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Modelling daily to seasonal carbon fluxes and annual net ecosystem carbon balance of cereal grain-cropland using DailyDayCent: A model data comparison

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ABSTRACT

Croplands are important not only for food and fibre, but also for their global climate change mitigation and carbon (C) sequestration potentials. Measurements and modelling of daily C fluxes and annual C balance, which are needed for optimizing such global potentials in croplands, are difficult since many measurements, and the correct simulation of different ecosystem processes are needed. In the present study, a biogeochemical ecosystem model (DailyDayCent) was applied to simulate daily to seasonal C fluxes, as well as annual net ecosystem carbon balance (*NECB*), in a cereal grain-cropland. The model was tested using eddy-flux data and other associated C flux measurements lasting for three years over a full cereal crop-rotation (corn-wheat-barley) from a long-term experiment (SOERE–ACBB; http://www.soere-acbb.com) in France. DailyDayCent simulated seasonal crop growth, regrowth of volunteers and cumulative net primary production (*NPP*) at harvest successfully. Fairly consistent agreement was obtained between measured and modelled daily *NPP* over the full crop rotation, with model efficiency (*EF*) of 0.59. The model underestimated heterotrophic respiration (R_h) on daily, seasonal and annual time scales by 43–53%. Although a reasonable model fit was found for daily *NEE* over the entire experimental period (*EF* ~ 0.47), the model overestimated cumulative annual net C uptake (*NEE*) by 28 times. DailyDayCent simulated net C harvest efficiently, and the leaching loss of C reasonably well. Both the modelled and measured mean annual *NECB* indicate that present cereal grain-cropland is a net C source and the cropland is losing C at a mean annual rate of 64.0 (modelled) to 349.4 $\text{g C m}^{-2}\ \text{yr}^{-1}$ (measured), thus the model overestimated mean annual *NECB* (or underestimated mean annual net C loss) in the present cropland by 82%. We conclude that overestimation of cumulative *NEE* on seasonal and annual time scales is the most likely reason for overestimation of *NECB,* and underestimation of R_h was the main driver for overestimation of cumulative seasonal and annual *NEE*. The model would benefit from further testing, particularly against direct measurements of R_h, and subsequent calibration, parameter estimation and model development for improving its ability to simulate R_h on daily to seasonal and annul time scales, cumulative seasonal and annual *NEE*, and net C balance, especially in cereal grain-croplands in the study region.

1. Introduction

The globally averaged concentration of carbon dioxide (CO_2) in the atmosphere reached the significant milestone of 400 parts per million (ppm) for the first time in 2015 and surged further to new records above 400 ppm in 2016 (WMO, 2016a, 2016b). The Paris Agreement (COP 21) of the United Nations Framework Convention on Climate Change (UNFCCC) entered into force in November 2016 after ratification of 115 countries (UNFCCC, 2016). The ambitious target of COP 21 is to limit global temperature rise to well below 2 °C above preindustrial levels within this century, through reduction of emissions of CO_2 and other greenhouse gases (GHG). Overwhelmingly, most of the signatory countries included agriculture in their National Climate Action Plans (INDCs) as one of the top sectors in which they intended to make adaptation measures and emissions reductions towards their targets. Agriculture is an important sector for mitigating global climate change, and excluding agriculture from emission mitigation targets would probably not only increase the cost of mitigation in other sectors, but

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ultimately could reduce the feasibility of meeting the 2 °C limit (Wollenberg et al., 2016).

Agricultural lands occupy 37.7% of the earth's land surface, in which croplands constitute 30–35% of the total agricultural lands and occupy around 12% of the ice free earth surface, and about half of croplands are under cereal production (FAO, 2013; Ramankutty et al., 2008; WB, 2013, 2014). Arable lands collectively have historically lost 25–75% (66–90 Pg) of their antecedent soil organic carbon (SOC) stocks globally through cultivation and disturbance, and 60–70% of this lost carbon (C) could be re-sequestered through improved management practices (Houghton, 1999; IPCC, 1995; Lal, 2013; Lal et al., 2007). Global C sequestration potential in cropland has been estimated to be of 40–60 Pg at the rate of 0.4-1.0 Pg C yr^{-1}, which is about 12–30% of the current rate of increase in atmospheric concentration of CO_2 (Lal, 2004; Lal and Bruce, 1999; Smith, 2004b). With the intention of delivering global climate change mitigation, GHG reduction, and improved soil health and sustainable crop production (Lal, 2013), policy makers have begun introducing different ambitious national projects to offset climate change through C sequestration in agriculture, for example the '4‰ Initiative' proposed by the French government (2015). Although C sequestration in croplands is a partial and short-term solution, it is cost-effective, and critical for meeting the global climate targets, and also buys time during which new cost-effective technologies for C emission reduction or accumulation in other sectors could be developed and take effect (Bajzelj et al., 2014; Lal, 2001, 2003; Smith, 2004a).

To optimize the climate change mitigation and C sequestration potential under agricultural land-uses, particularly in croplands, understanding, quantification, assessment and evaluation of C balances and its component fluxes from daily to seasonal and annual scales are needed under different crops, crop-rotations and management practices across different regions globally. Unlike most ecosystems, croplands are intensively managed to avoid resource constraints and maximize yield (Lokupitiya et al., 2009). Daily and seasonal C fluxes, and the annual C balance in croplands, are influenced by many factors and most of these factors vary both on temporal and spatial scales *viz.* climatic conditions, soil types, past land use and management history, timing and intensity of crop management practices (crop rotation, cover-cropping, green manuring, planting/sowing, tillage, application of manure, fertilizer, irrigation and pesticides, harvesting, fallowing and crop residues management: Ceschia et al., 2010; Ciais et al., 2010; Eugster et al., 2010; Huang et al., 2009; Jans et al., 2010; Kutsch et al., 2010; Moors et al., 2010; Osborne et al., 2010; Smith et al., 2010). Each crop and its cultivars have their own specific C-fingerprints, both in terms of timing and magnitude, which influence ultimately the amount of C exchange and the net C balance in cropland (Jans et al., 2010; Kutsch et al., 2010; Moors et al., 2010). Many studies have quantified seasonal C fluxes and estimated C balances in croplands for single crops and crop-rotations on a seasonal and annual basis, however there is no consensus on the sink-source properties of the croplands globally. Croplands have been reported to be weak to strong C sources (43–372 g C m^{-2} yr^{-1}) (Anthoni et al., 2004; Aubinet et al., 2009; Baker and Griffis, 2005; Béziat et al., 2009; Ceschia et al., 2010; Grant et al., 2007; Jans et al., 2010; Janssens et al., 2003; Kutsch et al., 2010; Loubet et al., 2011; Verma et al., 2005), neutral (Suyker and Verma, 2012; Verma et al., 2005) and low to moderate C sinks (16–161 g C m^{-2} yr^{-1}) (Béziat et al., 2009; Gervois et al., 2008; Hollinger et al., 2005). These variations in cropland C balances are probably due to the variation in environmental conditions and cropland management practices across different regions. Most of these studies are based on eddy-covariance and net C balance techniques under corn-soybean, wheat-corn, corn-wheat-barley-mustard, sugar-beet-wheat-potato and rapeseed-wheat-sunflower rotations, or on individual crops, either for a single year or few years. However, currently there is limited understanding of the interplay between different crop management practices and C balance along with its component fluxes, and uncertainties in the cropland C budget remain large (Smith et al., 2010; Vuichard et al., 2016). It is, therefore, imperative to establish a better understanding of cropland C dynamics, from daily to seasonal and annual time scales, to evaluate different management practices, to allow recommendations to be made to reduce emissions and optimize C storage in croplands, and also for determining the key factors controlling the sink-source activities of croplands (Béziat et al., 2009; Moureaux et al., 2008; Wattenbach et al., 2010). Detailed studies with daily to seasonal C fluxes and annual C balance under full cereal crop rotations (*e.g.,* corn-wheat-barley) separately for individual crops, along with entire crop rotations, are rare (Kutsch et al., 2010; Wang et al., 2015).

Estimation of the cropland C budget is challenging and uncertain since many measurements of various C fluxes to and from the cropland are necessary at each site to assess the full C balance (Béziat et al., 2009; Janssens et al., 2003; Smith et al., 2010). Gross primary production (*GPP*) represents the gross uptake of atmospheric CO_2 through photosynthesis, where about half of the assimilated C is consumed by autotrophic respiration (R_a), and the remainder is defined as net primary production (*NPP*) *(i.e.* the rate at which solar energy is fixed in the living plant biomass). Part of the *NPP* is harvested or exported out of the system, and the rest enters into the soil. Soil loses C through heterotrophic respiration (R_h), erosion, fire, leaching and emissions of methane (CH_4) and volatile C. Net ecosystem exchange (*NEE*) represents the balance between *NPP* and R_h. Application of organic manure and fertilizer is external C input, which adds C to the system. The total balance of all the component C fluxes in and out of the cropping system is defined as net ecosystem C balance (*NECB*) (Chapin et al., 2006; Smith et al., 2010). When integrated over time and space, *NECB* equals the net biome productivity (*NBP*). Eddy-covariance is a state-of-the-art technique for measuring *NEE* continuously from days to years, and thus helps to quantify and understand timing, seasonality and magnitude of net CO_2 flux, along with its annual balance (Aubinet et al., 2000; Baldocchi, 2003; Sus et al., 2010). Quantification of *NECB* in croplands is difficult even in field scale, as measurements of all component C fluxes along with the eddy-flux (*NEE*) are often unavailable for experimental sites (Smith et al., 2010). Again, assessment of the seasonal component C fluxes and estimates of C budget are limited to the conditions under which they were determined, and thus the results cannot be used for evaluation of other management practices (Grant et al., 2007). Furthermore, spatial variation of croplands in terms of crop species, cultivars, crop-rotations, management practices, human interferences, soil types and climatic conditions has made the task of upscaling the field scale results to regional, national, or global scale more difficult, even with an extensive network of well-established experimental sites (Ceschia et al., 2010; Kutsch et al., 2010; Moors et al., 2010). Processed-based models are important tools for a) use as Supplementary information to gap-fill incomplete measurements to capture the full C budget, b) evaluation of alternative management practices for improved C balance and sustainable crop production, c) assessing mitigation strategies, d) upscaling field results, and e) projections under future scenarios (Grant et al., 2007; Smith and Smith, 2007; Wallach et al., 2014).

Different types of dynamic system models have been developed to simulate C dynamics in different ecosystems. However, dynamic global vegetation models (DGVM), for example ORCHIDEE (Krinner et al., 2005) and LPJ (Sitch et al., 2003), often lack detailed description of crop growth parameters and their interactions with detailed management practices such as tillage, harvest, irrigation, residue incorporation and crop rotation. On the other hand, biophysical crop-specific models, for example APSIM (McCown et al., 1995) and DSSAT (Jones et al., 2003), are mainly focused on optimization of plant growth and crop yield, and their dependence on detailed crop management practices, climatic and environmental factors, and nutrient supply, but rarely simulate SOC dynamics, daily C exchange and C balance explicitly. In contrast, biogeochemical ecosystem models, such as DailyDayCent (Del Grosso et al., 2011; Parton et al., 1998) or DNDC (Li et al., 2000), are intermediate and relatively simple, but simulate detailed plant growth,