen CarboEurope IP cropland site during the period 2004–2007.

Parameter	Value unit
Land-use type	Upland crop field
Soil texture	Sandy clay
Bulk density	$1.16\,g\,cm^{-3}$
Soil pH	6.5
Field capacity	0.6
Permanent wilting point	0.28
Clay fraction	0.43
Hydrological conductivity	$0.0078\,m\,h^{-1}$
Soil organic matter content	$0.00307\,kg\,C\,kg^{-1}$
Initial soil NO_3^- concentration	$240\,mg\,N\,kg^{-1}$
Initial soil NH_4^+ concentration	$26\,mg\,N\,kg^{-1}$

Table 2
The crop rotation of the last 14 years, using the Swiss Integrated Pest Management (IPM) system, at Oensingen.

Year	Crop
1994	Spring wheat
1995	Rapeseed
1996	Winter barley
1997	Temporary grassland
1998	Temporary grassland
1999	Temporary grassland
2000	Winter wheat
2001	Potato
2002	Winter wheat
2003	Rapeseed
2004	Winter wheat
2005	Winter barley
2006	Potato
2007	Winter barley
2008	Rapeseed
2009	Winter wheat

crops grown at the Swiss CarboEurope-IP cropland site CH–Oen2 in Oensingen during six years (2004–2009) and (ii) to simulate the consequences of a temperature increase (+2 and +4 °C) on net ecosystem CO_2 exchange (NEE) at the same site for a specific year.

2. Materials and methods

2.1. The DNDC model

The DNDC model is composed of three modules: (i) climatic conditions (temperature, precipitation, CO_2 concentration, wind speed, irradiation, [N] in rain), (ii) soil parameters (e.g. texture, organic matter content, microbiological activity) and (iii) farming management (including sowing and harvesting dates, tillage, fertilisation and manure amendment events, weeding, irrigation, grazing and cutting). Moreover, it is possible to calibrate the crop properties to match actual conditions, e.g. maximum yield, grain:stem:root ratio or maximum LAI. The model uses a daily time-step. In this study, we used version 9.3 of the model.

2.2. Site description and flux measurements

The 1.55 ha cropland site under investigation is located near the town of Oensingen (Canton Solothurn, Switzerland, 47°17′11.1″N, 7°44′01.5″E, 452 m a.s.l.). The soil is a fluvisol composed of 42% clay, 33% silt and 25% sand (Table 1; Alaoui and Goetz, 2008). The mean temperature (1964–1991) was 8.4 °C, according to the nearest long-term weather station Wynau, and the annual precipitation of roughly 1000 mm are typically well distributed over the whole year. The field is cultivated following the Swiss Integrated Pest Management (IPM) regime, with varying crop types in a long-term crop rotation system (Table 2) in a repeated four-year cycle (Kutsch et al., 2010).

In December 2003, an eddy covariance tower was installed in the centre of the field as part of the CarboEurope Integrated Project. CO_2 and H_2O fluxes were measured continuously at 20 Hz resolution with a LICOR 7500 infrared absorption spectrometer in combination with a Gill Solent R3-50 ultrasonic anemometer-thermometer. Data were recorded digitally on a laptop computer with in-house data acquisition software running under the Linux operating system (see Eugster and Plüss, 2010, for more details). Fluxes were computed as 30-min averages using the eth-flux software that participated in the CarboEurope flux data software inter-comparison (Mauder et al., 2008). Briefly, flux averages were computed as 30-min block averages after a two-dimensional co-ordinate rotation procedure that aligns the co-ordinates with the mean streamlines. The time lag between wind vector and CO_2 or H_2O concentration data was determined using a cross-correlation procedure that finds the best correlation in a prescribed physically reasonable time window (0–1 s). Typically, this time lag was 0.15 s. Fluxes were then corrected for high-frequency damping losses (Eugster and Senn, 1995), followed by the density flux correction (Webb et al., 1980) that corrects for apparent fluxes resulting from the fact that an open-path gas analyser does not measure concentrations as mixing ratios. Finally, all fluxes were discarded when (i) the optical path of the Licor 7500 gas analyser was affected by rain (a window dirtiness threshold of 70% was used to separate such conditions), (ii) the momentum flux was not directed towards the soil surface (Eugster et al., 2003), or (iii) the CarboEurope data flag indicated lowest quality, and gaps between accepted data were then filled using a rectangular hyperbolic light response approach (Papale et al., 2006; Moffat et al., 2007).

Precipitation data were available from the weather station Moos, 1.5 km to the west of our field site, and temperature data were measured directly at the tower in the field. The farming management information was provided by the farmer.

2.3. Model simulations

The model simulations were performed for a six-year period, from 1 January 2004 to 31 December 2009. Several crop properties in the DNDC model were adjusted to conform to Swiss standards, in particular actual yield, temperature degree-day (TDD), grain:stem:root ratio and the C/N ratio of grain, stem and root (Table 3). Soil parameters were set according to measurements and best estimates obtained for year 2004 (Table 1). The daily rates and the cumulative CO_2 and water vapour fluxes were compared qualitatively. The year that showed the best agreement (daily rates and cumulative fluxes) between simulated data and measurements was chosen for the estimates of NEE with increased temperature. For this exercise, meteorological data collected in that year were increased by 2 °C or 4 °C, thereby retaining the original variation and seasonality of the temperature. All other climatic conditions (e.g. precipitation) and site parameters (e.g. crop and soil properties, farming managements) were left unchanged.

3. Results and discussion

Generally, the DNDC model predicted the seasonal trends and the absolute magnitude of the CO_2 fluxes in a realistic way (Fig. 1). Cumulative DNDC predictions agreed well with NEE measurements obtained with the eddy covariance (EC) method and they were in most of the cases within $\pm 1000\,kg\,C\,ha^{-1}\,year^{-1}$ as suggested by Rannik et al. (2006) and Oren et al. (2006). However, discrepancies were found between model results and measured fluxes that required special attention and are addressed in what follows. During winter, the eddy covariance measurements showed the typical net CO_2 release from the field, with larger net losses due

Table 3
The main parameters for the crops modelled in the period 2004–2009.

Crop	Planting year	Grain yield [kg C ha^{-1}]	Grain:stem:root [%]	C:N grain	C:N stem	C:N root	TDD [°C]
Winter wheat	2004	4500	50:30:20	40	50	100	1800
Winter barley	2004	4200	50:40:10	40	60	100	1900
Cover crop	2005	50	1:45:54	20	30	80	1500
Potato	2006	3000	80:10:10	40	40	80	2100
Winter wheat	2006	4500	50:30:20	40	50	100	1900
Winter rapeseed	2007	4500	50:30:20	40	80	100	3000
Winter wheat	2008	4500	50:30:20	40	50	100	1900
Cover crop	2009	50	1:45:54	20	30	80	1500

to enhanced soil activity (respiration) when soil temperature was above 0 °C. Although there is no doubt about photosynthetic assimilation by the young crop under such winter conditions, the eddy covariance measurements clearly show the dominance of the respiration process at that time of the year. DNDC instead showed a considerable net CO_2 uptake (best seen until day 70 in years 2005 and 2008) that is directly related to plant activity only and that seems to underestimate respiratory fluxes. In the best cases, DNDC showed a zero net flux (beginning of years 2004, 2006, 2009) where EC measurements indicate net C loss. We suppose that the model has an unrealistically strong response of assimilation to temperature during winter: the warmer it is, the higher the assimilation rate. Although this appears reasonable as a general qualitative statement, it seems to neglect the correlation between assimilation and leaf area index (Saigusa et al., 1998; Suyker and Verma, 2001). Namely, plants can only take up significant amounts of carbon dioxide if adequate photosynthetically active leaf surface is present.

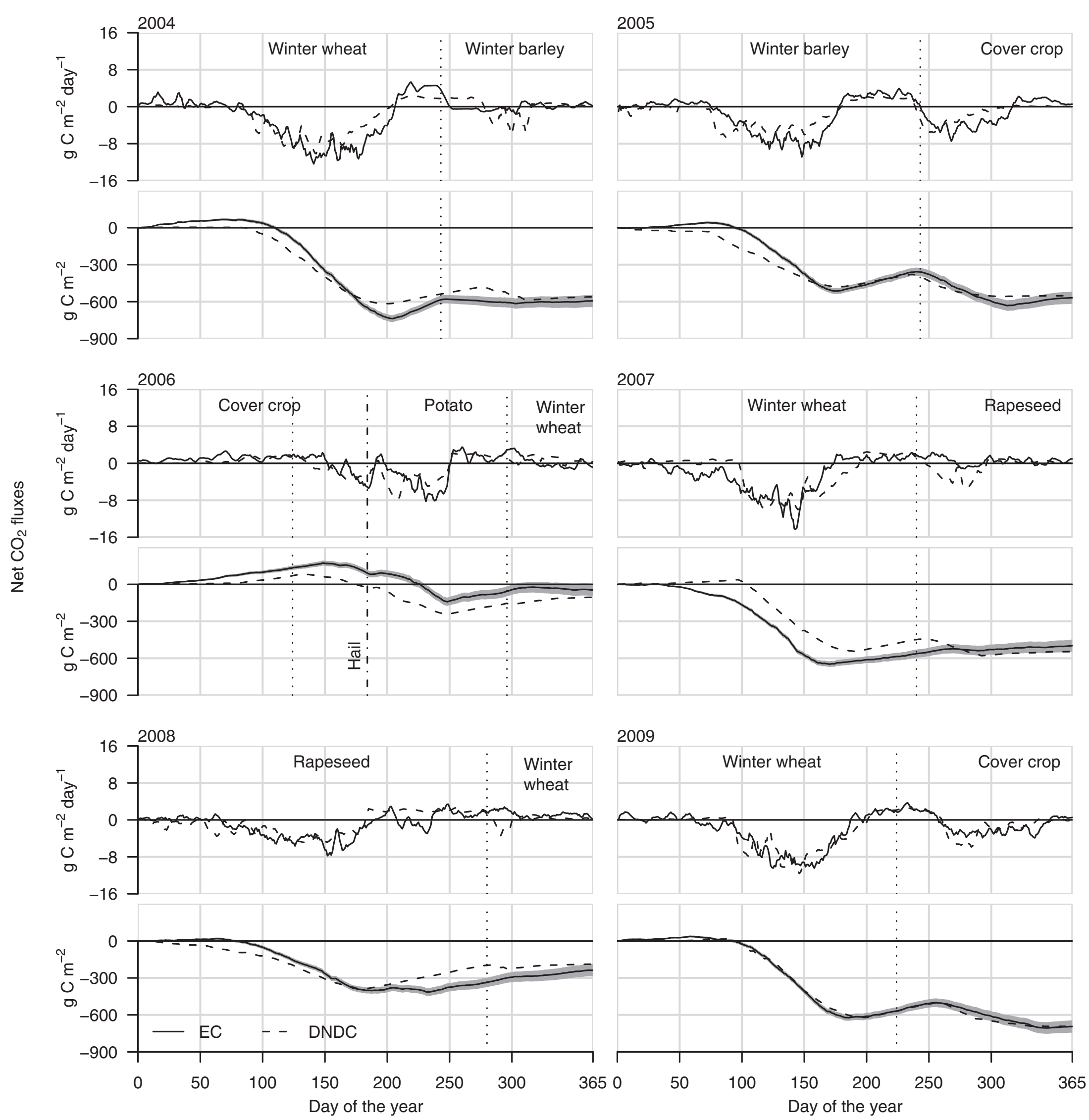

Fig. 1. Comparison between the measured eddy covariance CO_2 fluxes and the modelled DNDC fluxes from January 2004 to December 2009. Curves were smoothed with a 4-days running mean filter. Dotted lines represent sowing dates of different crops. Dashed line represents hail storm in 2006. The grey interval represents the uncertainty in measured cumulative fluxes based on error propagation as suggested by Oren et al. (2006) and Rannik et al. (2006).

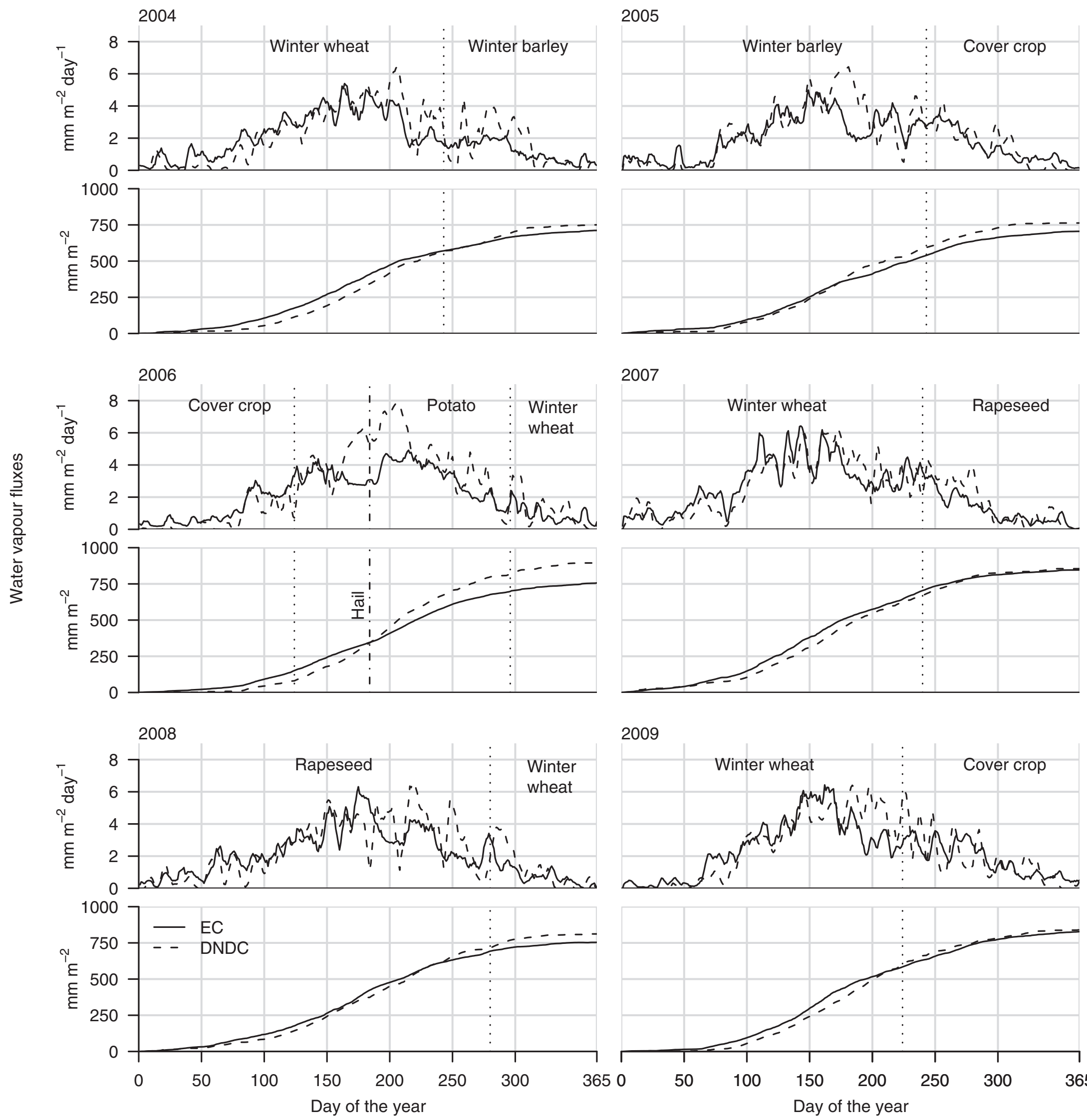

Fig. 2. Comparison between the eddy covariance water vapour fluxes and the modelled DNDC fluxes from January 2004 to December 2009. Curves were smoothed with a 4-days running mean filter. Dotted lines represent sowing dates of the different crops. Dashed line represents hail storm in 2006.

A net CO_2 uptake overestimation was observed for several crops sown in fall (winter barley in 2004, winter rapeseed in 2007 and winter wheat in 2008). We interpret this behaviour of DNDC as a result of inadequate representation of the reaction of the plants to the actual photoperiod (photoperiod feedback), which typically becomes shorter in summer and autumn. DNDC apparently only considers the plant reaction to temperature (temperature feedback). In reality, winter crops develop slower than spring crops because, even though temperature is still favourable, growth rate is reduced by the quality and quantity of the light available during short autumn days (Downs and Borthwick, 1956). Measurements showed that vegetation reacted differently to temperature if a crop was sown in fall as compared to crop sown in spring (data not shown), whereas DNDC did not. It should be mentioned, however, that this can be almost neglected in tropical and sub-tropical regions, where photoperiod does not fluctuate between seasons, but it can become an important variable in Switzerland, where daylight length and quality vary significantly during the year. The agreement between model and measurements was much better during maturation and harvest periods, indicating that these processes were less influenced by photoperiod and more by temperature.

In 2004 and 2005, there was a general net CO_2 uptake underestimation of the daily fluxes during the main growth period of the main crop, but this disappeared in the following years. (Hastings et al., 2010) performed a sensitivity analysis of several DNDC input values and observed that the model had an elevated sensitivity to SOC, soil density and temperature. Thus, part of the DNDC miss-estimations in this initial years (2004, 2005) might be related to our best estimates used for SOC (3.1 g C kg^{-1} soil, difficult to estimate due to spatial heterogeneity; see (Smith, 2004)). The importance of the initial SOC value in latter years might have decreased, if modelled SOC approached the actual SOC. However, no attempt to compared it was made due to lack of data.

In 2006, a severe hailstorm on 7 July (day 184, Fig. 1, dashed line) seriously damaged the potato crop. As DNDC does not consider the possibility of episodic destructive events such as hail damage, we attempted to model this event with harvest and re-sowing of the crop. The model reacted well after re-sowing but then overestimated the net CO_2 uptake, probably because plant growth rate after hail diverged from that after germination as was expected by DNDC. Because of these particular conditions, it would not be correct to attribute the miss-estimations of 2006 fluxes to DNDC. In fact, our results show how relevant such infrequent but not uncom-

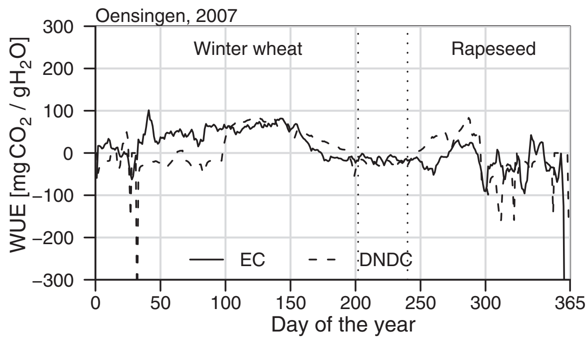

Fig. 3. Water Use Efficiency (WUE) of winter wheat during 2007, calculated as the ratio between the measured ecosystem CO_2 and water vapour fluxes. The dotted lines are the harvest date of winter wheat and the sowing day of winter rapeseed, respectively.

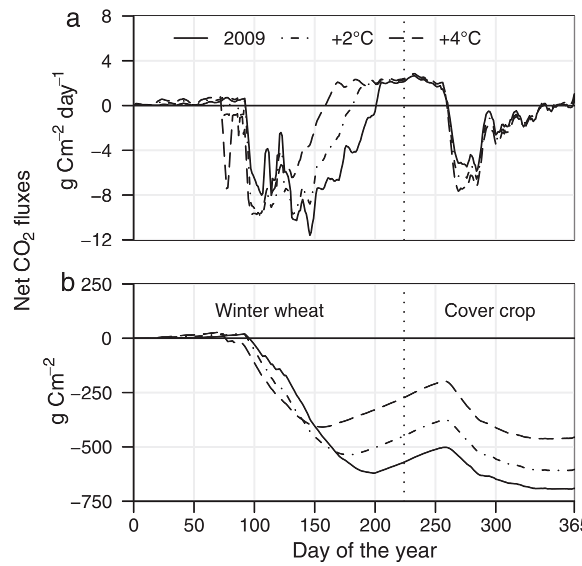

Fig. 4. Comparison between simulated (a) net CO_2 fluxes and (b) cumulative fluxes in 2009 with no temperature increase, +2 °C and +4 °C. The total NEE values were −691, −604 and −458 g C m^{-2} with no temperature increase, +2 °C and +4 °C, respectively. The total NEE decreased with increasing temperature because maturation of winter wheat was faster in a warmer climate.

mon destructive events are, and that next-generation crop models should include implicit treatments of such events to increase our ability to simulate cropland CO_2 fluxes more realistically also under changed climate variability.

In 2007 the modelled NEE of winter wheat was close to 0 g C m^{-2} until day 100, whereas measured NEE showed a net CO_2 uptake (about 200 g C m^{-2}). The cumulative modelled NEE would not have agreed with the measurements without the overestimated C uptake of winter rapeseed late in the year. The cumulative modelled NEE of the last year (2009) was almost identical to measurements. Noteworthy is how accurate the net C emissions between day 200 and day 250 was modelled in this particular year.

Seasonal water vapour fluxes predicted with DNDC agreed rather well with the EC fluxes (Fig. 2), with a few characteristic discrepancies between model and measurements. (i) The cumulative water vapour fluxes indicated that the model underestimated fluxes during winter–spring and overestimate them during summer–autumn. (ii) Peak estimates in daily rates were also more accurate in winter–spring. (iii) In five out of six simulated years (2004–2007, 2009), DNDC overestimated water vapour fluxes during maturation of the main crop. This behaviour was however not observed for the CO_2 fluxes. Water vapour fluxes and net CO_2 uptake were similarly overestimated for crops sown in autumn (winter barley in 2004, and winter wheat in 2006 and 2008).

Transpiration and assimilation by plants are closely related, and therefore the question arises whether DNDC is also able to reproduce the correct relationship between the two fluxes as expressed by the water use efficiency (WUE) field observations. WUE is normally defined for a single plant, but Baldocchi (1994) showed that eddy covariance CO_2 and water vapour measurements are a good approximation of WUE also at canopy level. As an example for the Oensingen site, the WUE during 2007 was analysed (Fig. 3). Without considering 2006, which was miss-estimated because of a destructive hail event, 2007 was a year with noticeable disagreements, whereas in other years WUE was modeled quite satisfactorily. In the central phase of the 2007 vegetation period (day 140–250), WUE derived from model and from measurements showed good agreement, but in winter and autumn the model predicted peaks that were not observed in the EC measurements.

The best year simulated by DNDC was 2009. Therefore, we used year 2009 for two climate change scenario simulations with temperatures increased by 2 °C and 4 °C (Fig. 4). The simulations indicated that with higher temperatures the net CO_2 uptake decreased (−610 g C m^{-2} in control year 2009, −604 and −458 g C m^{-2} with +2 °C and +4 °C, respectively). As expected (Jamieson et al., 1995), the reason was the faster development of winter wheat that resulted in early maturation. Because in the model harvest time was not modified, mature winter wheat was kept in the field but it was not photosynthetically active. Thus, soil respiration was not compensated anymore and the parcel showed a longer period of net CO_2 emission compared to the 2009 simulation. Faster maturation can be an opportunity for farmers, namely it would be possible to cultivate an additional crop during the main vegetation period. Assuming that other resources are not limited (e.g. water availability), this would intensify crop production, delivering additional yield to farmers and, from an ecological point of view, allow more net CO_2 uptake. However, climate change is expected to modify growing conditions in a complex way (Frei et al., 2007) and this assumption may not be always fulfilled.

4. Conclusions

We assessed the ability of the De-Nitrification De-Composition (DNDC) model to simulate net ecosystem CO_2 and water vapour fluxes for the crops grown at the Swiss CarboEurope-IP site Oensingen.

Net CO_2 uptake overestimations in winter and of several crops sown in autumn were the main problems observed during simulations. However, these only had a minor impact on the cumulative CO_2 fluxes. The qualitative analysis of this study has shown that DNDC is a valid model for predicting CO_2 and water vapour fluxes. We therefore suggest, that DNDC can be used in a realistic way to estimate NEE under more complex future climatic conditions.

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