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C-Farm: A simple model to evaluate the carbon balance of soil profiles

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ABSTRACT

Soil carbon cycling is an essential component of agroecosystems models. Simulating soil carbon (C_s) cycling has become an issue of societal importance for C_s storage can play a role reducing the rate of increase of atmospheric CO_2 concentration. To participate in carbon trading markets, growers have to evaluate their local, site-specific options to increase C_s or reduce C_s losses. This paper introduces C-Farm, a daily time step cropping systems model that allows calculating the Cs balance using a one-pool soil organic matter sub-module. In C-Farm the C_s turnover rate depends non-linearly on C_s and on environmental and management controls. Two long-term experiments were selected to evaluate C-Farm: a wheat-summer fallow 70+ years experiment at Pendleton, Oregon, and the continuous wheat experiment at the Rothamsted experiment station in the United Kingdom. C-Farm simulated well the long-term C_s evolution observed in these experiments. In addition, simulations performed in the dryland US Pacific Northwest show its applicability for assessing C_s storage rates in a region with large variation in precipitation. C-Farm can be easily customized to a large array of local conditions, providing robust estimates of short- and long-term on-farm carbon storage rates. The model is being further developed to provide estimates of nitrous oxide emission.

1. Introduction

Soil carbon cycling is an essential component of comprehensive agricultural and ecological models. Organic matter is composed of fractions with different properties. These fractions range from living tissue (micro and macrofauna, microbial biomass, plant residues and roots), and a continuum of decomposing materials from root exudates, animal excreta, and dead animals and vegetation to highly stabilized soil organic matter, including charcoal (Skjemstad et al., 2002). This paper is concerned with the modeling of carbon in soil organic matter (C_s or soil organic carbon) and crop residues. In particular, this paper introduces C-Farm, a cropping systems model created around a simple C_s model that can aid in obtaining robust estimates of C_s evolution under different environmental and management conditions for the entire soil profile. We first describe the advantages and drawbacks of other methods used to simulate C_s to provide a justification for the development of C-Farm.

Soil organic carbon is composed of an array of organo-mineral complexes whose turnover rates vary along a continuum from labile or fast turnover fractions to highly recalcitrant fractions. Representing this continuum has been a challenge for soil scientists and biological systems modelers. Early models of C_s cycling consisted of one C_s pool and one residue pool (e.g., Hénin and Dupuis, 1945). As basic knowledge on C_s dynamics expanded, new multi-compartment models represented explicitly the microbial pool and separated residues and C_s in several pools (Jenkinson and Rayner, 1977; Paul and Van Veen, 1978; McGill et al., 1981; Paul and Juma, 1981; Parton et al., 1988; Verberne et al., 1990; Coleman and Jenkinson, 2005). Other models represented mathematically the C_s turnover rate continuum (Ågren and Bosatta, 1987).

Multi-compartment models separate C_s in pools with different turnover rates. Each pool decomposes due to microbial attack at different rates assumed to depend on the chemical recalcitrance and physical protection of the organic matter fraction: the higher the recalcitrance and physical protection the lower the turnover rate. The carbon lost by a pool can have as destiny the atmosphere (CO_2 from microbial respiration), the microbial biomass pool, or another carbon pool through chemical reactions or physical aggregation. The transfer of carbon from one-pool to another is accompanied by fluxes of other elements such as nitrogen and phosphorus. There are several inherent weaknesses of the multi-pool approach for modeling. First, there are uncertainties at defining the fraction of C_s to be allocated to each pool and their average turnover

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rate (e.g., Collins et al., 2000), and the transfer coefficient among pools. In simulation models, long-term pre-run periods are used to stabilize the size of each pool and their distribution with depth. Second, the assumption that the intrinsic turnover rate of each pool is constant (environmental factors aside), even after losing or gaining carbon, is weak and can be problematic for long-term simulations where a steady change of the turnover rate of various pools can cause an important drift in C_s evolution. Third, given the prevalent use of first order kinetics to represent decomposition, there is interdependence between pool size and rate; if the size of a pool is underestimated, the net carbon flux from that pool can be compensated by an overestimation of the pool's turnover rate and vice versa. Six et al. (2002) concluded after an extensive literature review that the success at matching measurable and modelable C_s pools has been minimal. Despite these limitations, multi-compartment models such us the Century model (Parton et al., 1988) have been widely used for assessing C_s evolution and variations of multi-compartment models have been incorporated in comprehensive cropping systems models (e.g., EPIC, Izaurralde et al., 2006; CropSyst, Stockle et al., 2003).

Agriculture can serve as a bridge to reduce the increase in greenhouse gases in the atmosphere before major breakthroughs in technology for energy generation or carbon storage develop (McCarl and Schneider, 2000). It is estimated that about 25–50% of the original C_s in native prairies and savannas was lost due to agriculture (Mann, 1986). In the words of Baker et al. (2007) "...tilled soils are viewed by many as a depleted carbon reservoir that can be refilled." Reduced tillage, no-till, and the incorporation of perennials in the rotation can increase C_s if there is an effective reduction in oxidation rate while maintaining or increasing carbon inputs. As consequence, growers have interest in evaluating their local potential to participate in carbon trading markets.

Tools that allow assessing and verifying carbon storage rates are required to develop such markets. In the United States, growers can trade carbon under agreements with the Chicago climate exchange (http://www.chicagoclimatex.com/) in which a fix number of carbon credits are allocated based on regionally defined management practices. Country-level assessments of carbon storage can be obtained by growers using tools such as the voluntary reporting of greenhouse gases-carbon management evaluation tool (Comet VR, http://www.cometvr.colostate.edu/) that rely on generalized estimates that depend on cropping system and location. However, generalized, database-driven calculators cannot provide estimates of carbon storage that represent local current C_s, residue production, and environmental conditions. If local conditions are known and specified, utilizing multi-compartment models to extrapolate long-term potential is not feasible given the parameter requirements to prepare typical simulation runs. Single-pool models can be effective in predicting soil carbon if formulated properly, and they are likely more desirable for management- or policy-oriented applications at watershed or cropping systems scales as calibration requirements are much simpler than those of complex models.

We have developed C-Farm, a user-friendly cropping systems model that allows calculating rates of carbon storage for the soil profile on a layer-by-layer basis. The model is built around a robust single-pool carbon model. The model utilizes daily weather data to simulate soil moisture and temperature, and computes crop growth, yield, and aboveground and belowground carbon inputs to calculate the C_s balance. Statistics of yields and description of crop management by growers are also used in the simulations, providing a high degree of customization to local conditions. This tool is useful for growers, consultants, and state and federal agencies that need to develop carbon storage estimates for local conditions. The objectives of this paper are to describe basic aspects of the model and to present test cases and applications.

2. The C-Farm model

C-Farm was designed to compute the inputs of carbon from crop residues and roots and to compute C_s decomposition and humification rates by soil layer at a daily time step. The C_s cycling follows in broad terms the approach by Hénin and Dupuis (1945) who proposed that C_s dynamics can be represented as follows:

$$dC_s/dt = hC_i - kC_s \tag{1}$$

where C_s is soil carbon (Mg ha^{-1}), t is time (yr), C_i is carbon inputs (Mg ha^{-1}), h is a humification factor and k is the apparent soil decomposition rate (yr^{-1}). This model, while simple, is adequate for hypothesis development and testing, and for field-level data interpretation (Huggins et al., 1998a,b). For a single-pool model to be useful, it must represent the integrated C_s turnover rate that results from the contribution of pools with different turnover rates. Therefore, we assumed that under constant temperature, water and oxygen levels, both h and k depend on the current C_s and a maximum or saturation C_s (C_x). The higher the ratio C_s/C_x the higher k (based on Huggins et al., 1998b), and the lower h (based on Hassink and Whitmore, 1997). The differential equation for each soil layer is as follows:

$$\frac{dC_s}{dt} = h_c[1 - (C_s/C_x)^n]C_i - f_e f_t k_x (C_s/C_x)^m C_s \tag{2}$$

where h_c is the organic carbon inputs humification (yr^{-1}), which is in turn a function of soil clay concentration and residue type (aboveground, belowground biomass, or manure), C_x is the saturation carbon concentration for that layer (Mg ha^{-1}), n and m are empirical constants, k_x is the apparent maximum C_s decomposition rate (yr^{-1}), and f_e and f_t are factors accounting for environmental and tillage effects on soil apparent decomposition rate. The terms multiplying C_i and C_s are h and k, respectively, of Eq. (1). The first order kinetics assumed by Hénin and Dupuis (1945) was therefore, substituted by a dependence of order m+1 and the humification modeled as a function of C_s.

Estimates of aboveground and belowground C_i are obtained in the model by using a simplified version of the crop module in CropSyst (Stockle et al., 2003), with generalized parameters for several major crops to define radiation interception, transpiration, and biomass accumulation. The daily growth estimate is allocated to shoots or roots based on an empirically derived function that provides partitioning factors based on phenology. Simulated root biomass at harvest in non-stressed crops amounts to approximately one third of the non-grain aboveground biomass, which is in agreement to that reported for maize by Amos and Walters (2006); root carbon exudates are considered equivalent to the amount of roots albeit with a lower humification rate as explained below. Grain yield is estimated based on the harvest index computed as presented in Kemanian et al. (2007). Dead material from aboveground residues, roots, and root exudates are kept in separate compartments. A generalized function of root distribution with depth (Dwyer et al., 1996) is used to allocate roots and root exudates to each soil layer at harvest or when a crop is killed. Tillage operations redistribute all carbon pools (in fact, all state variables) among layers affected by the operation.

The carbon saturation level (C_x) is computed following Hassink and Whitmore (1997), who found that C_x depends linearly on the mass fraction of clay (f_{clay}). This approach can be improved by considering different types of clay particularly in tropical soils. The linear function, which returns C_x in mg C kg^{-1} soil, is:

$$C_x = 21.1 + 37.5 f_{clay}. \tag{3}$$

Estimates of h reported in the literature are approximately 0.10–0.20 yr^{-1} for fresh residues (Rasmussen and Collins, 1991; Huggins et al., 1998a) and 0.30–0.35 for manure-derived carbon

(Kätterer and Andrén, 1997). Buyanovsky and Wagner (1997) suggested that a humification constant of 0.4 should be used for native prairies and permanent pastures, but the results that we reviewed are not conclusive. In C-Farm, the maximum humification rate h_c for aboveground and root biomass (Eq. (4a)) and root exudates (Eq. (4b)) are computed as follows:

$$h_{ca} = 0.09 + 0.11(1 - \exp(-5.5 f_{clay})), \tag{4a}$$

$$h_{ce} = 0.08(1 - \exp(-5.5 f_{clay})). \tag{4b}$$

In setting up the parameters for these equations we targeted calculated values of humification from long-term experiments such as the Morrow Plots (Darmody and Peck, 1997) and the Sanborn Field (Buyanovsky and Wagner, 1997) and those published by Rasmussen and Collins (1991) and Huggins et al. (1998a). As indicated by these equations, the humification rates vary between 0.1 and 0.2 for aboveground and belowground residues. For root exudates, lacking any information we assumed a low humification rate (<0.08) which makes a minor contribution to the C_s balance. As indicated in Eq. (2), these factors are further adjusted by the ratio C_s/C_x to the power n ($n = 6$). The power adjustment causes a sharp drop in humification when C_s is about 80% of the saturation value for a given layer and therefore, only plays a role at high C_s. The underlying assumptions are that organic matter that is not protected in organo-mineral complexes is exposed to microbial attack and the degradation products cannot be accumulated as organic matter, and that the higher f_{clay} the larger the capacity for organic matter protection in these complexes. This prevents having a linear relationship between C_i and equilibrium C_s as implied in the Hénin and Dupuis (1945) model.

Estimates of k for Midwest soils in the United States range from 0.8 to 3.5% yr^{-1} (Huggins et al., 1998b) with variation associated to soil type, management, and C_i level. Andriulo et al. (1999) reported a positive relationship between temperature and k for cultivated soils in the plow layer, with k of 8% yr^{-1} for average annual temperature of 27 °C. Thus, according to this data the constant k_x in C-Farm, which represents the maximum turnover rate for an undisturbed soil, was set to 5.5% yr^{-1} for soils at or near field capacity and at 35 °C. Deviations from these environmental conditions due to colder or warmer soils or varying soil moisture are accounted for by the factor f_e which varies from 0 to 1. The factor f_e is computed daily for each layer as the product of both soil temperature, soil water potential, and aeration limiting factors. Soil temperature and water content are simulated daily for each soil layer by running soil water and energy balances. Another central assumption of C-Farm is that the higher the C_s the more exposed the organic matter and therefore, the faster the turnover rate, which is adjusted by the ratio C_s/C_x to the power m ($m = 0.5$) (Eq. (2)). Thus, the turnover rate is effectively dependent on $C_s^{3/2}$ and not linearly dependent on C_s as in the Century model (Parton et al., 1994) and most carbon cycling models.

Tillage accelerates k (factor f_t) and mixes soil layers along with other pertinent state variables (moisture, organic matter, and residues); tillage does not affect the humification rate. Tillage effects on k are accounted for with an empirical factor that depends on the tool utilized, number of operations and soil texture. It is assumed that tillage breaks up soil aggregates exposing organic matter to microbial attack and therefore, the higher the deaggregation caused by tillage the higher f_t. The effect of each tool was developed by modifying the methodology used by the USDA National Resource Conservation Service to compute the soil disturbance rating (d_r) in the Soil Conditioning Index (NRCS, 2002). Each tool is given a rating that ranges from 0 to 30. The lower ratings are associated with tools or operations that gently disturb the soil and the higher ratings (range 25–29) correspond to offset disks, moldboard plows and other tools that break up and mix soil aggregates aggressively. Each operation adds the corresponding tool rating to the current cumulative rating for all the affected soil layers. This cumulative value is used to compute f_t as follows:

$$f_t = \frac{f_{tx} d_r}{(d_r + \exp(5.5 - 0.05 d_r))} \qquad f_{tx} = 1 + 4\exp(-5.5 f_{clay}) \tag{5}$$

Thus, texture controls how much the turnover can be accelerated (f_{tx} ranges from ~1.4 for clay soils to ~4.0 for sandy soils on a daily basis) and the cumulative disturbance d_r controls the extent of the disturbance. A typical conventional tillage operation sequence including moldboard plow, offset disk, cultivator and a planter are sufficient to accelerate the turnover rate near the maximum values. Each day, f_t is decreased as function of soil moisture at maximum rate of 2% day^{-1} for soils at field capacity. Roughly, a conventional tillage sequence affects the soil turnover rate with a progressively decreasing effect for about 90 days if the soil remains moist and for longer if drier.

3. Model implementation

C-Farm has been implemented in Visual Basic 9 with inputs managed through an interface able to import previous settings from Excel. Outputs along with the run settings are printed in Excel files. The inputs needed to run the model are: (1) a description of the location (latitude, longitude and elevation) and long-term daily weather data, (2) the initial soil profile on a layer by layer basis, (3) a description of the crops and the rotation sequence, (4) the sequence of tools and tillage operations associated to the rotation, and (5) criteria for irrigation (fixed dates and amounts, or automatic irrigation based on soil water content threshold). The soil information is easily obtainable from soils databases or from soil analysis; pedotransfer functions (Saxton and Rawls, 2006) are embedded in the code to compute bulk density, field capacity and wilting point when not provided by the user. Inputs of texture and soil organic matter concentration per layer are mandatory. For each crop the following information is needed: typical seeding, flowering, and harvest date, fraction of soil covered by the crop at full canopy development (to account for row crops seeded at wide inter-row distances in areas with low water supply). Tillage tools, dates and tillage depths are easily selected from dropdown menus. The outputs are available on a daily or annual basis for several soil and crop variables, including crop yield, residues yield, root biomass per layer, soil carbon balance per layer, crop transpiration, soil evaporation, runoff, percolation, and other variables of interest.

An error checking routine controls that the simulation set up is correct and warns the user about potential errors in cropping sequences, operations overlap, irrigation volumes, and the quality of the input weather data. Consultants or growers can learn to operate the model in a 1 h guided session. The simple structure of the model allows linking the model to soil and weather databases to compute regional estimates of C_s storage rates, and if available, modules of the model calculating canopy cover and even soil and canopy water evaporation could be replaced with information calculated based on remotely sensed data (Couralt et al., 2005) for real time simulations.

4. Comparison with other models

C-Farm has been designed to offer a simple set up and reliable estimates of C_s cycling for the entire profile in different climates and agricultural soils. More comprehensive models such as CropSyst (Stockle et al., 2003), EPIC (Izaurralde et al., 2006), the DSSAT suit of models (Jones et al., 2003), APSIM (Keating et al., 2003), and RZWQM (Ahuja et al., 1998), include soil carbon multi-compartment models for which the difficulties for accurately representing soil carbon cycling have been discussed above, and are input- and training-requirements intensive. Crop rotations including perennial and annual crops are easily built in C-Farm.

The Century model (Parton et al., 1988) is a multi-pool carbon model with a comprehensive linkage between carbon, nitrogen, phosphorus and sulfur cycling. Crop growth is handled in a simple manner to provide water use, nutrient removal, and residue input. Tillage effects can be accommodated but no explicit tool-specific effect on C_s cycling is included. The EPIC and APEX models run Century as the C_s cycling subroutine (Izaurralde et al., 2006) and the turnover rate is accelerated depending on the change in bulk density caused by tillage. C-Farm explicitly considers the effect of each tool on carbon cycling. Century simulates carbon cycling in the top soil only (~0.2 m), without stratification of organic matter within that depth. In contrast, C-Farm simulates the entire soil profile and stratifies carbon inputs, humification and decomposition for each layer.

Other soil carbon specific models such as the Roth-C model (Coleman and Jenkinson, 2005), C-TOOL (a simplified version of CN-SIM, Petersen et al., 2005), ICBM (Katterer and Andren, 1999), and AMG (Saffih-Hdadi and Mary, 2008) have limited applicability for several reasons. The Roth-C model requires defining an inert C_s fraction and has been designed to simulate tilled soils. Nonetheless, Skjemstad et al. (2004) reported that C_s pools in the Roth-C model can be equated to C_s pools obtained by a fractionation scheme, a most desirable feature of C_s models. While results were satisfactory when utilizing the model without modifications, the authors reported the need to change the decomposition rate of the resistant plant material pool to improve simulation results. The models Roth-C, C-TOOL and AMG have no explicit way of considering no-tillage or different tillage sequences. Both ICBM and AMG run on an annual time step and are simpler than Roth-C or C-TOOL. ICBM requires locally determined parameters to account for environmental factors that are not easily transferable to other locations.

Both the simplification relative to input-intensive models such as CropSyst or EPIC, and the more comprehensive approach in C-Farm compared with simpler models (e.g., C-TOOL, ICBM, and AMG) constitute advantageous features that make C-Farm applicable and useful for simulating C_s cycling in farming systems. Except the customized version of Roth-C developed by Skjemstad et al. (2004), no simulation model includes explicitly the carbon present in charcoal; disposal of charcoal generated as a byproduct of biofuel production will require an explicit consideration of this carbon pool. For applications at the farm level exceeding the estimation of the C_s balance and considering production economics, models like FARMSIM (Tittonell et al., 2007) seem appropriate.

5. Model evaluation

Two long-term experiments were selected to test C-Farm. These experiments are the long-term wheat-summer fallow experiments at Pendleton Oregon, in the Pacific Northwest, and the long-term continuous wheat experiment at Rothamsted experiment station in the United Kingdom. A brief description of these experiments follows.

Pendleton, Oregon. This experiment consists of continuous summer fallow winter wheat grown under conventional tillage using moldboard plow. The site is located in the Columbia Plateau, east of the Cascade Range (45°43′17″ N, 118°37′38″ W, 455 m above sea level). Climate is semi-arid with 420 mm of annual precipitation and 10 °C of average temperature. Most precipitation falls in early fall, winter and early spring. Soils are silt loam, coarse silty mixed mesic Typic Haploxerolls (USDA classification system), well drained, with approximately 18% clay and 70% silt in the top horizon. Winter wheat is seeded in early October and harvested in July. Tillage depth is ca. 0.2 m; the soil is plowed in the spring after harvest, with subsequent tillage to control weeds during the fallow phase (disking plus two passes with a cultivator). There is an array of treatments in the experiment. The two results presented here are for continuous winter wheat with no residue burn, unfertilized or fertilized with 90 kg N ha^{-1} crop^{-1}. Soil carbon and nitrogen content have been determined at *ca.* 10 yr intervals and the aboveground residue input reported on an annual basis (Rasmussen and Smiley, 1997).

Rothamsted, UK. The experiments at Rothamsted (Broadbalk experiment) are described in detail elsewhere (Anonymous, 2006), and useful information is provided in Jenkinson et al. (1992). The Broadbalk experiment is located at Harpenden in the United Kingdom (51°48′34″ N, 0°22′23″ W, 130 m above sea level). The weather is temperate, with annual precipitation of approximately 700 mm and average temperature of 9.2 °C, which has increased to 10 °C since 1980. Soils are well or moderately well drained flinty loams (Aquic Paleudalf in the USDA classification system). The data used here belongs to the long-term continuous winter wheat grown with no fertilizer or with 144 kg N ha^{-1} yr^{-1}. The experiments began in the mid 19th century. For the simulated plots, the period 1853–1926 was continuous wheat, the 1927–1962 was wheat-fallow to control weeds, and during 1963–2005 the plots returned to continuous wheat. The tillage sequence totaled six operations per year: plow disk, disking, cultivator, and harrowing in the fall prior to seeding, seeding plus fertilizer application, and harvest in the next summer. During the fallow years three cultivator passes were included for weed control.

Simulations for both Pendleton and Rothamsted continuous wheat plots are shown in Figs. 1 and 2. At Pendleton, although the

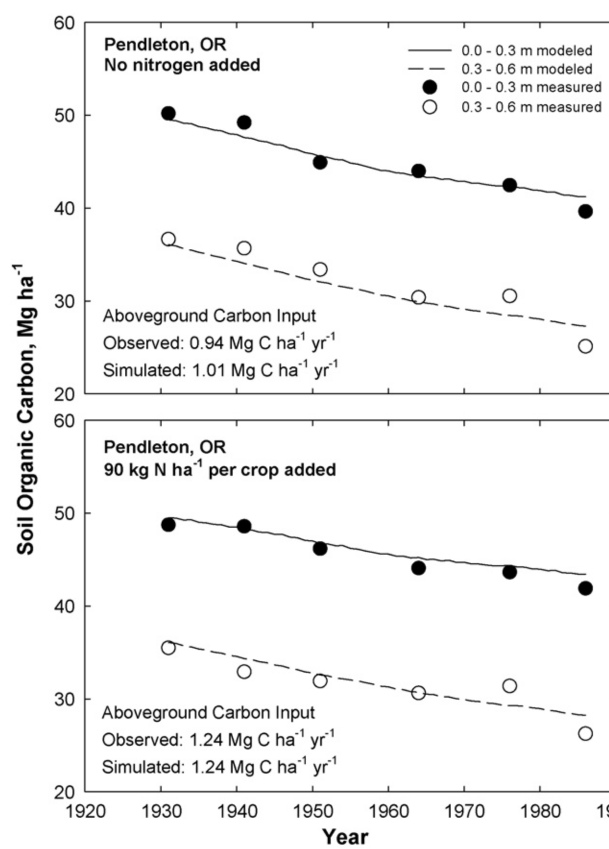

Fig. 1. Observed and simulated carbon evolution at Pendleton, Oregon, for conventionally tilled winter wheat – summer fallow rotation. The upper panel represents a control with no fertilizer added and the lower panel shows data for plots with 90 kg N ha^{-1} crop^{-1} added. Each point is the average of two plots.

model shows a slight overestimation of the documented carbon losses, the trend tracks well the fertilized and unfertilized treatments, and the difference between these two treatments at the end of the simulation period. The decreasing trend of C_s shown between 0.3 and 0.6 m has been accurately captured by the model. The simulated humification rate in the top 0.3 m was 0.14 yr^{-1} and the apparent soil carbon turnover rate was between 1.0 and 1.4% yr^{-1} during the fallow years, when the soil is moist during spring and summer (no crop water uptake), and it was about half those figures during the years with a growing crop. We estimated that by the mid 1980s, the contribution of nitrogen from organic matter mineralization averaged 24 kg N yr^{-1} (assuming an organic matter C/N ratio of 10) or 48 kg N ha^{-1} per crop cycle. The reported N uptake for the non-fertilized treatment was 34 and 9 kg N ha^{-1} per harvest for grain and straw, respectively (Rasmussen and Smiley, 1997), which is equivalent to 43 kg N ha^{-1}.

At Rothamsted, the model represented well the difference between treatments and the simulated C_s trend was within the bounds shown by the data. The downward trend during 1927 and 1962, when carbon inputs were lower due to the fallow years, was well represented by the model (Fig. 2); the detrimental effect of fallow years on C_s is well documented (Rasmussen et al., 1998). The modeled trend of C_s is similar to that presented by (Jenkinson et al. (1992), their Fig. 3) using the Roth-C model.

The degree of independence between modeled and observed results requires comments. In setting up the parameters of the equations determining humification we targeted published information or humification rates calculated from the raw data of long-term experiments such as the Morrow Plots (Darmody and Peck, 1997), the Sanborn Field (Buyanovsky and Wagner, 1997), and those published by Rasmussen and Collins (1991) and Huggins et al. (1998a). Thus, for Pendleton, the humification rates simulated are not entirely independent from the observed data published by Rasmussen and Collins (1991). The apparent soil carbon turnover rate k, however, depends on k_X, which was selected independently based on Andriulo et al. (1999). The temperature and soil moisture effects depend on the energy and water balance and the tillage turnover enhancement, being therefore, independent of the original data set. The effect of the ratio C_s/C_X, which was set arbitrarily and affects k, has no impact on the simulation given the C_s levels. Furthermore, when applying the model, we are accepting that the factor f_e represents appropriately the environmental conditions of each soil layer, but the actual computations depend on the daily temperature and water balance, which in turn depend on the computed runoff, soil water evaporation, plant transpiration, and infiltration, the daily evolution of crop and residue cover, and the effect of tillage tools.

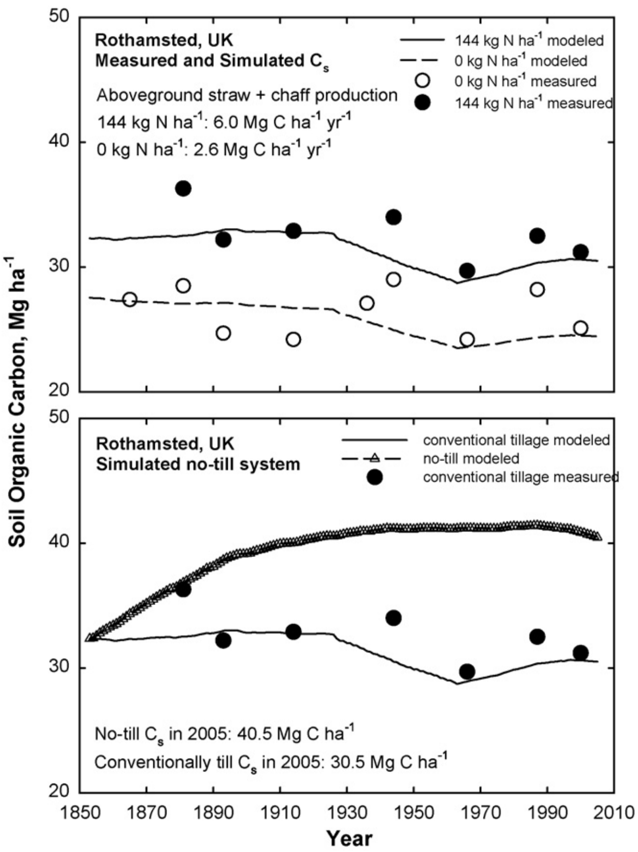

Fig. 2. Observed and simulated soil carbon evolution at Rothamsted, United Kingdom, for conventionally tilled continuous winter wheat with no-nitrogen and with 144 kg N ha^{-1} yr^{-1} (top panel). The years 1853–1926 were continuous wheat, the years 1927–1962 were wheat-fallow to control weeds, and during 1963–2005 the plots returned to continuous wheat. In the bottom panel, a simulation of carbon evolution under no-till is presented superimposed with that of the 144 kg N ha^{-1} yr^{-1} for reference. In the no-till case the simulation was continuous wheat from 1853 to 2005.

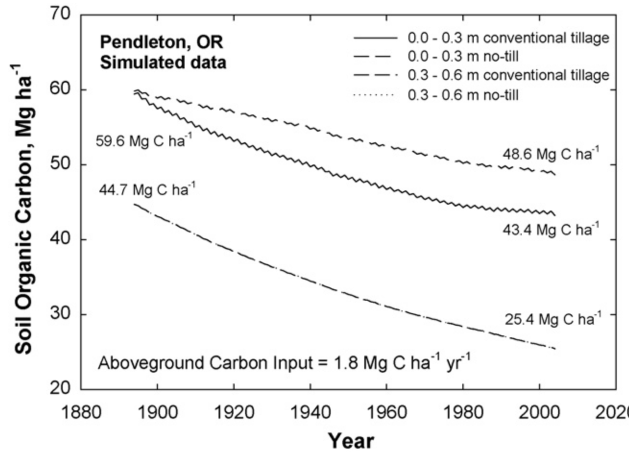

Fig. 3. Simulated soil carbon evolution at Pendleton, Oregon, under conventional till and no-till management. The initial soil carbon corresponds to that of the original sagebrush-grassland undisturbed soil. The rotation was winter wheat – summer fallow with yields adjusted for current technological conditions. It was assumed that, on average, winter wheat crops leave 8.4 Mg of biomass per harvest year, corresponding to average inputs of aboveground residues of 1.8 Mg C yr^{-1}. The numbers on the graph show initial and final soil carbon in the top 0.3 m and in the 0.3–0.6 m layer. The results for the layer 0.3–0.6 m for both systems are the same and only one line is shown.

Regardless, the application of the model requires testing the model with actual data from the region of interest and likely some degree of calibration, as it is the case with any agricultural systems model. However, this task is easy to accomplish with C-Farm given the relative simplicity of the model structure and input requirements.

6. Model applications

In this section, we show two applications of C-Farm to quantify C_s storage rates. First, we use the Pendleton and Rothamsted long-term experiments and compare simulated conventionally tilled and no-till systems. Second we used C-Farm to determine the feasibility of carbon storage in the dryland Pacific Northwest within a region with a gradient of precipitation and different initial C_s.

6.1. Pendleton and Rothamsted plots

For long-term experiments like those at Pendleton and Rothamsted having plots under no-till would have provided extremely

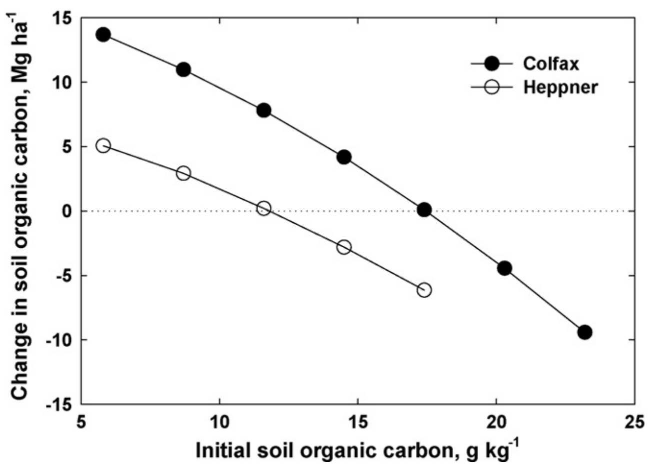

Fig. 4. Simulated 50-year change of organic carbon (C_s) in the top 0.3 m of soil as a function of initial C_s at two locations: Colfax, Washington and Heppner, Oregon. Residue inputs (shoots plus roots) were 3.2 and 1.4 Mg C ha^{-1} yr^{-1} for Colfax and Heppner, respectively.

useful information on the long-term impact of no-till. Lacking those plots, we used the C-Farm model to estimate what would have been the C_s evolution under not till. We initialized the soil with the original C_s before the beginning of agriculture and simulated the evolution of C_s under conventional tillage and no-till using C_i of 1.8 Mg C yr^{-1} of aboveground inputs, commensurate with current technologies. The simulation (Fig. 3) shows that the carbon loss seem to have been inevitable, even under no-till, most likely due to both reduced C_i compared to pre-agriculture perennials and the inclusion of a summer fallow period, in which the soil can be relatively moist and hot during late spring and early summer, in particular with depth. In the top soil, gains of carbon with no-till seem feasible. However, carbon losses in deep layers should be considered carefully, as no-till systems with annual crops may evolve abruptly stratified carbon profile with carbon-rich top layers (top 0.05 m) and carbon-poor layers deeper in the profile (Angers and Eriksen-Hamel, 2008).

At Rothamsted, starting the Broadbalk experiment with not till would have caused C_s gains for about 90 years (Fig. 2), with initial gains of 0.16 Mg C ha^{-1} yr^{-1} that gradually decrease to 0 after 90 years. The new equilibrium C_s simulated was ~40 Mg C ha^{-1} for the top 0.23 m of the soil profile, about 8–10 Mg above that of the conventionally tilled system. Thus, given that the current levels of C_s do not exceed 33 Mg ha^{-1}, C_s gains are possible with conservation tillage provided that carbon inputs do not decrease below current levels. In fact, the plots including additions of 1.9 Mg C ha^{-1} yr^{-1} of plant residues plus farmyard manure at 3.0 Mg C ha^{-1} yr^{-1}, the latter having a larger fraction of recalcitrant carbon than fresh plant residues, have shown initial C gains of 0.3 Mg C;ha^{-1} yr^{-1}, and the system was still gaining C at rates of 0.05 Mg C ha^{-1} yr^{-1} in the last decades (see Jenkinson, 1990, Fig. 4).

6.2. Dryland pacific northwest

In the cropping area of the dryland inland US Pacific Northwest (PNW), the combination of rain patterns, snowdrift, and landscapes with complex topography determines large spatial variation in C_s. Data for the silt loam soils of the area presented by Rodman (1988) show that in cultivated soils, C_s ranges from 40 to 250 Mg C ha^{-1}, with low values in eroded, steep slopes, and high values in depositional positions. The carbon distribution with depth also varies for different soil profiles. As both total C_s and its distribution with depth affect future long-term C_s evolution, initial conditions must be known to estimate with certainty the carbon storage rates.

To assess conditions found by growers in the region, we ran C-Farm for scenarios based on cropping systems information provided by no-till producers (Table 1). These scenarios represent typical rotations for locations with annual precipitation ranging from 350 to 550 mm, providing different levels of residue production. Two initial C_s values for the predominant soil at the location of the producer's farms were considered. The C_s levels correspond to the lower and upper C_s concentration provided by the SSURGO soils database from the US Department of Agriculture, Natural Resources Conservation Service. Simulations were run for 50 years.

Table 1 summarizes the simulation results. Overall, residue inputs increase along with precipitation modulated by rotation

Table 1
Simulated soil organic carbon (C_s) gain or loss in the upper 0.3 m and below 0.3 m of the soil profile as a function of cropping systems and high/low initial C_s at selected locations in the inland US Pacific Northwest. Residue input is total for 50-year simulation periods. For a given rotation and location, residue inputs were forced to the same value regardless of the initial C_s. All cases are direct-seeded dryland farming systems.

Location	Precip.	Rotation*	Residue input		Soil carbon in top 0.3 m			Soil carbon at > 0.3 m		
	mm		Root Mg ha^{-1}	Shoot	Initial	Final	Change	Initial	Final	Change
Cottonwood, Idaho	550	WW-SW-F	45.2	74.5	65.6	59.4	−6.2	24.6	23.2	−1.4
					35.2	41.0	5.8	12.1	12.0	−0.1
		WW-SW-SC	43.0	70.9	65.6	58.9	−6.7	24.6	23.1	−1.5
					35.2	40.3	5.1	12.1	12.0	−0.1
		WC-WW-SC-WW-F	62.6	103.2	65.6	62.0	−3.6	24.6	23.5	−1.1
					35.2	44.9	9.7	12.1	12.5	0.4
Colfax, Washington	500	WW-CF-SW-SB	60.1	99.1	82.3	72.3	−10.0	107.7	88.2	−19.5
					38.5	47.2	8.7	40.6	36.0	−4.6
		MZ-WW-MZ-MZ	67.8	111.9	82.3	73.6	−8.7	107.7	91.2	−16.5
					38.5	48.9	10.4	40.6	37.2	−3.4
		WW-SW-WW-CP	65.0	107.9	82.3	73.4	−8.9	107.7	89.1	−18.6
					38.5	48.6	10.1	40.6	36.4	−4.2
Davenport, Washington	380	SB-SW-SW-WW	48.7	80.4	86.0	76.7	−9.3	133.1	111.6	−21.5
					45.2	50.8	5.6	49.9	45.5	−4.4
Heppner, Oregon	350	WW-F	25.4	41.7	45.1	41.6	−3.5	44.1	35.0	−9.1
					19.7	24.0	4.3	14.7	13.3	−1.4
		SB-SC-SW-CF-WW	26.7	44.1	45.1	42.4	−2.7	44.1	35.8	−8.3
					19.7	24.5	4.8	14.7	13.4	−1.3

* WW—winter wheat, SW—spring wheat, SB—spring barley, MZ—maize, CP—chickpea, F—fallow, SC—spring canola, WC—winter canola, CF—chemical fallow.

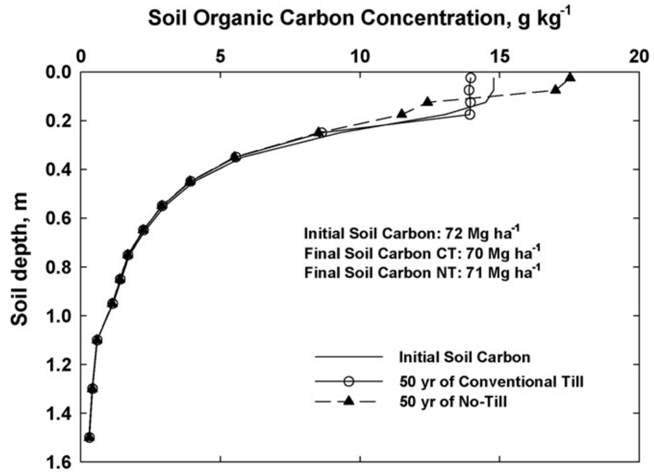

Fig. 5. Stratification of soil carbon after 50 yr of no-till as simulated with the C-Farm model. Both the simulation with conventional tillage (CT) and no-till (NT) started with the same soil profile. Carbon inputs were kept almost identical, although inputs for conventional tillage treatment were slightly (<1%) greater than under no-till. Including shoots and roots, inputs totalize approximately 4 Mg C ha^{-1} yr^{-1}.

intensity and crops in the rotation. In these no-till fields, surface residues decomposed into the top layer (approximately 0.05 m) while roots add carbon preferentially to the top 0.3 m and decreasing amounts further down the soil profile. The 50-year change in C_s showed both gains and losses in the top 0.3 m, with gains obtained with low initial C_s scenarios and vice versa. Below 0.3 m, changes in C_s were always negative, with the carbon loss attenuated when the initial C_s was low.

Fig. 4 shows simulated 50-year C_s gain or loss in the top 0.3 m of soil as a function of initial C_s ranging from 5 and 25 g C kg^{-1} soil, and for high (Colfax, Washington) and low (Heppner, Oregon) residue input conditions under no-tillage. The simulated equilibrium point (no gain or loss) was ∼17.5 and 12.0 g C kg^{-1} soil for Colfax and Heppner, respectively. Growers with soils with current C_s above the equilibrium point will not be able to store carbon, unless technology and improved management allow significant increases in the amount of residue returned – unlikely in these water-limited environments – or perennial crops are included in the system improving the distribution of C_i throughout the profile.

Stratification of carbon plays a significant role in quantifying carbon gains when comparing tillage vs. no-till situations. Simulations performed with C-Farm at Pullman, Washington, for a 1.5 m soil with 72 Mg of C_s representing a summit landscape position show that when starting from the same initial condition, soils under no-till accumulate carbon in the top layer and lose carbon in the bottom layer (Fig. 5) since no replenishment of carbon from crop residues by tillage occurs. Over time, carbon losses in deeper layers can overtake the surface carbon gain moving soils from sinks to sources of CO_2.

7. Concluding remarks

The relatively simple single-pool carbon cycling model implemented in C-Farm and the ability to take into account producer-specific management practices and crop yield statistics are significant advantages over more complex models to evaluate the potential for carbon storage of farming systems under specified local conditions. C-Farm can produce useful and robust estimations of long-term C_s change as shown in the results obtained for experimental plots at Pendleton (Oregon, USA) and Rothamsted (United Kingdom). Further evaluation is desirable to gain confidence in the model transferability among locations and agronomic conditions. Application of C-Farm for no-till cropping systems in the dryland inland US Pacific Northwest highlighted that the main factors defining carbon storage potential in this region are initial C_s (low better than high) and residue input to the soil (high better than low). In the process of evaluating the local potential for carbon storage, greater certainty will be achieved with accurate knowledge of initial C_s, crop yield statistics, tillage operations, and crop sequence.

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