CropSyst Simulation of the Effect of Tillage and Rotation on the Potential for Carbon Sequestration and on Nitrous Oxide Emissions in Eastern Washington Agriculture.

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Introduction

Concern has been growing over the past several decades regarding global climate change. Mounting evidence indicates that global warming is a reality (Hamlet et al., 2005; Mote, 2006). Much research has focused on agriculture's impact on global climate change (Williams et al., 1992; Matson et al., 1998; Mosier, 1998; Smil, 1999; Robertson et al., 2000). Duxbury (1994) estimated that agriculture (both land clearing and current management) account for 25%, 65% and 90% of anthropogenic emissions of CO_2, CH_4 and N_2O, respectively. We need to evaluate how agriculture might help mitigate the deleterious effects of global climate change.

Numerous researchers have investigated how agricultural practices could enhance carbon sequestration to help mitigate global warming (e.g., Bruce et al., 1999; Lal et al., 1999; Allmaras et al., 2000; Deen and Kataki, 2003). Conventional tillage (CT), which imposes considerable disturbance on the topmost layer of soil, warms the soil by reducing surface residue. CT also aerates the surface layer of soil and breaks up soil aggregates, and these effects enhance the microbial activity that feeds on and reduces the quantity of soil organic carbon (SOC). CT also incorporates surface residue into the soil where the residue decomposes rapidly. The residue decomposition products enter the SOC pool. Crop rotations that increase the production of residue therefore stand to contribute more to SOC. Some (e.g., Allmaras et al., 2000) suggest that a shift from CT to no-tillage (NT) management will increase carbon sequestration. In theory, such an increase seems reasonable since the lack of tillage would likely reduce oxidation of soil organic matter in the upper layer of soil affected by the tillage. The mechanism involved relates to a degree of physical protection of SOC from microbial attack (Balesdent et al., 2000; Six et al., 2004a), protection that is reduced by tillage that breaks up soil aggregates.

It is, however, common to overstate the potential benefits of NT based on studies that only sample a shallow soil depth where the residue input concentrates under NT (Baker et al., 2007; Angers et al., 1997). Deen and Kataki (2003) and Yang and Wander (1999) provide evidence that the relative advantage of NT over CT exists only in the upper portion of the soil profile, and that carbon is lost below the very shallow depth that receives surface residue inputs in NT. A comprehensive data analysis (West and Post, 2002) showed a significant increase in SOC when comparing NT with CT for the soil depth 0-7cm (n=59). The increase reduced dramatically for the 7-15 cm depth (only 15% on average of the difference observed at 0-7cm depth, n=55), and no significant difference in SOC was found for lower depths. Hassink and Whitmore (1997) argued that the net rate of accumulation of SOC depends not on the protective capacity of a soil *per se* but on the extent to which this capacity is already occupied by organic matter. They suggest that the concentration of residue input into the top few centimeters of soil in NT systems could saturate the potential for physical protection of SOC. The remaining non-protected SOC would be subject to somewhat enhanced decay. In addition, deeper layers within the CT till zone that have received surface residues for many years are likely to lose SOC after NT conversion and essentially no surface residue input. The balance between a faster SOC decay due to tillage (e.g., Yang and Wander, 1999) and the effect of a different distribution of residues will determine the relative performance of CT and NT systems regarding carbon sequestration potential.

Changes in N_2O fluxes have the potential to offset carbon gains since N_2O has 298 (100-yr time horizon) times the global warming potential of CO_2 (Forster et al., 2007). However, it is unclear whether switching from CT to NT management has an overall effect on N_2O emissions. Six et al. (2004b) concluded that N_2O fluxes were higher under NT than under CT, but the trend eventually reversed in humid climates. Greater soil compaction and higher soil bulk density associated with NT help drive higher N_2O emissions. In wet regions where ample soluble carbon is available and where fertilizer rates are high, higher N_2O emissions can occur under NT than CT (Dalal et al., 2003). Other researchers have found evidence for lower emission from NT compared to CT (Chatskikh and Olesen, 2007; Kroeze et al., 1999), so it is not possible to reach a general conclusion without evaluating closely the conditions under which the conclusions of different studies were drawn.

Comparisons of CT and NT carbon sequestration potential require accounting for tillage effects on SOC decomposition. As discussed by Balesdent et al. (2000) and Six et al. (2004a) physical protection of SOC associated with soil macro- and micro-aggregates is reduced by the perturbation created by tillage operations, thus enhancing the oxidation of SOC. Although studies of tillage effects on carbon pools in soil aggregates are available, along with some associated information on SOC decomposition rates (Beare et al., 1994), the data are generally insufficient to provide much guidance for modeling efforts designed to estimate SOC changes under tillage. In addition, tillage intensity (degree of perturbation) is variable for different tillage practices. In this study, we have chosen reasonable but arbitrary lower and upper boundaries of tillage effects on SOC oxidation rates to obtain a range of NT – CT soil organic carbon changes (ΔSOC) after NT adoption.

The process of C sequestration is highly variable and depends on numerous factors that are not easy to evaluate empirically. Computer simulations are a practical approach to obtain meaningful conclusions concerning the long-term effects of agricultural management practices on global warming potential (Dalal et al., 2003). Simulations allow conditions and factors to be standardized or isolated for meaningful comparisons.

We applied a cropping systems simulation model, CropSyst (Stöckle et al., 1994, 2003), to evaluate the long-term effects of reduced tillage intensity on net SOC conservation and N_2O emission for selected cropping systems in eastern Washington. CropSyst is a process-oriented, robust model based on mechanistic principles, allowing for applications to a large number of crops in any world location. CropSyst is a multi-year, multi-crop, daily time step cropping systems simulation model developed to serve as an analytical tool to study the effect of climate, soils, and management on cropping systems productivity and the environment. CropSyst simulates soil-plant-atmosphere water and nitrogen dynamics, crop phenology, canopy and root growth, biomass production, crop yield, residue production and decomposition, soil erosion by water, and salinity. These processes are affected by weather, soil characteristics, crop characteristics, and cropping system management options including crop rotation, cultivar selection, irrigation, nitrogen fertilization, soil and irrigation water salinity, tillage operations, and residue management. Depending on the process, CropSyst calculations are made at hourly or daily time steps.

The model has been evaluated and used in the US Pacific NW (e.g., Pannkuk et al., 1998; Peralta and Stöckle, 2002; Marcos, 1997; Marcos, 2000; Jara and Stöckle, 1999; Stöckle and Jara, 1998; Kemanian, 2003; Kemanian et al., 2007) and in many world locations (e.g., Stöckle et al., 1994, Stöckle et al., 2003; Pala et al., 1996, Donatelli et al., 1997; Stöckle et al, 1997, Stöckle and Debaeke, 1997; Sadras, 2004; Monzon et al., 2006; Wang et al., 2006; Benli et al., 2007; Todorovic et al., 2009).

Other cropping system models have been developed in the US including DSSAT (Jones et al., 1998) EPIC (Williams et al., 1984), and RZWQM (Ahuja et al., 2000), and elsewhere including STIC (Brisson et al., 2003) and APSIM (McCown et al., 1996), but none of them have been tested in the US PNW. For more information on cropping systems models, readers are referred to a special issue of the European Journal of Agronomy (van Ittersum and Donatelli, 2003). CropSyst is the only model in this group that calculates biomass gain based on crop transpiration and transpiration-use efficiency, an approach that has been shown more robust than the radiation capture and radiation-use efficiency approach used by other models (Steduto and Albrizio, 2005; Steduto et al., 2007; Stöckle et al., 2008). Estimating crop growth and yield as a function of water is particularly advantageous for applications in dryland regions.

Reviews of models for estimating SOC dynamics have been presented by Powlson et al. (1996), Molina and Smith (1998), and Shaffer et al. (2001), including single-pool and multiple-pool models. Multi-pool models separate SOC into pools with different turnover rates. Each pool decomposes due to microbial attack at different rates assumed to depend on SOC chemical recalcitrance and physical protection. An important fraction of the carbon released by decomposition of SOC in a given pool leaves the soil as CO_2 from microbial respiration, and the remainder is transferred to the microbial biomass pool or another carbon pool through chemical reactions or physical aggregation (Kemanian and Stöckle, 2010). As discussed by Kemanian and Stöckle (2010), multiple-pool models have several limitations (e.g., SOC has a continuum of chemical and physical characteristics and interactions, which is difficult to represent by prescribed pools), nevertheless they have been widely used and proved useful for assessing soil carbon evolution.

The Verberne model (Verberne et al., 1990; Whitmore et al., 1997) and the Century model (Parton et al., 1988; Parton et al., 1994) are among the most comprehensive SOC models, allocating SOC into multiple pools with specified decomposition rates and C/N ratios, and with specified transfer coefficients of C and N among pools. The Verberne model was designed to simulate soil organic matter dynamics using a multiple pool approach based on previous efforts by van Veen (e.g., van Veen and Paul, 1981; van Veen et al., 1984).

Century is an ecosystem model developed to estimate soil carbon changes on the top 20-cm of soil and under different types of vegetation including agricultural crops. The model performs calculations using a monthly time step and it simulates crop residue inputs using simple crop growth functions. More recently, a daily-time-step version was developed to allow the estimation of short-term trace gas fluxes from different ecosystems. US cropping systems models such as DSSAT (Gijsman et al., 2002) and EPIC (Izaurralde et al., 2006) have incorporated algorithms from Century to allow the evaluation of carbon sequestration in response to cropping systems. We have followed a similar approach by incorporating soil carbon dynamics concepts from the Verberne and the Century models, (see below). The result is an increase in the capabilities of CropSyst, allowing the model to estimate SOC sequestration potential in response to cropping systems and its effect on residue input and SOC accumulation and decay.

The Model

Additional information on CropSyst can be found in Stöckle et al. (1994, 2003), and other sources given above. We will briefly refer here to the SOC model, which describes the decay and humification of organic residues (crop, manure, wastewater solids, etc.), which are either on the soil surface, in the soil as root residue or incorporated into the soil by tillage, and the loss and gain of SOC allocated to multiple pools and soil layers.

A diagram of the SOC model in CropSyst is presented in Fig. 23.1. The following pools (Table 23.1) are included in the model, with a separate set of pools defined for each soil layer.

Figure 23.1. Pattern of carbon flows modeled by CropSyst.

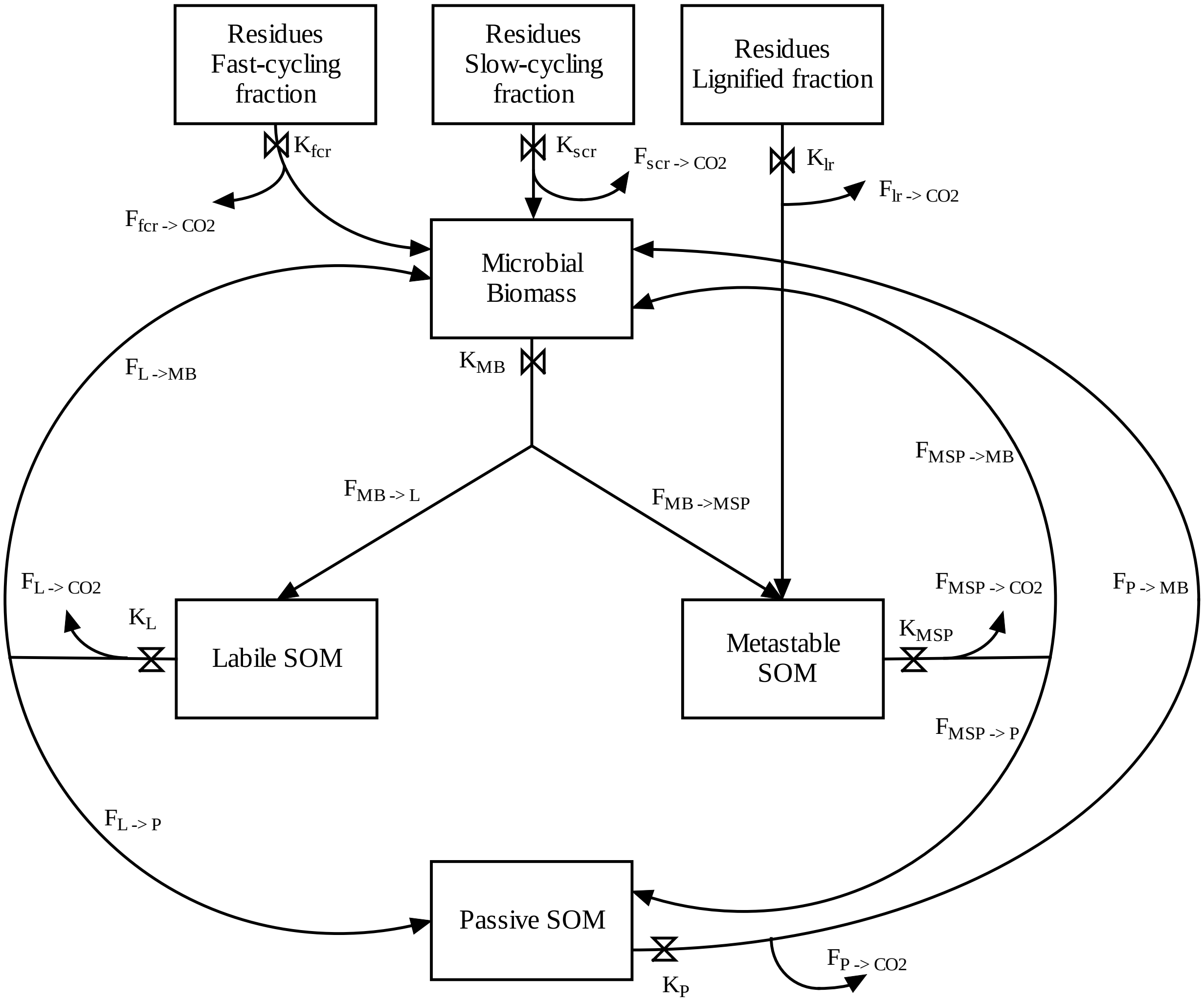


Table 23.1. Carbon pools that are modeled in CropSyst in each soil layer.

Pool	**Description**	**C/N ratio**
fc_r	Fast-cycling organic residue	10
sc_r	Slow-cycling organic residue	Variable
l_r	Lignified organic residue	100
MB	Microbial biomass	8
L	Labile soil organic matter	15
MS	Metastable soil organic matter	12
P	Passive soil organic matter	10

Decomposition of organic residues and organic matter follows first-order kinetics with the decomposition constants (day^{-1}) shown in Table 23.2. A non-microbial decomposition rate can be added to account for physical detritions of surface residue. Except for the passive pool the decomposition constants in Table 23.2 are similar to those proposed for the Verberne/MOTOR model (Whitmore et al., 1997). Our passive-pool decomposition constant was set after several hundred-year runs for conventional tillage practice for all locations/cropping systems in this study (see below) so as to obtain a fraction of passive SOC of 50% to 60% of the total SOC (Gjisman et al., 2002) at near equilibrium. The resulting value is within the range given by Whitmore et al. (1997) and Verberne et al. (1990) for the Verberne model, and is similar to the value of ~500 years turnover time (range 200 to 1500 years) suggested for the Century model (Parton and Rasmussen, 1994).

Table 23.2. Decomposition constants for residue and SOC pools modeled in CropSyst.

Pool*	Notation	Decomposition constant (day^{-1})
		Residue Pools
fc_r	K_{fcr}	0.2
sc_r	K_{scr}	0.1
l_r	K_{lr}	0.02
		SOC Pools
MB	K_{MB}	0.05
L	K_L	0.015
MS	K_{MSP}	0.0009
P	K_P	0.000005

*Abbreviations as in Table 23.1

A significant fraction of the carbon resulting from the decomposition of the different pools is lost as CO_2, and the rest is transferred to other pools (Fig. 23.1) according to the following transfer coefficients, where $F_{X\text{->}Y}$ represents the fraction of carbon transferred from pool X to pool Y and other abbreviations are as in Tables 23.1 and 23.2.

Residue transfer coefficients

$F_{fcr \to CO2} = 0.6$ $F_{fcr \to MB} = 1 - F_{fcr \to CO2}$

$F_{scr \to CO2} = 0.7$ $F_{scr \to MB} = 1 - F_{scr \to CO2}$

$F_{lr \to CO2} = 0$ $F_{lr \to MSP} = 1$ $F_{lr \to MB} = 0$

Microbial biomass transfer coefficients

$F_{MB \to MSP} = 0.5 / (1 + (Sand\_Fraction / 0.4)^3)$

$F_{MB \to L} = 1 - F_{MB \to MSP}$

$F_{MB \to P} = 0$

Labile SOM transfer coefficients

$F_{L \to P} = 0.001$

$F_{L \to CO2} = 0.75 (1 - F_{L \to P})$

$F_{L \to MB} = 0.25 (1 - F_{L \to P})$

Metastable SOM transfer coefficients

$F_{MS \to P} = 0.01$

$F_{MS \to CO2} = 0.8 (1 - F_{MS \to P})$

$F_{MS \to MB} = 0.2 (1 - F_{MS \to P})$

Passive SOM transfer coefficients

$F_{P \to CO2} = 0.8$

$F_{P \to MB} = 1 - F_{P \to CO2}$

The carbon transferred among pools also determines the nitrogen transfer, which is equal to the amount of nitrogen required to preserve the carbon/nitrogen ratio of the receiving pools. In this process, if the amount of nitrogen released by the decomposing pool is greater than the amount of nitrogen required by the receiving pools, mineral nitrogen in the form of ammonium is released to the soil layer (mineralization). If the opposite is true, ammonium (first source) and nitrate (secondary source) from the soil layer is taken up for microbial consumption (immobilization). If not enough mineral nitrogen is available in the soil to supply the microbial demand, the decomposition is reduced in all pools proportionally to the fraction of immobilization demand not satisfied.

CropSyst includes calculations to estimate nitrogen uptake, nitrogen movement with water, nitrogen interaction with the soil matrix, and nitrogen transformations. Nitrous oxide emissions from denitrification are based on concepts described by del Grosso et al. (2000). Emissions of N_2O due to nitrification are modeled separately (Maag and Vinther, 1996).

The effect of tillage was calculated as described by Kemanian and Stöckle (2010), based on soil disturbance ratings (SDR) used by the US Department of Agriculture Natural Resource Conservation Service (USDA NRCS, 2002) to characterize a large number of operations including mechanical operations other than tillage. Each operation is given a rating from 0 to 30, with the lower ratings associated with operations that gently disturb the soil, and the higher ratings (25 to 30) to high soil disturbance operations such as offset disks, moldboard plows, and other operations that aggressively break up soil aggregates. SDR increases with each operation and decreases as a function of time and soil water content at a rate ~2% per day for a soil at field capacity (Kemanian and Stöckle, 2010). The value of SDR and the soil clay content are used to determine a tillage adjustment factor ($F_t > 1$) that multiplies the SOC decomposition constant of all pools to enhance SOC decay. The adjustment factor is calculated as follows:

$$F_t = 1 + [F_{cx} + (F_{sx} - F_{cx}) \exp(-5.5 f_{clay})] [1 - \exp(-0.025 C_{SDR})] \qquad \text{[Eq. 1]}$$

where

F_t = SOC decomposition rate adjustment factor due to tillage

F_{cx} = Maximum adjustment factor for clay soil

F_{sx} = Maximum adjustment factor for sandy soil

f_{clay} = Soil clay fraction

C_{SDR} = Cumulative soil disturbance rate.

For this study, Eq. 1 was parameterized to obtain a lower and a higher boundary of SOC oxidation enhancement due to tillage and other operations. For the lower boundary, F_{cx} and F_{sx} were set to 0.5 and 1.5, respectively, while these factors were 2 and 6 for the higher boundary. These settings provided a maximum enhancement of ~1.8 (lower boundary) and ~4 (higher boundary) immediately after a typical set of heavy tillage operations for the silt loam soils in the drylands of the study region. The approach of increasing SOC decomposition constants to account for tillage effects is commonly used in SOC models (Balesdent et al., 2000; Krull et al., 2003).

For example, in an application using the Century model for a loamy Acrisol in Brazil, parameters for cultivation effects were adjusted from the default value of 1.6 to 5.0, and the duration of the tillage effect was also increased from one month to a few months after tillage, adjustments that were done to improve the simulation of tillage effect on SOC decomposition (Carvahlo Leite et al., 2004). There is enough uncertainty associated with the effect of tillage on SOC decomposition to justify the use of boundaries as done in this study.

Methodology

The locations, crop rotations and tillage intensities simulated in this study are presented in Table 23.3. Lind, St. John and Pullman are all in the eastern Washington dryland production zone; Paterson is irrigated. Pullman was the only location that included simulations of two crop rotations (Table 23.3). Subsequently, the Pullman rotation that included spring barley will be designated, Pull-b, and the rotation with spring pea will be designated, Pull-p.

Table 23.3. Eastern Washington locations, average annual rainfall, tillage intensities and crop rotations simulated by CropSyst.

Location	**Rainfall (mm)**	**Tillage intensities**†	**Crop rotation**‡
Lind	250	CT, RT	WW - SF
St. John	435	CT, NT	WW – SB - SF
Pullman	550	CT, RT, NT	WW – SB - SW
Pullman	550	CT, RT, NT	WW – SW - SP
Paterson	Irrigated	CT, RT	SC – SC - P

†CT – conventional tillage; RT – reduced tillage; NT – no tillage

‡WW – winter wheat; SF – summer fallow; SB – spring barley; SW – spring wheat; SP – spring pea; SC – sweet corn; P – potato

Most of the parameters used to define each crop at each location were taken from CropSyst default values, and some were calibrated to reproduce the phenological stages for the selected crop cultivars at a given location and to match within 5% the target yields (Appendix Table 23.A1) specified for each crop at each location (Painter, 2009), thus ensuring that crop development and residue production were consistent with field observations. Field operations that defined each set of tillage options are presented in Appendix Table 23.A2. Crop tissue characteristics that affected residue decomposition for each crop are presented in Appendix Table 23.A3.

Although the simulations are identified with particular locations, no particular spot in the landscape is simulated. The topography of the region is very complex, consisting of rolling hills with varying aspects and slopes, leading to differences in irradiance, soil water content, soil temperature, crop yields and residue production. In addition, agricultural soils in the region have been redistributing and losing carbon since the inception of agriculture about 150 years ago, and different locations and positions in the landscape are in different stages in the process of reaching equilibrium with the prevailing wheat-based conventional tillage systems. Thus, switching from CT to NT will lead to situations with different initial SOC, residue input, and equilibrium conditions. For this reason, all simulation runs for each crop rotation/location were initialized with values of SOC and its distribution among pools after equilibrium with the residue input was reached and the passive carbon pool in the top 30 cm of soil had stabilized within the range of about 50 – 60% of the total soil carbon. Since CT prevailed in the region for most of the time since ground breaking, the equilibrium was established using CT scenarios. This approach provided a standardized basis to evaluate the conversion of CT to RT or NT. Our initial conditions of SOC and carbon partitioning among the various carbon pools are presented in Appendix Tables 23.A4 and 23.A5.

Conversion to RT or NT was simulated for 30 years in all cases. The change in SOC (ΔSOC) resulting from conversion to NT (or RT) was calculated as $\Delta SOC = NT_{SOC} - CT_{SOC}$. The weather data used to drive the simulations were based on current weather patterns, i.e., climate change over the simulation period was not considered. Weather data were simulated from a base of historic data using the weather data generating program, ClimGen (Castellvi and Stöckle, 2001). ClimGen generates daily precipitation, daily maximum and minimum air temperatures, solar radiation, air humidity and wind speed.

Although our main intent was to examine the potential for changes in tillage, and to a lesser extent, rotation, to alter the SOC conservation potential, N_2O emissions were also evaluated. We conducted 2 complete sets of simulations using the lower and higher boundaries of change in SOC decomposition rates due to tillage discussed in the model description section above. Both sets used the same environmental conditions, crop rotations and tillage intensity.

Results and Discussion

Figure 23.2 shows average annual ΔSOC in the top 15 cm of the soil profile for 12- and 30-year time spans. All locations showed a gain in SOC relative to CT with decreasing intensity of tillage. The same trends that were apparent in the lower boundary runs were also apparent in the upper boundary runs (Fig 23.2). By increasing the oxidation rate of SOC due to tillage, the difference between CT and RT or NT was larger (cf. Fig 23.2A, 23.2B), but the difference was not particularly large, generally no more than about 0.05 Mg CO_2e ac^{-1} yr^{-1}. Less severe tillage management, whether RT or NT, provided greater C benefits when evaluated over 12 years than when evaluated over 30 years. In fact, the largest gain for NT takes place during the first 6 years, particularly if steady state surface residue buildup is accounted for (see below), as shown in Figure 23.3 for Pul NT-b scenario. This trend is explained by the dynamics of SOC after the implementation of less intense tillage. When CT is replaced with either RT or NT, C accumulates rapidly in the top 15 cm of soil, but the rate of change decreases with time as SOC approaches a new steady state consistent with the new tillage environment. Since no NT operations extend below 15 cm, this upper soil layer is where the benefits of NT are concentrated.

Figure 23.2. Simulated annual ΔSOC obtained by converting from CT to either RT or NT in the top 15 cm of soil for 12- and 30-year time spans for various tillage intensities and crop rotations at four locations in eastern Washington State. Lnd = Lind; SJ = St. John; Pul = Pullman; Pat = Paterson; RT = reduced tillage; NT = no tillage; -b or –p = barley or pea in the rotation (see Table 23.3).

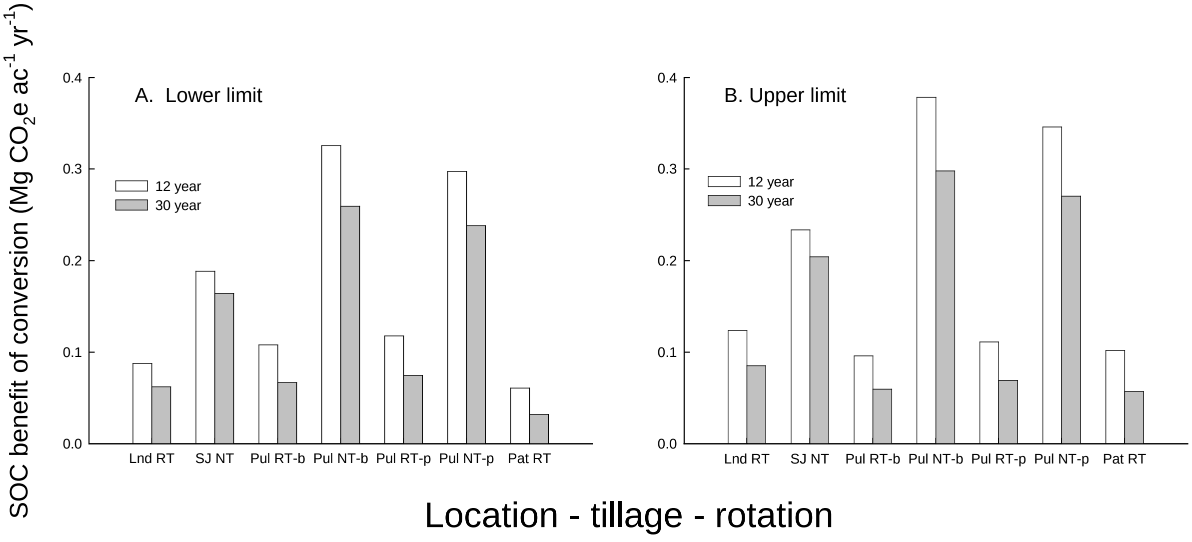
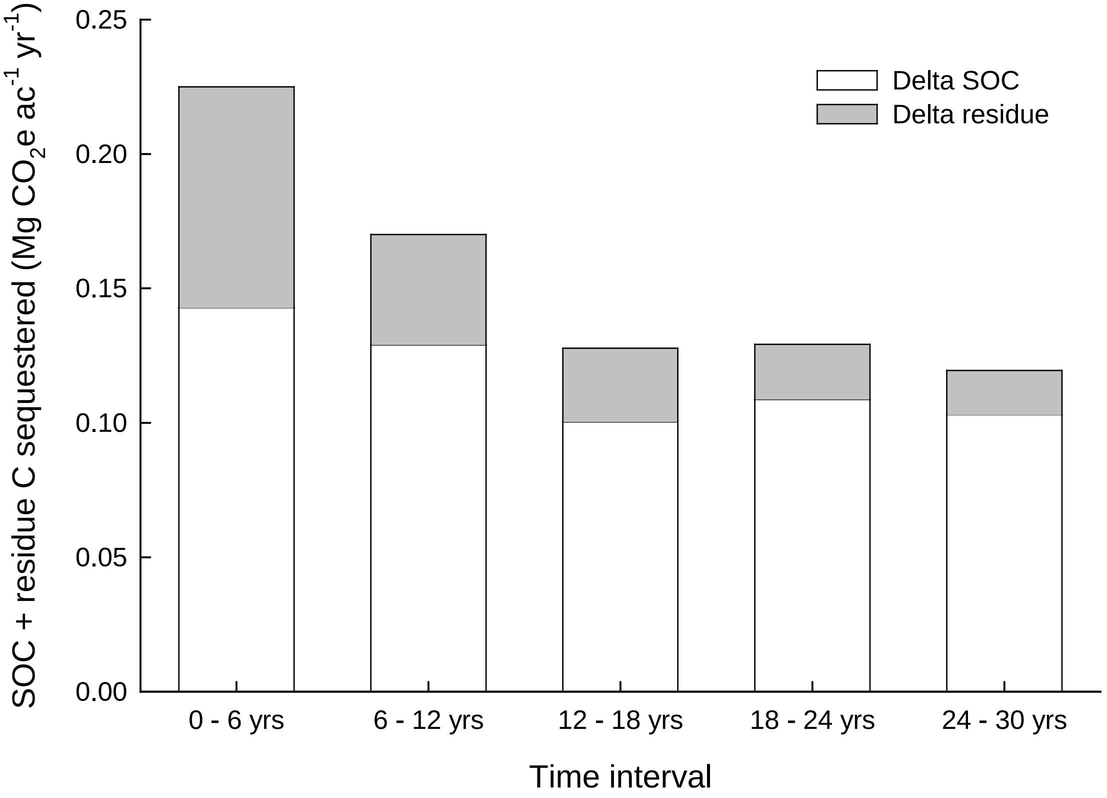


Figure 23.3. Simulated annual ΔSOC with Δ residue carbon obtained by converting from CT to either RT or NT in the top 30 cm of soil for 6-year increments for the Pullman-b NT rotation in eastern Washington state.



Average annual ΔSOC in the top 30 cm of the soil profile for 12- and 30-year time intervals are presented in Figure 23.4. In Lind under RT, the annual soil C benefit was nearly identical when considered in the top 30 cm of soil and in the top 15 cm (cf. Figs. 23.2 and 23.4). This result indicated that soil C was neither being gained nor lost between 15 and 30 cm relative to CT. Other dryland scenarios had lower rates of annual ΔSOC in the top 30 cm compared with the top 15 cm, indicating that C was being lost from the 15-30 cm layer relative to CT. This is to be expected because NT, and to some extent RT, does not add residues from the soil surface below a few centimeters, while CT distributes incorporated residue to deeper depth. In all locations and rotations except in Pullman RT-b , a reduction in tillage intensity resulted in positive ΔSOC in the top 30 cm of soil. The exception for RT-b in Pullman is because there is still enough tillage in this scenario that the difference between RT and CT is not that great (Table 23.A5). Overall, the difference between the lower and higher boundaries of tillage impact is larger for the 0-30 cm than the 0-15 cm analysis.

Figure 23.4. Simulated annual ΔSOC obtained by converting from CT to either RT or NT in the top 30 cm of soil for 12- and 30-year time intervals for various tillage intensities and crop rotations at four locations in eastern Washington State. Lnd = Lind; SJ = St. John; Pul = Pullman; Pat = Paterson; RT = reduced tillage; NT = no tillage; -b or –p = barley or pea in the rotation (see Table 23.3).

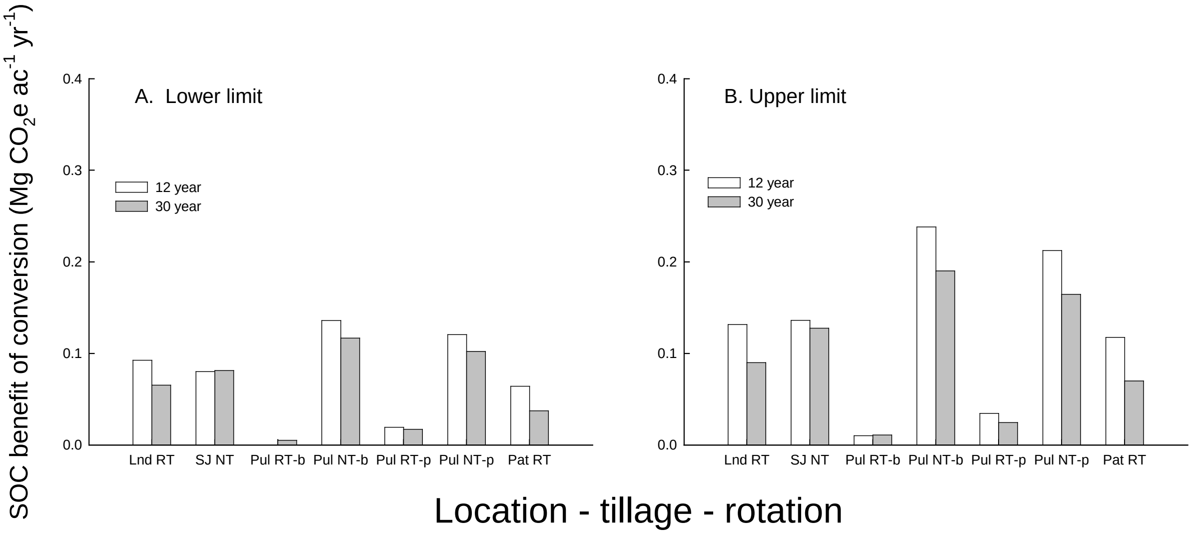
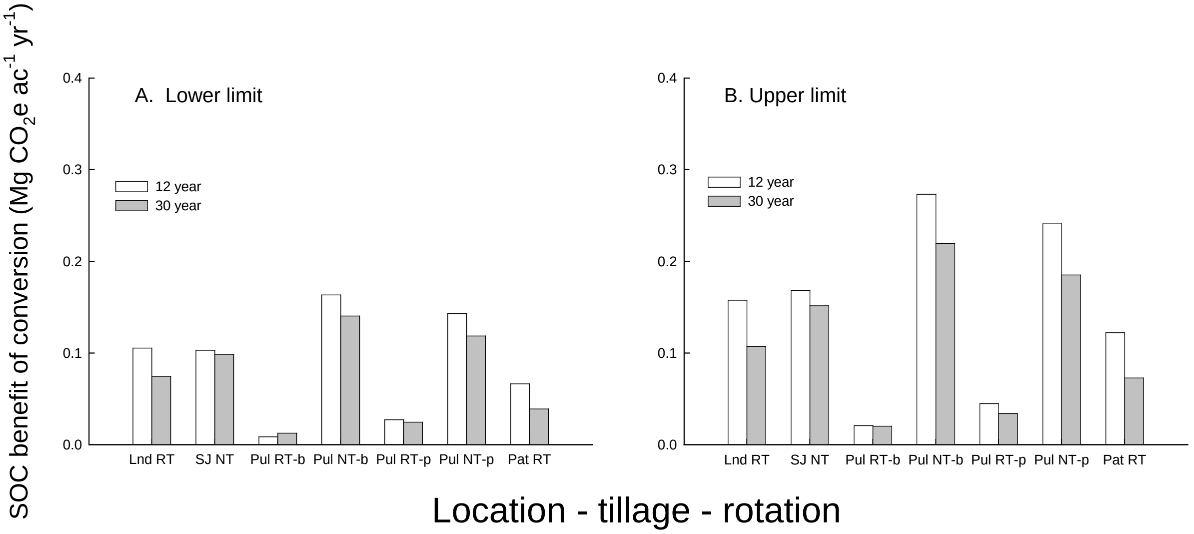


Figure 23.5 presents average annual ΔSOC from conversion for the entire soil profile. Trends in ΔSOC were virtually identical whether examined in the top 30 cm or in the entire profile (cf. Figs. 23.4, 23.5), but the rate of soil C benefit when evaluated over the entire profile was slightly higher (with the exception of Paterson) than when evaluated over the top 30 cm (cf. Fig. 23.4, 23.5). That the differences were relatively small was an indication that this large bulk of deeper soil (0.3 to 1.7 m) had little influence on the outcome of converting to RT or NT. Except for the minor effects on temperature and soil water below 30 cm, the root residue input is not expected to be much different for CT and NT. Qin et al (2005) reported root length density of corn being larger for NT than CT for the first 10 cm, but the opposite was true from 10 to 25 cm. They took no measurements below 25 cm. A similar trend was found for winter wheat (Qin et al., 2004) in the top layer of soil, but no difference between CT and NT root length density was found below 30 cm.

Figure 23.5. Simulated annual ΔSOC obtained by converting from CT to either RT or NT in the entire soil profile for 12- and 30-year time spans for various tillage intensities and crop rotations at four locations in eastern Washington State. Lnd = Lind; SJ = St. John; Pul = Pullman; Pat = Paterson; RT = reduced tillage; NT = no tillage; -b or –p = barley or pea in the rotation (see Table 23.3).

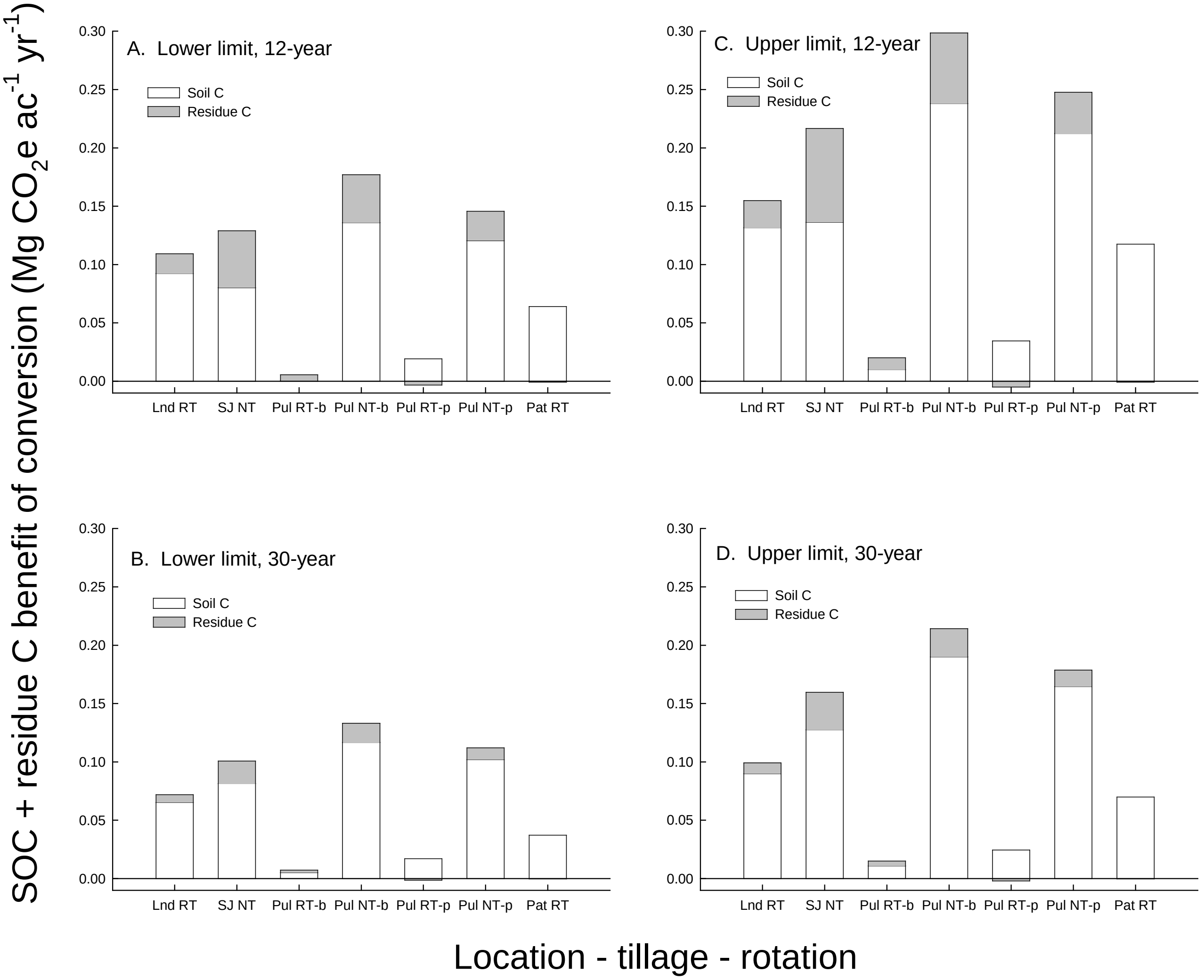


Taken together, Figures 23.2, 23.4 and 23.5 present evidence not only that reduced tillage intensity benefits soil C, but that for proper comparison of CT and RT or NT carbon dynamics need to be considered to a soil depth of 30 cm. In cool, humid eastern Canada, NT led to increased soil C, relative to CT with moldboard plowing, in the top 20 cm of the soil profile, but led to decreased soil C between 20 and 40 cm (Angers et al., 1997). Baker et al. (2007) also concluded that studies need to consider more than just the top few centimeters of soil. Deen and Kataki (2003) concluded that zero tillage management increased soil C (relative to chisel and moldboard plow treatments) “only for the surface layer, but not for the entire profile.”

Figures 23.2, 23.4 and 23.5 present only SOC. An additional source of C is that contained in residue, i.e., dead but non-decomposed plant material derived from both shoots and roots. The total amount of carbon retained by a farming system is the sum of ΔSOC and the C contained in the system’s residue. Residue contained within a given field varies considerably from season to season and year to year, but a long-term steady state amount can be counted as contribution toward C storage, providing some additional advantage to NT systems. CropSyst simulates above- and below-ground residue levels at a daily resolution. We took residue C to be the minimum amount of residue, both above- and below-ground, that existed 95% of the time for the last 27 years of the 30-year simulations. Since CropSyst output does not separate below-ground residue among soil layers, the below-ground residue reported here is for the entire soil profile. Residue differences due to tillage below 30 cm are not large, however, so assessing residue for the entire profile will have minimal effect on our analysis. This amount of residue C was divided by 12 for its annual contribution to total C in the 12-year analysis. It was divided by 30 for the 30-year analysis.

The addition of Δ residue to the annual rate of ΔSOC for 0 – 30 cm is presented in Figure 23.6. The ratio of residue C to SOC was much higher over a 12-year period than a 30-year period because the same quantity of residue was divided by 12 or 30, respectively. Not surprisingly, the residue contribution was greatest under NT. A conversion to RT conserved little to no additional C over that in SOC alone, except in Lind where several CT fallow tillage operations were replaced with herbicides under RT (Appendix Table 23.A5). Tillage incorporates surface residue into the soil where decomposition is more rapid, so the less tillage that occurs, the more residue there will be, all else being equal. The exceptions were seen in Pullman with pea in the rotation, and in Paterson. Pea does not produce much residue, and the residue produced decays rapidly. So conversion to RT with pea in the rotation obtains no benefit from the consideration of residue C (Fig. 23.6). The same was true for Paterson because potato residue decomposes rapidly, and because, with potato in the rotation, substantial soil disturbance still occurred during potato field preparation and harvest.

Figure 23.6. Simulated annual ΔC obtained in the top 30 cm of soil by converting from CT to either RT or NT for both soil organic C and residue C at 12- and 30-year periods for various tillage intensities and crop rotations at four locations in eastern Washington State. Lnd = Lind; SJ = St. John; Pul = Pullman; Pat = Paterson; RT = reduced tillage; NT = no tillage; -b or –p = barley or pea in the rotation (see Table 23.3).



From the standpoint of C benefits, several important observations can be made on the basis of simulated results presented in Fig. 23.6. Regardless of location or rotation, there was a benefit to conversion to RT or NT from CT. The most favorable time frame for the calculation of the rate of C benefit was the shorter 12-year time frame. Under the most favorable conditions of location and rotation, CropSyst predicted a benefit of carbon storage in the top 30 cm of about 0.24 (0.30 if residues are accounted for) Mg CO_2e ac^{-1} yr^{-1}. The benefit of conversion to RT was much greater in Lind than in Pullman. Conversion to NT provided substantially greater benefits than conversion to RT, which is consistent with the findings of West and Post (2002) based on a large global data analysis of C sequestration in response to tillage. Although residue C was a significant contribution to the total C conserved, the pool of residue C can be particularly ephemeral. Even one tillage operation, such as disking to control an outbreak of weeds or to prepare a seedbed, could destroy most of the surface residue and, to the depth of tillage, accelerate the decomposition of below-ground residue.

In the CropSyst simulations, the amount of N applied to the crops was the same within location and rotation. The average annual N applied was 40, 67, 113, 80 and 191 kg N ha^{-1} for Lind, St. John, Pullman-b, Pullman-p and Paterson, respectively. Any differences in total N availability within a location/rotation were therefore due to differences in the net amount of N mineralized (total mineralization minus immobilization). Table 23.4 shows a consistent trend of decreasing net mineralization with decreasing tillage intensity. As discussed above, tillage creates conditions that favor decomposition. These same conditions favor N mineralization.

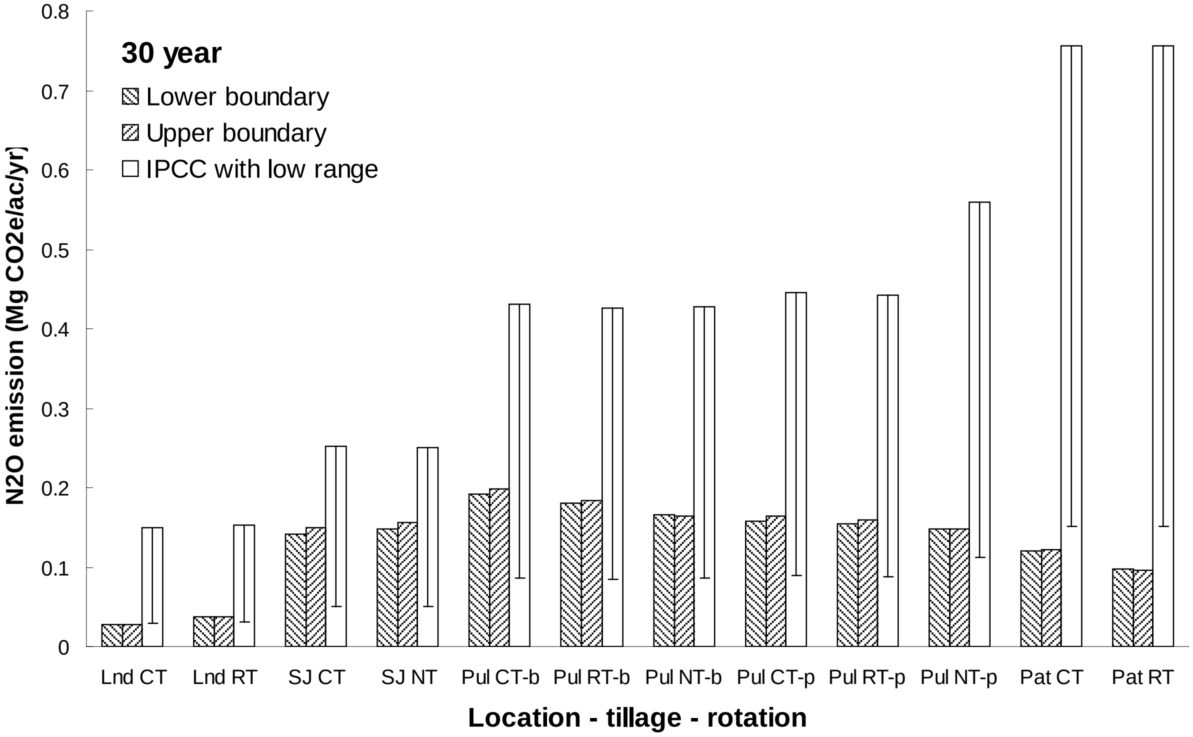
Table 23.4. Simulated net N mineralized (total mineralization – immobilization) for several locations, tillage regimes and rotations at four locations in eastern Washington state. Lower boundary data were generated at low SOC oxidation rates; upper boundary data were generated at high SOC oxidation rates.

	Location – tillage – rotation*											
	Lind CT	Lind RT	SJ CT	SJ NT	Pull CTb	Pull RTb	Pull NTb	Pull CTp	Pull RTp	Pull NTp	Pat CT	Pat RT
	Net N mineralized annually (kg N ha^{-1} yr^{-1})											
Lower boundary	12.1	8.4	19.8	14.9	41.8	35.7	29.6	50.2	44.5	40.2	68.8	63.6
Upper boundary	14.5	12.5	23.0	21.2	43.4	41.8	39.6	53.8	52.1	49.9	69.6	66.2

*SJ = St. John; Pull = Pullman; Pat = Paterson; CT = conventional tillage; RT = reduced tillage; NT = no-tillage.

Figure 23.6 summarizes the C benefits of converting from CT to either RT or NT. But the C benefits do not tell the whole story. Some of the C benefits may be offset by N_2O emissions, and the deleterious effects of this greenhouse gas may need to be subtracted from the C benefits. Simulated N_2O emissions from CropSyst showed relatively small responses to tillage intensity (Fig. 23.7). Simulated N_2O emissions in dryland were lowest in Lind which was the driest location and where fertilizer was applied only every other year. The next lowest emission was simulated in Paterson under irrigation, which was surprising given the high fertilizer inputs and irrigation. Paterson soil was greater than 91% sand which, combined with a high N uptake by the crops grown there, may have restricted the anaerobic conditions and high NO_3^- availability required for denitrification. In Pullman, when pea was in the rotation, simulated N_2O emissions were lower than when barley was in the rotation. This lower emission was correlated with the lower quantity of fertilizer applied. Although N mineralization was higher when pea was in the rotation (Table 23.4), mineralized N was not enough to make up for the lower fertilizer rate. In Pullman and Paterson, simulated N_2O emissions tended to decrease with decreasing tillage intensity (Fig. 23.7). These lower simulated emissions were probably due to lower soil temperatures under residue and less frequent anaerobic conditions due to residue interception of rainfall. CropSyst does not presently simulate some soil factors known to affect N_2O emission, e.g., changes in soil bulk density in response to tillage. Compaction and higher bulk density under NT, had these effects been simulated, would likely have increased N_2O emissions under NT.

Figure 23.7. Annual N_2O emissions, averaged over 30 years, either simulated by CropSyst or calculated according to the IPCC equation, for various tillage intensities and crop rotations at four locations in eastern Washington State. Simulated data presented for either low SOC oxidation rate in response to tillage (Lower boundary) or high oxidation rate (Upper boundary). Lnd = Lind; SJ = St. John; Pul = Pullman; Pat = Paterson; RT = reduced tillage; NT = no tillage; -b or –p = barley or pea in the rotation (see Table 23.3).



For some scenarios, N_2O emissions had the potential to more than offset C benefits accrued by converting to less intense tillage (cf. Figs. 23.6, 23.7). Management that would reduce N applications or that would apply N to more closely match demand (both amount and timing), would have the capacity to offset some of the N_2O emission.

IPCC estimates of N_2O emissions are also presented in Fig. 23.7. The IPCC estimates are based primarily on the amount of nitrogen applied as fertilizer with adjustments based on broad assumptions including return of residue N to soil (IPCC, 1996). The IPCC (1996) calculations estimate N_2O emissions as 1.25% ± 1% of an adjusted N application rate for agriculture. Figure 23.7 presents the midpoint (based on 1.25% of adjusted applied N) along with the lower value in the range. The IPCC estimates are not only high relative to CropSyst estimates of N_2O emissions from the modeled agricultural systems (Fig. 23.7), but they are also unreasonably high relative to locally-collected field data, where such data exist. The lower boundary of the IPCC range corresponds reasonably well, however, to CropSyst estimates (Fig. 23.7).

For Paterson, the IPCC midrange estimated N_2O emission of 0.76 Mg CO_2e ac^{-1} yr^{-1} (Fig. 23.7) is more than 7 times the value presented by Haile-Mariam et al (2008) for a similar rotation and tillage modeled herein. The CropSyst estimate for Paterson, averaged over both CT and RT, was 0.109 Mg CO_2e ac^{-1} yr^{-1}, which was only 2% higher than the Haile-Mariam et al (2008) measurement, although their measurement only included the period May-September. The bulk of fertilization applied was ammonium N and it is likely that a significant fraction of the N_2O emission came from nitrification rather than denitrification, particularly considering that small, frequent center-pivot water applications combined with the site's sandy soils is unlikely often to result in anaerobic conditions. CropSyst simulations showed that between 50% and 60% of yearly N_2O emissions were associated with nitrification, in agreement with the discussion and lack of evidence of anaerobic conditions during the experiment reported by Haile-Mariam et al (2008). The low temperatures, no irrigation or fertilization, and the infrequent large rainfall events over these sandy soils outside the May-September period of the experiment would suggest a small contribution to total N_2O emission outside this May – September period.

Near Pullman, measured N_2O emission over a 5-wk period on a fallow soil with a high rate of N fertilization (220 kg N ha^{-1} as anhydrous ammonia), starting May 21, was about 0.1% of applied N (Cochran et al, 1981). These authors concluded that the observed N_2O emission resulted from nitrification of the applied anhydrous ammonia-N. CropSyst simulations for Pullman resulted in 55% to 58% of the yearly N_2O emission derived from nitrification. An unfertilized control in the experiment of Cochran et al. (1981) provided an average daily emission of <0.9 g N ha^{-1} day^{-1} (with a maximum of 2 g N ha^{-1} day^{-1}). Data collected on a NT spring wheat field by Huggins and coworkers (USDA, Pullman, WA) at Pullman showed N_2O emission values of 1.8 g N ha^{-1} day^{-1} (October 24, 2005) and 1.1 g N ha^{-1} day^{-1} (August 17, 2006), which compares well with the data from the control treatment of Cochran et al. (1981). Another set of measurements on May 4, 2006 following application of 107 kg N ha^{-1} of UAN32 (75% ammoniacal N) on May 1 gave N_2O emission rates of 12 g N ha^{-1} day^{-1}, while a treatment receiving enough water to fill the top 20 cm of soil to 80% water filled porosity resulted in a maximum emission rate of 56 g N ha^{-1} day^{-1} (also on May 4).

Taking the maximum rate of 2 g N ha^{-1} of the unfertilized treatment from Cochran et al. (1981) as representative of daily N_2O fluxes from nitrification outside the 5-week window after fertilizer application (2.9 g N ha^{-1} day^{-1} after temperature adjustment), and the maximum rate for the watered treatment from Huggins and coworkers as an estimate of maximum N_2O emission rate due to denitrification (122 g N ha^{-1} day^{-1} after temperature adjustment), an estimate of N_2O emission was done for each day on year 1976 at Pullman (year of data collection by Cochran et al., 1981). A daily temperature adjustment for nitrification and denitrification N_2O emission rates was based on a CropSyst function with an optimum temperature of 35 °C, and minimum and maximum temperatures for no microbial activity of -5 °C and 50 °C, respectively. Denitrification was assumed to occur in each day with a rainfall amount exceeding 8 mm. With these assumptions, N_2O emissions from nitrification and denitrification were estimated as 0.47 and 0.63 g N ha^{-1} $year^{-1}$, for a total of 1.1 kg N ha^{-1} $year^{-1}$, equivalent to 0.21 Mg CO_2e ac^{-1} yr^{-1}. Data from Alberta, Canada on dryland croplands (~450 mm annual precipitation) ranged from 0.08 to 0.49 Mg CO_2e ac^{-1} yr^{-1}, with an average of 0.3 Mg CO_2e ac^{-1} yr^{-1}.(Lemke et al., 1998). These data, based on measurements on selected days of the year (minimum of 14 and maximum of 39), were collected at mid afternoon (higher temperature) and were assumed to be constant for the entire day, likely leading to overestimation as stated by the authors. Another four data sets for rainfed cropland from Sterling, CO (340 mm annual precipitation) give an average of 0.14 Mg CO_2e ac^{-1} yr^{-1} (range: 0.12 to 0.16 Mg CO_2e ac^{-1} yr^{-1}). The CropSyst estimate of annual N_2O emission, averaged over all Pullman scenarios was 0.17 Mg CO_2e ac^{-1} yr^{-1}. The midrange IPCC estimate for Pullman, however, was 0.46 Mg CO_2e ac^{-1} yr^{-1}.

Values in Fig. 23.7 are large enough to reduce or negate any gains in carbon storage presented here, indicating the need to pay careful attention to the management of nitrogen fertilization. However, from a relative viewpoint, given that N_2O emissions are not expected to differ much as a function of tillage intensity, the benefit of conversion to NT discussed above should still be valid.

Results reported in the literature are mixed concerning the effect of agricultural practices on net C sequestration. A global analysis of SOC sequestration rates by West and Post (2002) indicated ΔSOC of 0.47 Mg CO_2e ac^{-1} yr^{-1} average for all wheat systems, 0.37 Mg CO_2e ac^{-1} yr^{-1} average for continuous wheat systems, and 0.03 Mg CO_2e ac^{-1} yr^{-1} average for wheat-fallow systems. However, most of the data are from shallow soil layers and are therefore biased in favor of NT systems as discussed previously. CropSyst estimations based only on the top 15 cm of soil (Fig. 23.2) give values of 0.33 (lower boundary) and 0.38 (upper boundary) Mg CO_2e ac^{-1} yr^{-1}, in reasonable agreement with West and Post (2002) data. However, these numbers were substantially lower when simulations considered the top 30 cm of soil (Fig. 23.4). In Illinois, after a decade of NT under a corn-soybean rotation, there was no significant increase in SOC (Yang and Wander, 1999). In Brazil, NT led not only to greater C storage compared to CT, but increased soil aggregation, too (Madari et al., 2005). In Ontario, Canada, zero tillage increased SOC only in the surface layer of soil, but not for the profile (Deen and Kataki, 2003). Baker et al (2007) concluded that evidence that conservation tillage promotes C sequestration is “not compelling.” And in eastern Canada, 10 years was not enough time to see an increase in soil organic matter in response to reduced tillage (Angers et al., 1997).

Near Pullman, Washington, evidence indicated that a combination of NT and CT could increase SOC compared to long-term NT (Purakayastha et al., 2008). In a recent compilation of research on soil carbon sequestration in the Pacific Northwest

(Brown and Huggins, elsewhere in this report), a wide range of results are reported concerning the effect of converting from CT to conservation tillage. They report that Fuentes et al. (2004) measured 0.1 Mg CO_2e ac^{-1} yr^{-1} in the top 10 cm of soil, but C was lost from the 5 – 10 cm layer. Granatstein et al. (1987, cited in Brown and Huggins elsewhere in this report) reported C accumulation of 0.05 Mg CO_2e ac^{-1} yr^{-1} over a 10-year period, but in their study, C was lost from the 10 – 30 cm layer and accumulated only in the 0 – 5 cm layer. Converting from CT to NT under continuous wheat for 16 years was reported to increase soil C at a rate of 1.42 Mg CO_2e ac^{-1} yr^{-1} in the top 25 cm of soil, with all layers accumulating C (Bezdicek et al, 1998 cited in Brown and Huggins elsewhere in this report). This latter result is hard to substantiate based on residue inputs and losses of C due to tillage, and can perhaps be due to samples including residue in the determination of SOC, which would influence their reported measure of SOC (Yang and Wander, 1999) or to redistribution of surface SOC by erosion, moving SOC from upslope positions to positions lower in the landscape where SOC would concentrate. Regardless, the highly variable results presented by Granatstein et al. (1987), Bezdicek et al. (1998) and Fuentes et al. (2004) for the same location and cropping systems are a clear indication of the difficulty of measuring SOC changes, particularly given the complex topography of the region.

The application of life-cycle analysis (LCA) to these CropSyst scenarios could provide a different picture (see Zaher et al. in this report). Certain CO_2 equivalents are required, for example, to fuel the tractors and produce the fertilizers and pesticides used in the various scenarios. If these CO_2 equivalents were factored into the equations implemented by the simulated tillage regimes, those scenarios that require less diesel or more pesticides may lead to different net C sequestration. LCA would also account for the carbon cost of producing the fertilizers used in the scenarios (Schlesinger, 2000).

Precision agriculture also has the potential to influence agriculture's impact on global warming. For example, targeting nitrogen applications to those portions of the field where they are most effective, and reducing N applications where they are excessive, would most likely result in lower N_2O emissions. The technology for targeted N application is available. The same is true for precision application of pesticides.

The simulations we implemented were conducted under the assumption of current atmospheric CO_2 concentration, and assumed no change from historic air temperature. Neither assumption is realistic, particularly over a 30-year time frame. Implementing simulations under increased [CO_2] and temperature would almost certainly influence our results.

Baker et al. (2007) report that the Chicago Climate Exchange (CCX) bases agricultural exchange offsets on the assumption that conservation tillage sequesters 0.5 Mg CO_2e ac^{-1} yr^{-1}. On the basis of our work, offsets of 0.5 Mg CO_2e ac^{-1} yr^{-1} are high for eastern Washington. This offset has been revised depending on region to range from a high of 0.6 to a low of 0.2 Mg CO_2e ac^{-1} yr^{-1} (National Carbon Offset

Coalition, 2008; Chicago Climate Exchange, 2009). CropSyst predicted, at best, a net C benefit rate of 0.24 Mg CO_2e ac^{-1} yr^{-1} (0.30 Mg CO_2e ac^{-1} yr^{-1} if residues were accounted for) for the upper limit of tillage impact on SOC oxidation. This value of 0.24 was obtained as the difference in annual net C sequestration between the Pullman NT-b and Pullman CT-b calculated over a 12-year time period for the top 30 cm of soil. One issue in addition to the value of the offset is the term of the carbon credit contract. Figure 23.3 shows that as time passes and a new SOC equilibrium value is approached, annual carbon sequestration decreases. So it would be reasonable to expect that 3 – 5 year contracts awarded immediately after converting from CT to conservation tillage should be worth more than contracts awarded 10 or 15 years after conversion. But the carbon benefit from converting to conservation tillage is only one of several substantial benefits. Conservation tillage also reduces erosion, improves soil moisture, reduces fuel usage, etc. These benefits have the potential to be at least as valuable as the direct carbon benefit.

Conclusions

Conversion to RT provides an improvement over CT in terms of C conservation, but the benefit may be small. The benefit from converting to NT, however, is more important, particular in higher rainfall regions of eastern Washington with greater potential for residue production. The effect appears to be mainly due to enhanced SOC oxidation under CT because residue inputs are essentially similar, although with a different distribution in the soil profile. Evaluating ΔSOC based on 0 – 15 cm could be misleading, providing an undue advantage when evaluating potential carbon benefits of NT systems. Comparisons should be made on the basis of the top 30 cm of soil profile. Based on the simulation results presented, carbon offsets for the Pacific Northwest could be lower than much of the rest of the country (National Carbon Offset Coalition, 2008; CCX, 2009), but perhaps be large enough to provide some incentive for growers to convert to conservation tillage.

Acknowledgements

This research was supported in part by a grant from the Paul G. Allen Family Foundation.

Literature Cited

Ahuja, L.R., J.D. Hanson, K.W. Rojas, and M.J. Shaffer. 2000. Model overview. p. 1–12. In L.R. Ahuja et al. (ed.) Root Zone Water Quality Model: Modeling management effects on water quality and crop productivity. Water Resour. Publ., Highlands Ranch, CO.

Allmaras, R.R., H.H. Schomberg, C.L. Douglas, Jr. and T.H. Dao. 2000. Soil organic carbon sequestration potential of adopting conservation tillage in U.S. croplands. J. Soil and Water Cons. 55:365-373.

Angers, D.A., M.A. Bolinder, M.R. Carter, E.G. Gregorich, C.F. Drury, B.C. Liang, R.P. Voroney, R.R. Simard, R.G. Donald, R.P. Beyaert and J. Martel. 1997. Impact of tillage practices on organic carbon and nitrogen storage in cool, humid soils of eastern Canada. Soil Tillage Res 41:191-201.

Baker, J.M, T.E. Ochsner, R.T. Venterea and T.J. Griffis. 2007. Tillage and soil carbon sequestration – What do we really know? Agriculture, Ecosystems and Environment 118:1-5.

Balesdent, J., C. Chenu and M. Balabane. 2000. Relationship of soil organic matter dynamics to physical protection and tillage. Soil & Tillage Res. 53:215-230.

Beare, M.H., M.L. Cabrera, P.F. Hendrix and D.C. Coleman. 1994. Aggregate-protected and unprotected organic matter pools in conventional- and no-tillage soils. Soil Sci. Soc. Am. J. 58:787-795.

Benli, B., M. Pala, C.O. Stöckle, and T. Oweis. 2007. Assessment of winter wheat production under early sowing with supplemental irrigation in a cold highland environment using CropSyst simulation model. Agric. Water Management 93:45 – 53

Bezdicek, D., J. Hammel, M. Fauci, D. Roe and J. Mathison. 1998. Effects of long term direct seeding on soil properties on Northwest farms. Proc. Northwest Direct Seed Intensive Cropping Conf., 1998, Pasco, WA. 7-8 Jan.

Brisson, N., Gary, C., Justes, E., Roche, R., Mary, B., Ripoche, D., Zimmer, D., Sierra, J., Bertuzzi, P., Burger, P., Bussière, F., Cabidoche, Y.M., Cellier, P., Debaeke, P., Gaudillère, J.P., Maraux, F., Seguin, F.B., Sinoquet, H. 2003. 'An overview of the crop model Stics.' European Journal of Agronomy 18: 309-332.

Brown, T.T. and D.R. Huggins. xxxx. Dryland agriculture's impact on soil carbon sequestration in the Pacific Northwest.

Bruce, J.P., M. Frome, E. Haites, H. Janzen, R. Lal, and K. Paustian. 1999. Carbon sequestration in soils. J. Soil and Water Cons. 54:382-389.

Carvalho Leite, L.F., Sa Mendonca, E., Oliveira de Almeida Machado, P.L., Fernandes Filho, E.I., Lima Neves, J.C. 2004. Simulating trends in soil organic carbon of an Acrisol under no-tillage and disc-plow systems using the Century model. Geoderma 120:283–295.

Castellvi, F. and C.O. Stöckle. 2001. Comparing the performance of WGEN and ClimGen in the generation of temperature and solar radiation. Trans. of the Am. Soc. of Agric. Engineers 44:1683-1687.

Chatskikh, D., Olesen, J.E., 2007. Soil tillage enhanced CO2 and N2O emissions from loamy sand soil under spring barley. Soil and Tillage Research, 97(1), 5-18.

Chicago Climate Exchange. 2009. Continuous conservation tillage and conversion to grassland soil carbon sequestration offset project protocol. Chicago Climate Exchange, Inc. http://www.chicagoclimatex.com/docs/offsets/CCX_Conservation_Tillage_and_Grassland_Conversion_Protocol_Final.pdf.

Cochran, V. L, L.F. Elliott and R.I. Papendick. 1981. Nitrous oxide emissions from a fallow field fertilized with anhydrous ammonia. Soil Sci. Soc. Am. J. 45:307-310.

Dalal, R.C., W. Wang, G.P. Robertson and W.J. Parton. 2003. Nitrous oxide emission from Australian agricultural lands and mitigation options: a review. Aust. J. Soil Res. 41:165-195.

Deen, W. and P.K. Kataki. 2003. Carbon sequestration in a long-term conventional versus conservation tillage experiment. Soil Tillage Res. 74:143-150.

Del Grosso, S.J., Parton, W.J., Mosier, A.R., Ojima, D.S., Kulmala, A.E., Phongpan, S. 2000. General model for N2O and N2 gas emission from soils due to nitrification. Global Biogeochem. Cycles 14:1045-1060.

Donatelli, M., C.O. Stockle, E. Ceotto, and M. Rinaldi. 1997. CropSyst validation for cropping systems at two locations of Northern and Southern Italy. European Journal of Agronomy 6:35-45.

Duxbury, J. M. 1994. The significance of agricultural sources of greenhouse gases. Nutrient Cycling in Agroecosystems 38:151-163.

Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz and R. Van Dorland. 2007: Changes in Atmospheric Constituents and in Radiative Forcing. *In* Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the

Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Fuentes, J.P., M. Flury and D.F. Bezdicek. 2004. Hydraulic properties in a silt loam soil under natural prairie, conventional till, and no-till. Soil Sci. Soc. Am J. 68:1679-1688.

Gijsman, A., Hoogenboom, G., Parton, W.J., Kerridge, P.C. 2002. Modifying DSSAT crop models for low-input agricultural systems using a soil organic matter-residue module from Century. Agron. J. 94:462-474.

Granatstein, D.M., D.F. Bezdicek, V.L. Cochran, L.F. Elliott and J. Hammel. 1987. Long-term tillage and rotation effects on soil microbial biomass, carbon, and nitrogen. Biol. Fert. Soils 5:265-270.

Haile-Mariam, S., H.P. Collins and S.S. Higgins. 2008. Greenhouse gas fluxes from an irrigated sweet corn (*Zea mays* L.) – potato (*Solanum tuberosum* L.) rotation. J. Environ. Qual. 37:759-711.

Hamlet, A. F., P. W. Mote, M.P. Clark, and E.P. Lettenmaier. 2005. Effects of temperature and precipitation variability on snowpack trends in the western United States. Journal of Climate 18:4545-4561.

Hassink, J., Whitmore, A.P., 1997. A model of the physical protection of organic matter in soils. Soil. Sci. Soc. Am. J. 61, 131–139.

Huggins, D.R., G.A. Buhanovske, G.H. Wagner, J.R. Brown, R.G. Darmody, T.R. Peck, G.W. Lesoing, M.B. Vanotti and L.G. Bundy. 1998. Soil organic C in the tallgrass prairie-derived region of the corn belt: effects of long-term crop management. Soil & Tillage Res. 47:219-234.

IPCC 1996. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. Reference Manual (Volume 3) (http://www.ipcc-nggip.iges.or.jp/public/gl/invs6.html).

Izaurralde, R.C., J.R. Williams, W.B. McGill, N.J. Rosenberg, M.C. Quiroga Jakas. 2006. Simulating soil C dynamics with EPIC: model description and testing against long-term data. Ecological Modelling 19:362-384.

Jara, J. and C.O. Stockle. 1999. Simulation of corn water uptake using models with different levels of process detail. Agronomy Journal 91:256-265.

Jones, J.W., Tsuji, G.Y., Hoogenboom, G., Hunt, L.A., Thornton, P.K., Wilkens, P.W., Imamura, D.T., Bowen, W.T., Singh, U., 1998. Decision support system for agrotechnology transfer DSSAT v3. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding options for agricultural production. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 157-177.

Kemanian, A. 2003. Radiation-based and transpiration-based modeling of barley and wheat growth. Ph.D. Dissertation, Washington State University.

Kemanian, A.R., C.O. Stöckle, D.R. Huggins, and L.M. Viega. 2007. A simple method to estimate harvest index in grain crops. Field Crops Research 103:208-216.

Kemanian, A.R. and Stöckle, C.O. 2010. C-Farm: A simple model to evaluate the carbon balance of soil profiles. European Journal of Agronomy 32:22-29.

Kok, H., R.I. Papendick and K.E. Saxton. 2009. STEEP: Impact of long-term conservation farming research and education in Pacific Northwest wheatlands. Journal of Soil and Water Conservation 64:253-264.

Kroeze, C., Mosier A.R., and Bouwman L., 1999. Closing the global N2O budget: A retrospective analysis 1500–1994. Global Biogeochem. Cycles 13:1–8.

Krull, E.S., Baldock, J.A., Skjemstad, J.O. 2003. Importance of mechanisms and processes of the stabilisation of soil organic matter for modeling carbon turnover. Functional Plant Biology 30:207-222.

Lal, R., R.F. Follett, J. Kimble and C.V. Cole. 1999. Managing U.S. cropland to sequester carbon in soil. J. Soil and Water Cons. 54:374-381.

Lemke, L.R., Izaurralde, R.C., Malhi, S.S., Arshad, M.A., Nyborg, M. 1998. Nitrous oxide emissions from agricultural soils of the Boreal and Parkland regions of Alberta. Soil Sci. Soc. Am. J. 62:1096-1102.

Maag, M., Vinther, F.P. 1996. Nitrous oxide emission by nitrification and denitrification in different soil types and at different soil moisture contents and temperatures. Applied Soil Ecology 4:5-14.

Madari, B, P.L.O.A. Machado, E. Torres, A.G. de Andrade and L.I.O. Valencia. 2005. No tillage and crop rotation effects on soil aggregation and organic carbon in a Rhodic Ferralsol from southern Brazil. Soil Tillage Res 80:185-200.

Marcos, J. 1997. Corn production under dryland conditions in eastern Washington. M.S. Thesis, Washington State University.

Marcos, J. 2000. Simulation-based assessment of alternative crops in the dryland Pacific Northwest. Ph.D. Dissertation, Washington State University.

Matson, P.A., R. Naylor, and I. Ortiz-Monasterio. 1998. Integration of environmental, agronomic, and economic aspects of fertilizer management. Science 280:112-115.

McCown, R.L., Hammer, G.L., Hargreaves, J.N.G., Holtzworth, D.P., Freebairn, D.M., 1996. APSIM: a novel software system for model development, model testing and simulation in agricultural systems research. Agric. Syst. 50, 255-271.

Molina, J.A.E. and P. Smith, 1998. Modeling carbon and nitrogen processes in soils. Adv. Agron. 62:253-298.

Monzon, J.P., Sadras, V.O., Andrade, F.H. 2006. Fallow soil evaporation and water storage as affected by stubble in sub-humid (Argentina) and semi-arid (Australia) environments. Field Crops Research 98 (2006) 83–90.

Mosier, A. R.. 1998. Soil processes and global change. Biol. Fert. Soils 27:221-229.

Mote, P.W. 2006. Climate-driven variability and trends in mountain snowpack in western North America. Journal of Climate 19:6209-6220.

National Carbon Offset Coalition, Inc. 2008. http://www.ncoc.us/subPages/cropland.htm

NRCS, 2002 Guide to using the soil conditioning index, 8p, available at

ftp://ftp-fc.sc.egov.usda.gov/SQI/web/SCIguide.pdf; software available at http://soils.usda.gov/sqi/publications/publications.html#sci.

Painter K., 2009. Crop Rotation Budgets - Dryland Grain Producing Region of the NW Wheat & Range Region, http://www.uidaho.edu/~kpainter

Pala, M., C.O. Stockle, and H.C. Harris. 1996. Simulation of durum wheat (triticum durum) growth under differential water and nitrogen regimes in a mediterranean type of environment using CropSyst. Agricultural Systems 51:147-163.

Pannkuk, C.D., C.O. Stockle, and R.I. Papendick. 1998. Validation of CropSyst for Winter and Spring Wheat under Different Tillage and Residue Management Practices in a Wheat-Fallow Region. Agricultural Systems 57:121-134.

Parton, W.J., Stewart, J.W.B and C.V. Cole. 1988. Dynamics of C, N, P and S in grassland soils. a model. Biogeochem. 5:109-131.

Parton, W.J., D.S. Ojima, C. Vernon Cole, D.S. Schimel, 1994. A general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management. In Quantitative modeling of soil forming processes. Special Publication 39 SSSA, Madison, WI, pp. 147-167.

Parton, W.J. and P.E. Rasmussen. 1994. Long-term effects of crop management in wheat-fallow: II. CENTURY model simulations. Soil Sci. Soc. Am. J. 58:530-536.

Peralta, J.M. and C.O. Stockle. 2002. Nitrate from an irrigated crop rotation at the Pasco-Quincy area (Washington, USA) available for groundwater contamination: A long-term simulation study. Agriculture, Ecosystems and Environment 88:23-24.

Powlson, D.S., P. Smith, and J.U. Smith. 1996. Evaluation of soil organic matter models using existing long-term datasets. NATO ASI Series, Vol. I 38.

Purakayastha, T. J., D.R. Huggins and J.L. Smith. 2008. Carbon sequestration in native prairie, perennial grass, no-till, and cultivated Palouse silt loam. Soil Sci. Soc. Am. J. 72:534-540.

Qin, R., Stamp, P., Richner, W. 2004. Impact of tillage on root systems of winter wheat. Agron. J. 96:1523–1530.

Qin, R., Stamp, P., Richner, W. 2005. Impact of tillage and banded starter fertilizer on maize root growth in the top 25 centimeters of the soil. Agron. J. 97:674–683.

Robertson, G.P., E.A. Paul and R.R. Harwood. 2000. Greenhouse gases in intensive agriculture: Contributions of individual gases to the radiative forcing of the atmosphere. Science 289:1922-1925.

Sadras, V. 2004. Yield and water-use efficiency of water- and nitrogen-stressed wheat crops increase with degree of co-limitation. Europ. J. Agronomy 21:455-464.

Schlesinger, W. H. 2000. Carbon sequestration in soils: some cautions amidst optimism. Agriculture, Ecosystems and Environment 82:121-127.

Shaffer, M.J, L. Ma and S. Hansen, 2001. Modeling carbon and nitrogen dynamics for soil management. CRC Press LLC, Boca Raton, Fl. 651p.

Six, J., H. Bossuyt, S. Degryze and K. Denef. 2004a. A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. Soil & Tillage Res. 79:7-31.

Six, J., S.M. Ogle, F.J. Breidt, R.T. Conant, A.R. Mosier and K. Paustian. 2004b. The potential to mitigate global warming with no-tillage management is only realized when practiced in the long term. Global Change Biol. 10:155-160.

Smil, V. 1999. Nitrogen in crop production: An account of global flows. Global Biogeochemical Cycles 13:647-662.

Steduto, P., and R. Albrizio. 2005. Resource use efficiency of field-grown sunflower, sorghum, wheat and chickpea. II. Water Use Efficiency and comparison with Radiation Use Efficiency. Agric. For. Meteorol. 130:269–281.

Steduto, P., T.C. Hsiao, and E. Fereres. 2007. On the conservative behavior of biomass water productivity. Irrig. Sci. 25:189–207.

Stöckle, C. O., S. Martin and G. S. Campbell. 1994. CropSyst, a cropping systems model: water/nitrogen budgets and crop yield. Agricultural Systems 46:335-359.

Stöckle, C.O., M. Cabelguenne, and P. Debaeke. 1997. Validation of CropSyst for water management at a site in southern France using submodels of different complexity. European Journal of Agronomy 7:89-98.

Stöckle, C.O. and P. Debaeke. 1997. Modelling crop nitrogen requirements: a critical analysis. European Journal of Agronomy 7:161-169.

Stöckle, C.O. and J. Jara. 1998. Modeling transpiration and soil water content from a corn field: 20 min vs. daytime integration step. Agriculture and Forest Meteorology 92:119-130.

Stöckle, C.O., M. Donatelli and R. Nelson. 2003. CropSyst, a cropping systems simulation model. Europ. J. Agronomy 18:289-307.

Stöckle, C.O., A.R. Kemanian, and C. Kremer. 2008. On the Use of Radiation- and Water-Use Efficiency for Biomass Production Models. In: L.R. Ahuja, V.R. Reddy, S.A. Saseendran, and Q. Yu (Eds.). Advances in Agricultural Systems Modeling 1. ASA-SSSA-CSSA, Madison, WI.

Todorovic, M., R. Albrizio, L. Zivotic, M. Abi Saab, C. O. Stöckle, and P. Steduto. 2009. Assessment of AquaCrop, CropSyst and WOFOST Models in the Simulation of Sunflower Growth Under Different Water Regimes. Agronomy Journal 101:509-521.

USDA NRCS, 2002 Guide to using the soil conditioning index, 8p, available at

ftp://ftp-fc.sc.egov.usda.gov/SQI/web/SCIguide.pdf; software available at http://soils.usda.gov/sqi/publications/publications.html#sci.

Verberne, E.L.J., J. Hassink, P. de Willigen, J.J.R. Groot., and J.A. Van Veen, 1990. Modelling organic matter dynamics in different soils. Netherlands J. Agric. Sci. 38:221-238.

van Ittersum, M.K., Donatelli, M. 2003. Modelling cropping systems–highlights of the symposium and preface to the special issues. European Journal of Agronomy 18:187-197.

van Veen, J.A., Paul, E.A. 1981. Organic carbon dynamics in grassland soils. I. Background information and computer simulation. Canadian J. Soil Sci. 61:185-201.

van Veen, J.A., Ladd, J.N., Frissel, M.J. 1984. Modelling C and N turnover through the microbial biomass in soil. Plant and Soil 76:257-274.

Wang, Z., Zhang, B., Li, X., Song, K., Liu, D., Zhang, S. 2006. Using CropSyst to Simulate Spring Wheat Growth in Black Soil Zone of Northeast China. Pedosphere 16:354-361.

West, T.O. and W.M. Post. 2002. Soil organic carbon sequestration rates by tillage and crop rotation: A global data analysis. Soil Sci. Soc. Am J. 66:1930-1946.

Whitmore, A.P., Klein-Gunnewiek, H., Crocker, G.J., Klír, J., Körschens, M., Poulton, P.R. 1997. Simulating trends in soil organic carbon in long-term experiments using the Verbene/MOTOR model. Geoderma 81:137-151.

Williams, E.J., G.L. Hutchinson and F. C. Fehsenfeld. 1992. NO_x and N_2O emissions from soil. Global Biogeochemical Cycles 6:351-388.

Williams, J.R., Jones, C.A., Dyke, P.T., 1984. A modeling approach to determining the relationship between erosion and soil productivity. Trans. ASAE 27, 129-144.

Yang, X-M and M.M Wander. 1999. Tillage effects on soil organic carbon distribution and storage in a silt loam soil in Illinois. Soil Tillage Res. 52:1-9.

Appendix

Table 23.A1. Several key crop phenological characteristics and target yields for several crops at five locations in the Pacific Northwest for which CropSyst simulations were generated.

Location	Crop	Planting	Flowering	Grain filling	Maturity	Harvest	Yield	Source
		Day of year	Day of year	Day of year	Day of year	Day of year	kg ha^{-1}	
Pullman	WW	272	159	171	203	213	6222	1, 2, 5, 16
	SW	95	176	185	211	220	4106	1, 3, 6, 7, 16
	SB	101	172	175	200	207	4144	1, 4, 6, 7, 16
	SP	103	172	179	197	204	2072	5, 6, 7, 8, 16
Lind	WW	242	153	162	191	200	3422	1, 6, 9, 10, 16
St. John	WW	253	151	161	198	214	5101	1, 6, 11, 12, 16
	SB	92	170	179	205	214	3108	1, 6,13, 16
Paterson	SC	97	180	185?	na	205	5505	14, 15
	P	76	126?	128?	242?	244	16084	14, 15
Sunnyside	SiC	129	206	219	264	264	16050	14
	Triticale	274	na	na	na	122	6990	14

1. www.nass.usda.gov/QuickStats/Create_County_All.jsp
2. http://variety.wsu.edu/2006/winter_wheat_data/Pullman.pdf
3. http://variety.wsu.edu/2006/spring_wheat_data/Pullman.pdf
4. http://variety.wsu.edu/2006/spring_barley_data/Pullman.pdf
5. Derek Appel, personal communication.
6. John Burns, personal communication.

7. Steve Keuhner, personal communication.
8. http://hermes.bionet.nsc.ru/pg/34/3.htm
9. http://variety.wsu.edu/2006/winter_wheat_data/Ritzville.pdf
10. Frank Young, personal communication.
11. Julie Dawson, personal communication.
12. http://variety.wsu.edu/2006/winter_wheat_data/St_John.pdf
13. http://variety.wsu.edu/2008/SpB/StJohn.pdf
14. Hal Collins, personal communication
15. Javier Marcos, personal communication
16. Kate Painter, CFF budgets

Table 23.A2. Crop rotations, tillage characteristics, field operations and timing of operations at four locations in the Pacific Northwest for which CropSyst simulations were generated. The respective tillage options, or treatments, e.g., conventional or reduced, are defined by the field operations and implements simulated. Dryland field operations and management regimes are similar to those used by D. Roe and A. Swannack in Kok et al. (2009).

Location/rain	**Rotation**	**Tillage**	**Date**	**Field operations and implements simulated**
Lind/dry	WW-SF	Conventional	30 August	Drill WW, deep furrow 12 – 18 in spacing
			1 April	Sprayer, post emergence
			1 August	Harvest WW
			1 Sept	Disk, offset, heavy
			1 April	Cultivator field with spike points
			1 May	Rodweeding
			1 June	Rodweeding
			15 June	Fertilizer application, shank, low disturbance 12 in.
			1 July	Rodweeding
			15 August	Rodweeding
Lind/dry	WW-SF	Reduced	30 August	Drill WW, deep furrow 12 – 18 in spacing
			1 April	Sprayer, post emergence
			1 August	Harvest WW
			1 Sept	Sprayer
			1 April	Sprayer
			1 June	Sweep plow, 20 – 40 in wide
			15 June	Fertilizer application, shank, low disturbance, 12 in.
			1 July	Rodweeding
St. John/moderate	WW-SB-SF	Conventional	10 Sept	Drill or air seed WW, hoe/chisel openers, 6 – 12 in spacing
			1 April	Sprayer, post emergence
			1 August	Harvest WW
			15 Oct	Plow, moldboard, 10 in depth
			15 March	Cultivator, field, 6 – 12 in sweeps
			20 March	Fertilizer application, shank, low disturbance, 12 in.

			25 March	Rodweeding 3
			1 April	Drill or air seed SB, hoe/chisel openers, 6 – 12 in spacing
			15 May	Sprayer, post emergence
			1 August	Harvest SB
			15 March	Chisel, straight point
			1 April	Cultivator, field, 6 – 12 in sweeps
			15 April	Rodweeding
			1 June	Fertilizer application, shank, low disturbance, 12 in
			15 June	Rodweeding
			10 July	Rodweeding
			1 Sept	Rodweeding
St. John/moderate	WW-SB-SF	No-till	10 Sept	Drill or air seed WW, hoe/chisel openers, 6 – 12 in spacing with fertilizer
			1 November	Sprayer, post emergence
			1 April	Sprayer, post emergence
			1 August	Harvest WW
			26 Sept	Shredder, flail or rotary
			18 October	Sprayer, kill crop
			22 March	Sprayer, kill crop
			1 April	Drill or air seed SB, hoe/chisel openers, 6 12 in spacing with fertilizer
			15 May	Sprayer, post emergence
			1 August	Harvest SB
			1 Oct	Sprayer
			1 May	Sprayer
			1 July	Sprayer
Pullman/high	WW-SB-SW	Conventional	29 Sept	Drill or air seed WW, double disk
			1 April	Sprayer, post emergence

			1 August	Harvest WW
			10 Sept	Plow, moldboard
			1 April	Cultivator, field, 6 – 12 in sweeps, two passes
			7 April	Rodweeding
			9 April	Fertilizer application, shank, low disturbance, 12 in.
			10 April	Drill or air seed SB, double disk
			14 May	Sprayer, post emergence
			1 August	Harvest SB
			10 Sept	Chisel, straight point
			30 March	Cultivator, field, 6 – 12 in sweeps, two passes
			2 April	Rodweeding
			4 April	Fertilizer application, shank, low disturbance, 12 in.
			5 April	Drill or air seed SW, double disk
			14 April	Sprayer, post emergence
			1 August	Harvest SW
			25 Sept	Chisel, straight point
			26 Sept	Fertilizer application, shank, low disturbance, 12 in.
			27 Sept	Rodweeding
			28 Sept	Harrow, spike tooth
Pullman/high	WW-SB-SW	Reduced	5 Oct	Drill or air seed WW, double disk
			1 April	Sprayer, post emergence
			1 August	Harvest WW
			20 Sept	Chisel, straight point
			25 Oct	Sprayer
			1 April	Cultivator, field, 6 – 12 in sweeps
			8 April	Fertilizer application, shank, low disturbance, 12 in.
			9 April	Harrow, coiled tine
			10 April	Drill or air seed SB, double disk
			14 May	Sprayer, post emergence
			1 August	Harvest SB
			1 Sept	Chisel, straight point

			5 Oct	Sprayer
			1 April	Cultivator, field, 6 – 12 in sweeps
			3 April	Fertilizer application, shank, low disturbance, 12 in.
			4 April	Harrow, coiled tine
			5 April	Drill or air seed SW, double disk
			14 May	Sprayer, post emergence
			1 August	Harvest SW
			20 Sept	Chisel, straight point
			30 Sept	Sprayer
			3 Oct	Fertilizer application, deep placement, heavy shank
Pullman/high	WW-SW-SP	Conventional	29 Sept	Drill or air seed WW, double disk
			1 April	Sprayer, post emergence
			1 August	Harvest WW
			5 September	Plow, moldboard
			26 March	Cultivator, field, 6 – 12 in sweeps, two passes
			2 April	Rodweeding
			3 April	Fertilizer application, shank, low disturbance, 12 in.
			5 April	Drill or air seed SW, double disk
			14 May	Sprayer, post emergence
			1 August	Harvest SW
			25 Sept	Chisel, straight point
			1 April	Cultivator, field, 6 – 12 in sweeps, two passes
			10 April	Rodweeding
			12 April	Harrow, spike tooth
			14 April	Drill or air seed SP, double disk
			15 April	Cultipacker, roller
			16 April	Sprayer, post emergence
			1 August	Harvest SP
			25 Sept	Chisel, straight point
			26 Sept	Fertilizer application, shank, low disturbance, 12 in.

			27 Sept	Rodweeding
			28 Sept	Harrow, spike tooth
Pullman/high	WW-SW-SP	Reduced	1 October	Drill or air seed WW, double disk
			1 April	Sprayer, post emergence
			1 August	Harvest WW
			10 Sept	Chisel, straight point
			15 October	Sprayer, kill crop
			1 April	Cultivator, field, 6 – 12 in sweeps
			3 April	Fertilizer application, shank, low disturbance, 12 in.
			4 April	Harrow, coiled tine
			5 April	Drill or air seed SW, double disk
			14 May	Sprayer, post emergence
			1 August	Harvest SW
			10 Sept	Chisel plow, straight point
			1 April	Cultivator, field, 6 – 12 in sweeps
			13 April	Harrow, coiled tine
			14 April	Drill or airseed SP, double disk
			15 April	Cultipacker, roller
			16 May	Sprayer, post emergence
			1 August	Harvest SP
			25 Sept	Fertilizer application, deep placement, heavy shank
Pullman/high	WW-SB-SW	No-till	5 October	Drill or air seed WW, double disk with fertilizer
			26 April	Sprayer, post emergence
			1 August	Harvest WW
			25 October	Sprayer
			1 April	Sprayer
			10 April	Drill or air seed SB, hoe/chisel openers, 6 – 12 in spacing with fertilizer
			14 May	Sprayer, post emergence
			1 August	Harvest SB

			10 October	Sprayer
			1 April	Sprayer
			5 April	Drill or air seed SW, hoe/chisel opener, 6 – 12 in spacing, with fertilizer
			14 May	Sprayer, post emergence
			1 August	Harvest SW
			28 Sept	Sprayer
Pullman/high	WW-SP-SW	No-till	5 October	Drill or air seed WW, double disk. with fertilizer
			25 April	Sprayer, post emergence
			1 August	Harvest WW
			25 October	Sprayer
			1 April	Sprayer
			14 April	Drill or air seed SP, hoe/chisel openers, 6 – 12 in spacing
			15 May	Sprayer, post emergence
			1 August	Harvest SP
			10 October	Sprayer
			1 April	Sprayer
			5 April	Drill or air seed SW, hoe/chisel openers, 6 – 12 in spacing with fertilizer
			14 May	Sprayer, post emergence
			1 August	Harvest SW
			1 October	Sprayer
Paterson/irrigated	SC-SC-Pot	Conventional	7 April	Plant SC, double disk opener with fertilizer
			24 July	Harvest SC
			29 March	Chisel st. pt.
			30 March	Disk tandem, secondary
			31 March	Cultipacker roller
			1 April	Chisel st. pt.
			2 April	Disk tandem, secondary

			3 April	Cultipacker roller
			7 April	Plant SC, double disk opener with fertilizer
			24 July	Harvest SC
			1 October	Shredder, flail or rotary
			8 March	Chisel st. pt.
			9 March	Disk tandem, secondary
			10 March	Cultipacker roller
			11 March	Chisel st. pt.
			12 March	Disk tandem, secondary
			13 March	Cultipacker roller
			16 March	Bedder, hipper, hiller 15 in high
			17 March	Plant potato in-row subsoiler
			5 April	Rodweeder
			22 April	Furrow diker
			1 September	Harvest, potato, with digger
			30 Sept	Drill or airseed WW-cover, double disk
			27 February	Sprayer kill WW-cover
			29 March	Chisel st. pt.
			30 March	Disk tandem, secondary
			31 March	Cultipacker roller
			1 April	Chisel st. pt.
			2 April	Disk tandem, secondary
			3 April	Cultipacker roller
Paterson/Irrigated	SC-SC-Pot	Reduced	7 April	Plant SC double disk opener with fertilizer
			24 July	Harvest SC
			7 April	Plant SC double disk opener with fertilizer
			24 July	Harvest SC
			1 October	Shredder, flail or rotary
			16 March	Bedder, hipper hiller 15 in. high

			17 March	Plant potato, in-row subsoiler
			1 Sept	Harvest potato, with digger
			1 October	Drill or airseed WW-cover, double disk
			27 February	Sprayer kill WW-cover
Sunnyside/Irrigated	SiC-Triticale	Conventional	8 May	Rototiller
			9 May	Plant SiC, double disk opener 18 in.
			20 Sept	Chop SiC for silage
			28 Sept	Disk tandem, secondary
			29 Sept	Cultipacker roller
			1 Oct	Drill Triticale or airseeder, double disk
			2 May	Harvest triticale for silage

Table 23.A3. Some chemical contents of tissues of several crops simulated by CropSyst.

Crop	Soluble C	Holocellulose[1]	Lignin	Source
Winter/Spring wheat	5	75	20	Sylvia et al, 2005
Spring barley	4	90	6	Henriksen and Breland, 1999
Spring pea	7	84	9	Henriksen and Breland, 1999
Potato	28	65	7	Henriksen and Breland, 1999
Sweet/Silage corn[2]	5	85	10	Sylvia et al, 2005
Triticale[3]	5	75	20	

[1] Calculated as 100 - Soluble C % - Lignin %. Holocellulose is the sum of cellulose and hemicellulose.

[2] Determined by rough proportion with wheat

[3] Assumed to be the same as wheat

Table 23.A4. Initial soil organic matter percentages used in CropSyst simulations at several locations in the Pacific Northwest. (As of 9-20-09)

Depth (cm)*	Lind/Shano s.l.	St. John/Athena s.l.	Pullman/Thatuna/Palouse s.l.	Paterson/Quincy fine sand
0-5	0.9	1.4	2.9	0.7
5-10	0.9	1.3	2.9	0.6
10-20	0.7	1.3	2.9	0.5
20-30	0.3	0.8	2.1	0.1
30-40	0.3	0.4	1.2	0.1
40-50	0.3	0.4	1.2	0.1
50-60	0.2	0.2	0.4	0.1
60-90	0.2	0.2	0.4	0.1
90-120	0.1	0.1	0.2	0.1
120-150	0.1	0.1	0.2	na
150-180	0.1	0.1	0.1	na
180-210	0.1	0.1	0.1	na

*In Lind, the top 3 depths are 0-3, 3-7 and 7-20, respectively.

Table 23.A5. Initial carbon partitioning, as a percentage of total carbon, among the microbial biomass, labile, metastable and passive carbon pools at four Pacific Northwest locations for which CropSyst simulations were generated.

		Li	nd			St.	John			Pull	man			Pat	erson	
Depth	Micro	Labil	Meta	Passv	Micro	Labil	Meta	Passv	Micro	Labil	Meta	Passv	Micro	Labil	Meta	Passv
0-5	2.6	3.5	33.6	60.4	0.6	3.1	44.2	52.1	1.4	2.8	28.4	67.4	7.2	7.9	27.2	57.7
5-10	0.8	2.0	33.5	63.7	0.4	2.2	44.0	53.4	1.3	2.3	28.5	67.9	1.1	5.9	29.3	63.8
10-20	0.7	1.2	23.1	75.0	0.4	2.1	45.0	52.6	0.6	1.8	29.3	68.4	0.4	1.5	19.8	78.3
20-30	0.4	0.5	14.0	85.1	0.1	0.4	17.4	82.0	0.2	0.3	10.7	88.8	0.9	2.4	37.4	59.3
30-40	0.4	0.4	13.5	85.6	0.1	0.5	18.8	80.6	0.2	0.3	9.6	89.9	0.9	2.2	35.4	61.5
40-50	0.3	0.4	13.6	85.6	0.1	0.5	18.1	81.3	0.2	0.3	9.2	90.4	0.8	2.0	32.9	64.3
50-60	0.5	0.6	21.4	77.5	0.2	0.7	24.3	74.9	0.5	0.8	25.5	73.3	0.7	1.7	28.3	69.3
60-90	0.5	0.6	19.7	79.2	0.2	0.6	20.4	78.9	0.4	0.7	21.7	77.2	0.7	1.4	24.7	73.3
90-120	0.7	1.1	27.3	70.9	0.3	1.1	37.5	61.1	0.5	0.9	27.3	71.4	0.5	0.9	17.1	81.5
120-150	0.4	0.5	12.8	86.3	0.2	0.6	21.5	77.7	0.2	0.4	13.8	85.5				
150-180	0.1	0.1	1.4	98.5	0.1	0.1	3.2	96.7	0.1	0.1	1.4	98.6				
180-210	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0				