Predicting Changes in Landscape-scale Soil Organic C Following the Implementation of Minimum Tillage

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Summary

In 2003, we established minimum tillage (MT) and standard tillage (ST) systems in a grower's field. We conducted intensive soil sampling in order to develop a data set of baseline soil C, N, and physical and chemical soil properties. From fall 2003 through fall 2004, we measured greenhouse gas (GHG) fluxes at several spatial and temporal scales after a wheat crop and before, during, and after a maize crop.

Our results indicated that spatial variability of total and particulate organic matter (POM) C and N as well as soil texture was highly variable across the field. Total C, total N, and $\delta^{15}N$ in the top 15 cm of soil were positively related to silt and clay content. However, clay was a poor predictor of new POM-C at the field scale.

Emission of CO_2 and N_2O from dry soil after wheat harvest in July 2003 was very small or zero. The flux from three CO_2 flux measurement methods (eddy co-variance, automated chambers, and portable chambers) compared reasonably well. Carbon dioxide exchange using the eddy-covariance approach clearly showed uptake by photosynthesis of weed growth and then corn growth during 2004. Carbon dioxide uptake for the MT treatment lagged behind that of the ST treatment until later in the crop growth period. The difference in photosynthesis was reflected in less growth for the MT and eventually a depressed grain yield.

Carbon dioxide flux at the soil surface as measured by chambers was highly spatially variable and did not show significant differences between the ST and MT treatments. A clear diurnal pattern to CO_2 flux was apparent with the peak fluxes occurring at maximum soil surface temperature. Very little or no emission of NO and N_2O occurred until fertilization and then decreased again to near zero values after harvest with only minor differences apparent between the two tillage treatments.

Initial simulations from the DNDC model appear to simulate ST yield fairly well, but could not reproduce the slower growth under MT. The model does not appear to simulate respiration well, either before or during the growing season. Simulated emissions of N_2O compare reasonably well.

Objectives

a. To identify underlying mechanisms that control the quantity of C input from below and aboveground crop components across a typical CA agricultural landscape;
b. To determine and quantify the processes that control the rate of CO_2 evolution as affected by minimum versus conventional tillage;

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c. To improve and validate existing C models in predicting soil C across farmer's fields following the implementation of minimum tillage.

Approach and Procedures

The research site chosen is a 30.8-ha irrigated field of a farm managed by Mr. Tony Turkovich near Davis. Irrigation is primarily by furrow irrigation, but sprinkler irrigation is used for seed germination if necessary. Mr. Turkovich already follows minimum tillage practices, and is committed to collaborating with us in the study of minimum tillage on C storage. He maintains records of production costs and income so that a cost-benefit analysis can be done. We also use the research site for teaching purposes, allowing students to visit the site and learn how landscape studies in agro-ecosystems can be conducted. Specifically, several graduate students, one postdoctoral scholar, three undergraduate interns, and two high school students in the Young Scholars Program participated in the research.

The irrigated, laser-leveled field site of this study was in minimum till wheat from Fall 2002 until July 2003. The wheat was planted directly into maize stubble, with no tillage. Thus, the "minimum tillage" practice was essentially no tillage at this point in time. With a part of our project emphasizing the inherent landscape variability in soil C and underlying processes, extensive baseline data were collected before the start of differential tillage treatments. Soil samples were taken at 0-15, 15-30, and 30-50 cm depths of 50 locations using a Dutch auger in February 2003, and above- and belowground biomass of wheat were determined at the same locations in May 2003. Partly based on the initial soil sampling, the 30.8-ha site was split into two fields to represent the grower's standard tillage (ST) and minimum tillage (MT) practices (*fig. 1*). The ST field was tilled in October 2003 and both fields remained fallow until maize planting in April 2004. Maize was planted in the two tillage treatments on April 12 and 13, 2004. Since the existing beds and furrows were deemed sufficient for maintaining reasonable irrigation uniformity, no operations to reform beds were necessary. Liquid urea/ammonium nitrate was applied in a band (10-cm depth) at a rate of 56 kg N/ha in the rows at planting. Both treatments were side-dressed (at 15-cm depth) with 168 kg N/ha on May 24 and 25, 2004. After planting, additional gas sampling chambers were placed in the rows and over the fertilizer injection bands.

Field Sampling and Instrumentation

Soil and plant sampling. After harvest of the wheat in June 2003, the soil profile was sampled to the 1-m depth in a grid and transect sampling scheme at 140 sampling locations across the two fields (see *fig 1*) to establish expanded baseline soil physical and chemical properties including a soil C inventory. The decision to use grid and transect sampling scheme was based on the prior soil sampling and yield maps. The two N-S transects were included to allow for detection of soil changes and properties across the treatment boundary. Sampling locations were on a regular grid with 72 GPS referenced locations and two transects with 34 additional locations each. Soil samples were taken in August 2003 and split into 0-15, 15-30, 30-50, 50-75, and 75-100 cm depth increments. After disking of the standard tillage plot, soils were again sampled at the 140 locations in December 2003, but only to a depth of 0-15 cm. The soil samples are being processed and analyzed for total organic C and N, $\delta^{13}C$ of the particulate organic matter (POM) fraction, particle size distribution, bulk density, soil water content, and other physical factors. In

addition, changes in microbial biomass in the top 15 cm of soil will be measured. In 2004, soil and crop samples were taken periodically during the year, and then processed and analyzed for soil C fractions.

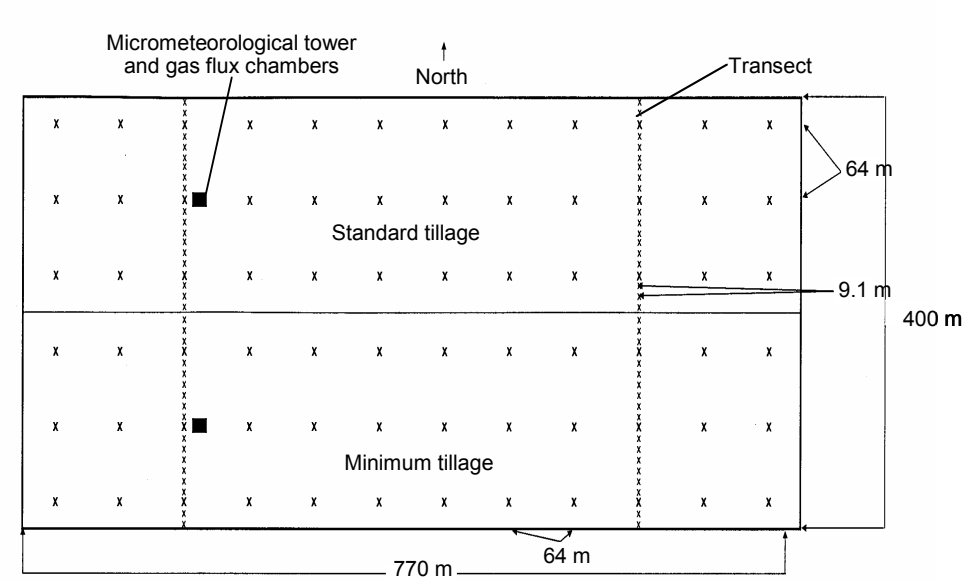

Figure 1. Field diagram showing the 140 soil sampling locations. The micromet towers, automated chambers, and below ground sampling locations are located near the west transect in the middle of each field.

The total amount of C and N input via shoot and root biomass of wheat was measured at 50 locations in May 2003. Total yield samples of wheat in the fields were collected by hand in June 2003 at all 140 sampling locations and then separated into grain and residue. The grower also collected grain yield data spatially with a yield monitor on the combine. Aboveground residue of wheat and maize (previous year) left on the surface were also collected in August 2003. Total yield samples of corn were collected at selected sites by hand in August 2004. The grower also collected grain yield data spatially with a yield monitor.

CO_2 emissions from eddy-covariance measurements. We used eddy-covariance to measure CO_2 exchange (Net Ecosystem Exchange, or NEE; see Paw U et al., 2000, 2004). Data analyzed were collected between September 2003 and July 2004. Eddy-covariance data were taken over bare soil (September to January), soil with weeds (January to April), after herbicide treatment (April), and the maize crop (April/May onwards). Initial estimates of exchange ignored the transient atmospheric storage of CO_2 within the canopy air space.

One eddy-covariance system was mounted on a guyed mast in each treatment. Measurements of vertical H_2O and CO_2 fluxes were made using two Campbell Scientific Inc. 3-D sonic anemometers (CSAT-3) and two fast-response LiCor 7500 open path infrared gas analyzers (IRGAs) which measured the velocity vector, sonic temperature, and the concentrations of H_2O and CO_2 at 10 Hz. Data were logged with Campbell Scientific Inc. CR-23X data-loggers and laptop computers. Turbulent statistics, included eddy-covariances, were estimated for 0.5 hour intervals. For the eddy-covariance calculations, point-by-point density adjustments were made

in light of the Webb et al. (1980) corrections. The fetch (50:1) over relatively homogeneous ecosystem elements, and relatively strong levels of turbulence, allowed us to assume that the mean advection terms were negligible under most conditions (Paw U et al. 2000; Park and Paw U). In addition to the fast-response instruments, two net radiometers, two ground heat flux plates, and two aspirated temperature and relative humidity sensors were placed on the masts, to assist with energy budget and other biomicrometeorological analyses.

Greenhouse gas emissions with portable chambers. It is clear from several studies (van den Pol-van Dasselaar et al. 1998; Yanai et al. 2003) that the spatial variability of greenhouse gas emissions from soils are quite large. Added to the large spatial variability, temporal variability of emissions also results in large uncertainty in estimating gas fluxes with chambers. For instance, Parkin and Kaspar (2004) determined that measuring CO_2 fluxes only every 20 days may result in cumulative flux estimates that could vary within ±40-60% of the actual flux. Thus, we are attempting to estimate greenhouse gas fluxes from measurements at several spatial and temporal scales. Each field was instrumented with 1) an eddy-covariance mast to measure field-scale CO_2 fluxes, 2) with one or two 0.62-m^2 automated chambers with the capability of assessing the temporal pattern of CO_2 and N_2O fluxes, and 3) with either nine 0.012-m^2 or with twenty 0.05-m^2 portable chambers in order to evaluate the spatial characteristics of CO_2 and N_2O fluxes. Measurements of gas fluxes were made for several weeks before and after tillage operations in mid September 2003 and throughout the 2003-2004 seasons.

Two types of portable chambers that cover the soil surface only (no plants) were used in the field. Insulated stainless steel chambers that moved from site to site and covered 0.012 m^2 of soil surface were used from September 2003 through April 2004. In May 2004, 0.051 m^2 PVC rings were installed in the field. The rings were pushed approximately 5 cm into the soil and left in place at positions in the middle of the bed, middle of the furrow, over the maize row, and over the side dressed fertilizer band. Portable PVC end caps were converted into chamber lids and were placed on top of the rings for sampling.

Using the portable chambers, the CO_2 and N_2O fluxes were measured approximately monthly during the fall and winter months of 2003-2004. Beginning in March 2004, both gases were sampled every two weeks. The CO_2 concentration inside the chambers was measured at 0, 30, 60, 120, 180, 240, and 300 seconds after placement of chambers over the soil surface with a Licor 6262 infrared gas analyzer (IRGA). N_2O was sampled from the chambers (vented) in nylon syringes after 10, 15, 20, or 30 minutes and analyzed within 24 hours on a Hewlett Packard 6890 series gas chromatograph (GC). Surface fluxes were calculated according to the protocol of Hutchinson and Livingston (2002).

NO flux measurements were made using a chemiluminescent NO_x ($NO + NO_2$) analyzer (Unisearch Model LMA-3). Preliminary NO flux measurements were made prior to the maize planting and first fertilizer application. After the planting, NO flux measurements were made regularly using the 0.051 m^2 PVC rings with the PVC end caps as chamber lids as described above and by Venterea and Rolston (2000). Flux measurements were made at least monthly on chambers that were installed in the middle of the beds, in the furrows, in the part of the bed where the maize and fertilizer was placed, and in the side-dressed area.

Below-ground measurements. We have modified and constructed soil gas probes (Burton and Beauchamp 1994) to include thermocouple and pressure transducer capabilities as well as gas-sampling ports at 1.5, 7.5, 22.5, 45, 75, and 105-cm depths. Eight of these gas probes are installed; each synchronized with tensiometers, TDR, and neutron probe instruments. One sampling site per tillage treatment also includes a piezometer. The sampling locations are within 9 m of the micromet towers and automated flux chambers and are arranged to provide duplicate measurements within a corn row and adjacent furrow. All six thermocouples within each gas probe continuously log temperature values averaged over 30-min intervals via Campbell Scientific data loggers. Pressure transducers were connected to all gas sampling probes to measure depth variations in total soil gas pressure, which was used to estimate irrigation effects on gas diffusion and convective flow.

DOC in Irrigation and Tail Water

For two irrigation events during 2004, the amount of irrigation water applied, the amount of tail water discharged from the fields, and various water quality measures were made. Irrigation and tail waters were analyzed for DOC, total dissolved solids, DON, and inorganic N.

Laboratory Incubation Experiments

To evaluate the singular and interactive effects of soil physical, chemical and biological factors on the production of greenhouse gases, we set up short-term incubation experiments. To sample soils for the incubation, 20 locations along each of the two 360-m transects were selected in April 2004, 6 months after disking of the ST field. Two adjacent intact soil cores (inner diameter: 5 cm; length: 15 cm) were sampled and analyzed for soil properties: 1) total microbial and particulate organic matter (POM) fraction C, N, and ^{13}C, 2) soil water holding capacity, 3) texture, 4) pH and 5) electrical conductivity (EC). The other set of samples was used for the incubation. Microbial biomass C was determined by the fumigation-extraction method, as adapted from Lovell et al. (1995). Biomass C was calculated as described by Vance et al. (1987): biomass C = 2.64 (C in fumigated soil – C in unfumigated soil).

For separation of POM fractions, 20 g of air-dried soil was weighed into 250 mL plastic bottles and dispersed with 100 mL of 0.5% sodium hexametaphosphate solution (5 g L^{-1}). After it was shaken for approximately 18 hours on a reciprocal shaker, the dispersed sample was passed through a series of three sieves (1,000, 250, and 53 μm) to isolate three size classes of POM. All POM fractions were oven-dried overnight at 50°C and weighed. Sub samples from each POM fraction were ground, and total C and N content were measured with a Carlo Erba C/N Analyzer (Carlo Erba, Milan, Italy).

To determine the production of CO_2, N_2O, and CH_4, the second set of intact soil cores maintained at field moisture were placed into mason jars equipped with air-tight lids, incubated at 25°C, and the headspace concentrations of the three greenhouse gases were measured at days 1, 2, 3, 5, 7, 10, and 15 using a Photoacoustic Multi-gas Monitor (INNOVA, Nærum, Denmark). For aeration, the jars were opened after each measurement for 10 minutes. In order to maintain constant moisture content, distilled water was added to the soil cores to compensate for loss of water during the incubation. After the 15-day incubation at field moisture, all cores were

adjusted to 60% soil water holding capacity (WHC), and gas production was measured again using the same time intervals.

Modeling

We used the DNDC model (Li et al.; 1992, 2004) to simulate GHG emissions from our research site and eventually to simulate the long-term change in soil C due to tillage practices. The intensive data set collected at a landscape level from the field site will be used to test and evaluate model performance. The model will be modified if necessary to better simulate the N and C cycling process under CA conditions.

The model requires a small number of fixed soil parameters (bulk density, pH, clay content) and initial soil carbon, a complete time series of meteorological data, and information on the farming system. The farming system includes details on the timing of management operations, fertilization and irrigation amounts, as well as crop genetic potential. The crop parameters have to some extent been gleaned from long term data (e.g., SAFS), although not all parameters are available (e.g., C:N ratios, root partitioning, degree day requirements) so there is some necessary tuning. Tuning of crop genetic potential is critical because residue management is a major determinant of annual and long-term carbon balance. In the case of cover crops, modeled genetic potential of the plants has an important impact on the modeled nitrogen nutrition of the following crop.

Results and Discussion

In order to understand variations in carbon cycling dynamics at the landscape scale, it is relevant to describe soil heterogeneity first (Terra et al. 2004). Among the most versatile soil attributes that can describe soil spatial variation is soil texture or soil particle size distribution. Traditional measurement techniques for soil particle size distribution are based on the sedimentation method (pipette and hydrometer methods) and are time-consuming, thereby limiting the number of soil samples to be analyzed. In contrast, modern techniques such as the laser scattering or diffraction method are relatively quick, allowing many samples to be analyzed in a short time frame. In this study we compared the two particle size distribution methods for 50 samples collected at the field site. Whereas there was an excellent correlation (*fig. 1*) between the two methods, absolute values in clay and silt content were systematically different. Correlation coefficients for the sand and clay fraction were 0.93 and 0.85, respectively. Specifically interesting was the large slope value for the clay analysis, indicating that there is a systematic underestimation of the clay fraction using the laser diffraction method. However, once a calibration has been established, the high correlation coefficients indicate that texture analysis can be confidently conducted using this new experimental technique. The Laser Diffraction (LD) method appears to be a valid new tool to determine soil textural variations across the landscape.

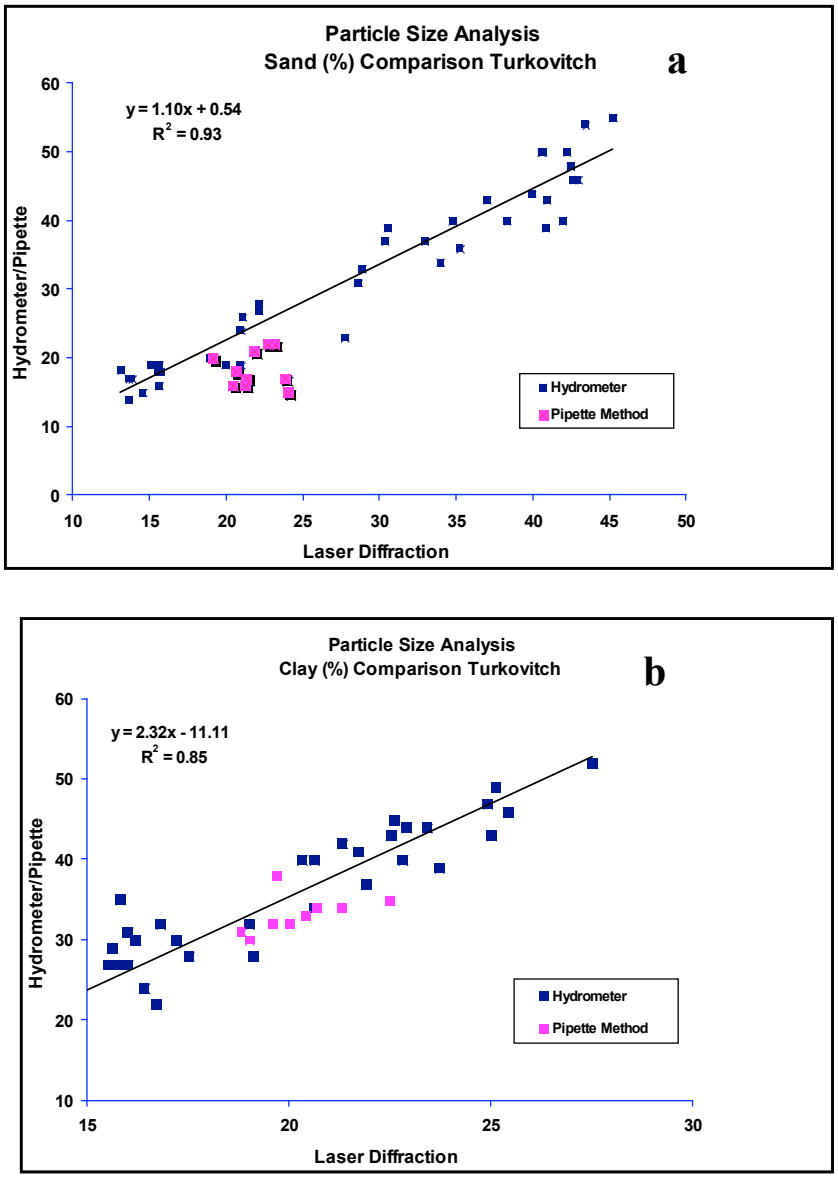

Figure 1. Comparison of sand (a) and clay (b) fraction between conventional sedimentation method (vertical axis) and laser diffraction method (horizontal axis) for a wide range in soil texture as determined from soil samples collected at the Turkovich field.

The baseline data collected in February 2003 were used to quantify the inherent variability of soil texture (0-15 cm) (*fig. 2*) and soil organic C and N across the field prior to implementation of conservation and standard tillage practices (*table 1*). The amount of C and N input via shoot and root biomass of wheat and the root:shoot ratios were determined. Correlation and regression analyses were performed among all variables. Other variables across the entire field were also estimated by kriging (*figs. 2, 3, 4*). The baseline data show that spatial variability of soil organic C and N as well as soil texture was great at the field scale, and that the root/shoot ratio was highly variable across the field. In addition, the coefficient of variation (CV) of C input by the biomass was approximately 50%. Total C, total N, and $\delta^{15}N$ in the top 15 cm of soil were

positively related to silt and clay content, suggesting that silt and clay contents may control the storage and sequestration of soil C and N. Carbon input by wheat biomass was a poor indicator for the spatial distribution of soil C and N. However, there was a significant relationship between C input via root biomass and sand or silt.

Table 1. *Total C, total N, delta ^{13}C, delta ^{15}N, soil texture, and the amount of C input via wheat biomass (n=50).*

	Depth (cm)	Mean	Range	CV (%)
Total C (%)	0-15	1.05	0.64 - 1.61	17
	15-30	0.77	0.32 - 1.03	17
	30-50	0.60	0.25 - 0.87	21
Total N (%)	0-15	0.11	0.08 - 0.14	13
	15-30	0.09	0.05 - 0.11	13
	30-50	0.07	0.04 - 0.09	15
Delta ^{13}C (‰)	0-15	-21.75	-22.90 - -19.00	3
	15-30	-23.44	-24.44 - -22.15	3
	30-50	-24.10	-25.03 - -21.46	3
Delta ^{15}N (‰)	0-15	5.02	3.58 - 7.41	15
	15-30	4.99	2.99 - 6.19	14
	30-50	4.92	2.74 - 6.46	16
Sand (%)	0-15	29.0	18.9 - 43.4	26
	15-30	24.5	15.5 - 45.2	32
	30-50	23.1	13.0 - 42.4	35
Silt (%)	0-15	52.9	41.6 - 60.9	10
	15-30	55.6	40.5 - 62.5	10
	30-50	55.4	42.3 - 63.3	10
Clay (%)	0-15	18.2	13.3 - 22.8	15
	15-30	20.0	14.2 - 25.1	15
	30-50	21.5	14.6 - 27.5	14
Shoot C input (kg ha^{-1})		3427	646 - 7452	51
Root C input (kg ha^{-1})		276	26 - 548	44
Total C input (kg ha^{-1})		3703	882 - 7890	47
Root/shoot ratio		0.11	0.01 - 0.37	76

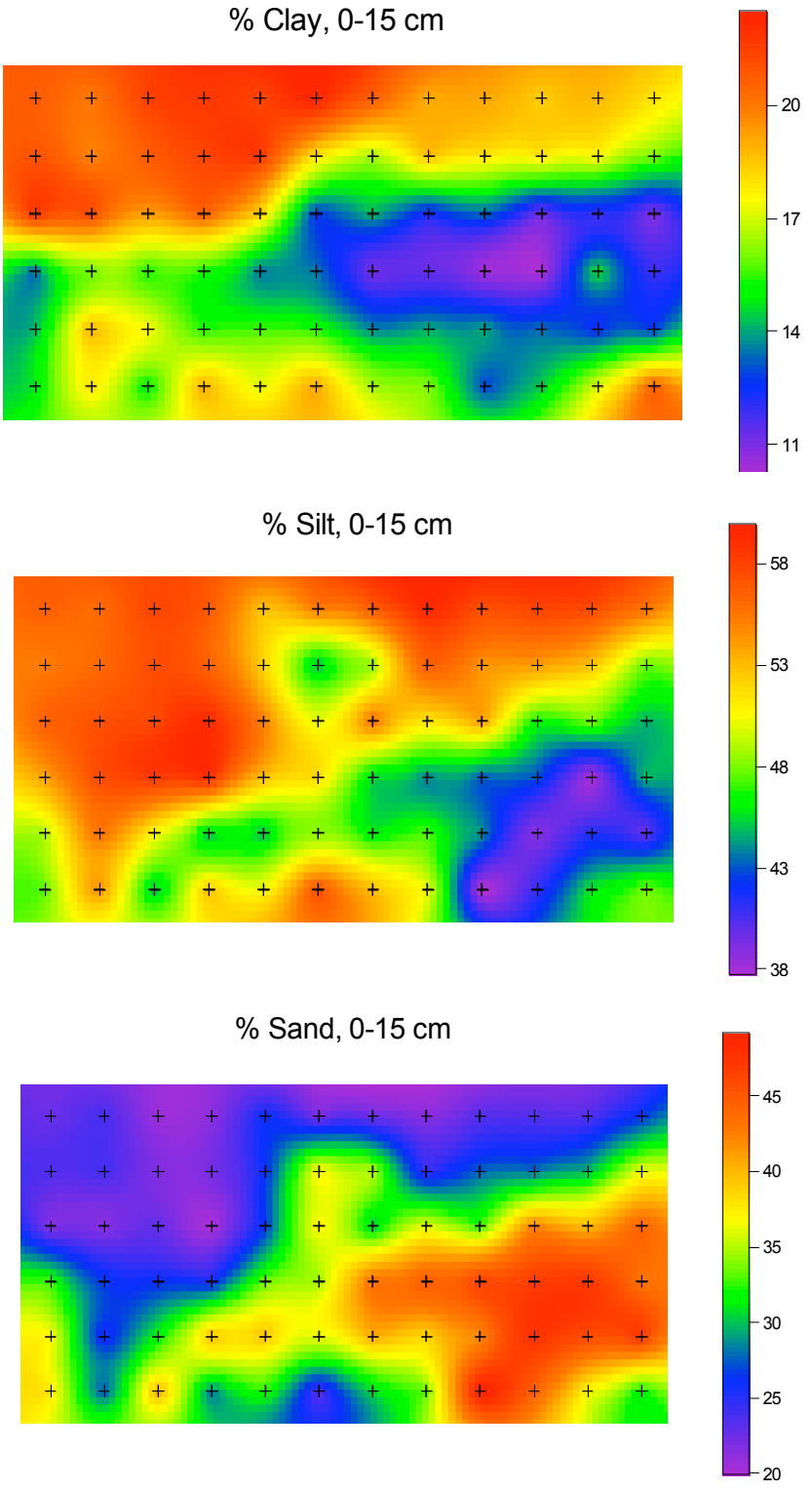

Figure 2. Soil particle size maps determined from the August 2003 soil sampling.

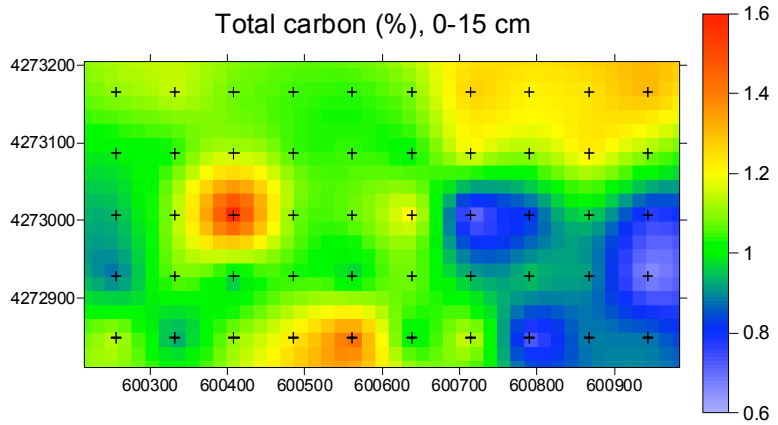

Figure 3. Estimation of total C across the field.

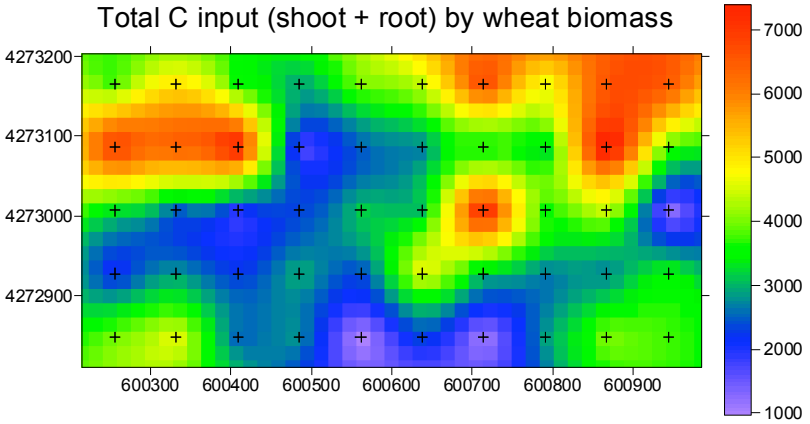

Figure 4. Estimation of the amount of C input via total biomass (shoot + root) of wheat across the field.

Bulk Density, Soil-Water Content, Precipitation, and Air Temperature

Figure 5 gives the bulk density and the soil-water content of the surface soil (0-15 cm) from August 2003 to October 2004. It is clear that the bulk density of the MT field was significantly higher than that of the ST field.

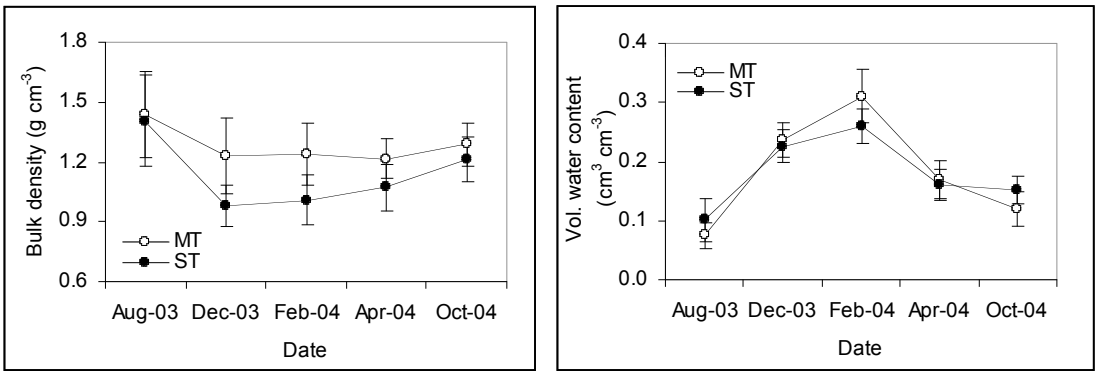

Figure 5. Bulk density and soil-water content of surface soil (0-15 cm).

Figure 6 shows the mean weekly precipitation and air temperature at the nearest weather station on the Davis campus from Nov. 1, 2003 through the end of December 2004.

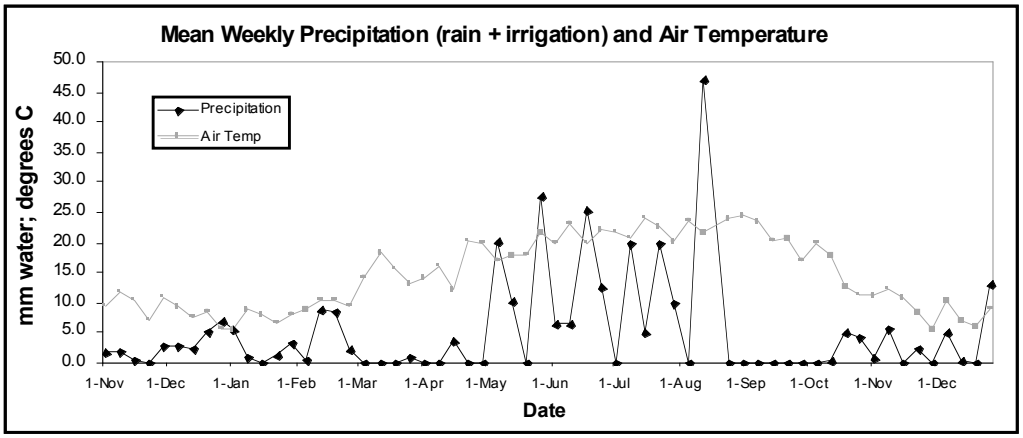

Figure 6. Precipitation and air temperature from November 2003 through December 2004.

CO_2 Exchange From the Eddy-Covariance Approach

Monthly diurnal patterns. Our results show a clear pattern as a function of season and timing of farming practices. Diurnal patterns were evident in all months, first related to a temperature dependence of soil respiration, and then later related to the light dependence of photosynthesis. The atmospheric eddy-covariance fluxes represent a net CO_2 flux as determined from soil/root respiration (positive flux) and photosynthesis (negative flux). Measurements started in September 2003 when the soils of both treatments were dry with stubble and trash and few or no live weeds. Consequently, only respiration occurred, with CO_2 emitted into the atmosphere. Only after the rains started did weeds start growing, and the CO_2 exchange gradually began to show appreciable net photosynthesis in January and February (*fig. 7*). Round-up was applied in March, resulting in a cessation of photosynthesis, leaving only respiratory activities. Maize was planted on April 10. Therefore, by May strong diurnal photosynthetic patterns were observed by the young growing plants (*fig. 7*).

Comparison of the different cultural treatments (minimum till and standard till. The fields showed differences both before and after tillage operations. In general, our measurements show that the standard till (ST) field released about 1.6 times more carbon to the atmosphere than did the MT field before tillage. Although the upper part of the soil profile was dry in all parts of the field during September, water content measurements from the August sampling at the 30-50 cm depth of the transect close to the towers showed a strong spatial trend of higher water content in the north field (ST) than in the south field (MT), which may partially explain the results for September. After tillage, the difference reduced somewhat (to 1.32 times). Both treatments showed an exponential decrease of respiration following the mid-October cultural operations, with a time constant of approximately 10 days (*fig 7*). However, tillage did not appear to increase the CO_2 emission, unless it occurred within three days of tillage. As the months passed, the ST released only slightly more CO_2 than the MT.

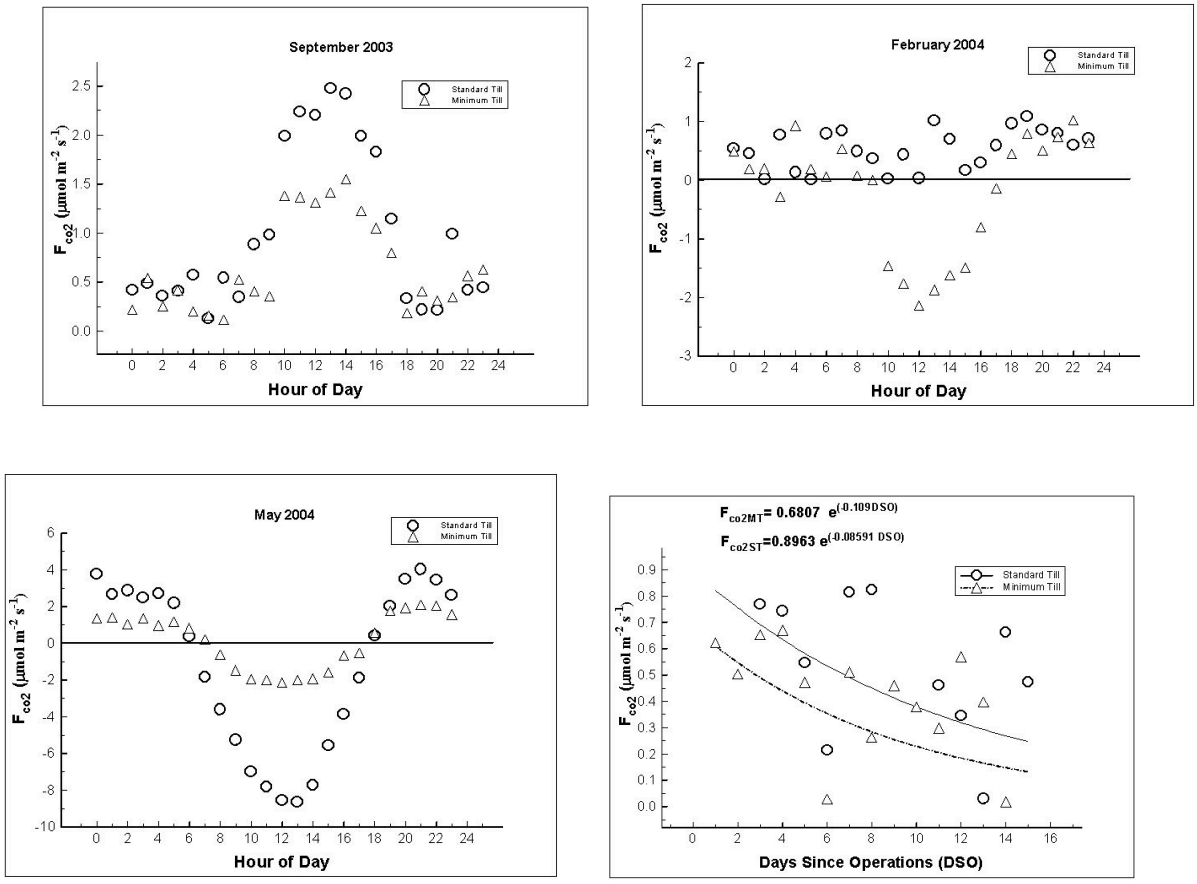

Figure 7. Mean CO_2 exchange on a diurnal basis for Sept. 2003 (before tillage), Feb. 2004 (weed growth), and May 2004 (corn growth) as measured by the eddy-covariance approach. The mean values are from two averaged measurements per hour for all days of the month where measurements were obtained. The lower right panel gives the change in daily mean CO_2 emissions starting three days following tillage in mid Oct. 2003.

With moist soil conditions, photosynthesis was apparent in January and February of the MT treatment indicating weed (mostly volunteer wheat) growth; meanwhile the standard tillage treatment shows minimal signs of photosynthesis. The weed biomass measured on 1/28/04 and on 3/2/04 for the MT was 3.3 and 1.8 times greater than that measured for ST. By early March when Roundup was applied, respiration dominated, related to the killing of the weeds and associated farming activities, and this continued into April. Finally, in May, maize growth was important, with the plants in the ST growing more vigorously than those in the MT. By July, however, the photosynthetic C uptake rates were approximately equal (*fig. 8*). Although we have not been able to determine the underlying causes which led to an early, more vigorous growth of maize under ST management, one cause may be the lower bulk density in the ST field compared to that of the MT field and maybe related to an increase in root related diseases in the MT system during the early part of the growing season.

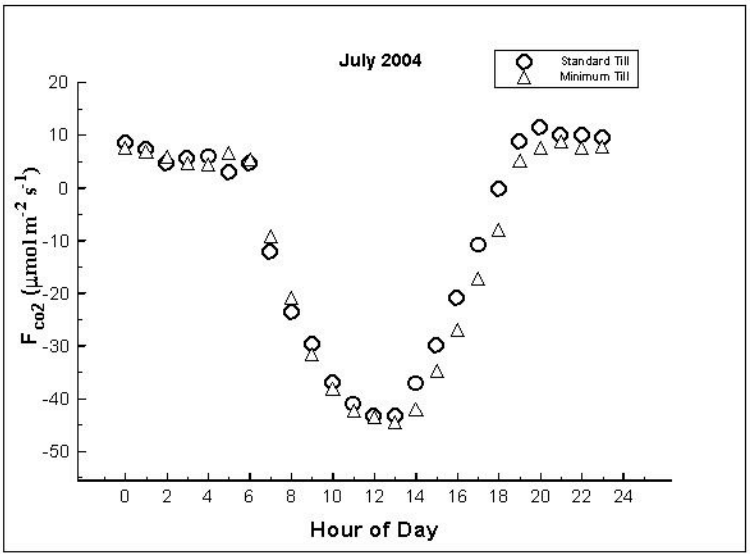

Figure 8. Mean CO_2 exchange on a diurnal basis for July 2004 as measured by the eddy-covariance approach.

A linear regression analysis was performed on the CO_2 exchange for the ST versus that for the MT. For the month of May, the ST treatment exhibited approximately triple and double the photosynthetic uptake of the MT treatment. By July, the maize in the MT field apparently caught up with the ST with the photosynthetic uptake being nearly equal between the two treatments (slope of 0.97, regression not shown). The same approximate ratio was observed for the nocturnal respiration rates, probably related to a linear proportionality in the nocturnal growth and maintenance respiration rates and the preceding photosynthate accumulation during the day. These differences in maize growth were evident in the visual appearance of the fields.

Figure 9 shows the mean CO_2 flux for December 2004 as a function of time of day for the ST and MT field sites. The mean fluxes for the ST and MT were 0.5 and 0.8 μ moles m^{-2} s^{-1}, respectively. At these very small fluxes there is a large amount of variability. Thus, one would conclude that during this period that the respiration from both tillage treatments was nearly equal. These fluxes are also similar to measurements made with the portable chambers during December 2004.

CO_2 Emissions Measured by Chambers

As expected, the spatial variability of CO_2 emission from the soil (respiration) was generally quite large. From the 0.35-m^2 chambers, until the rainy season began, we found no significant fluxes of CO_2 or N_2O at the soil surface. When the soil moisture level increased, however, measurable CO_2 flux began (*fig. 10*). On average, CO_2 emissions have been slightly higher in the no-till treatment, where fresh residue on the wet soil surface may provide abundant carbon for microbial respiration. However, the flux values are very spatially variable, and the flux values are generally not significantly different between the two tillage treatments.

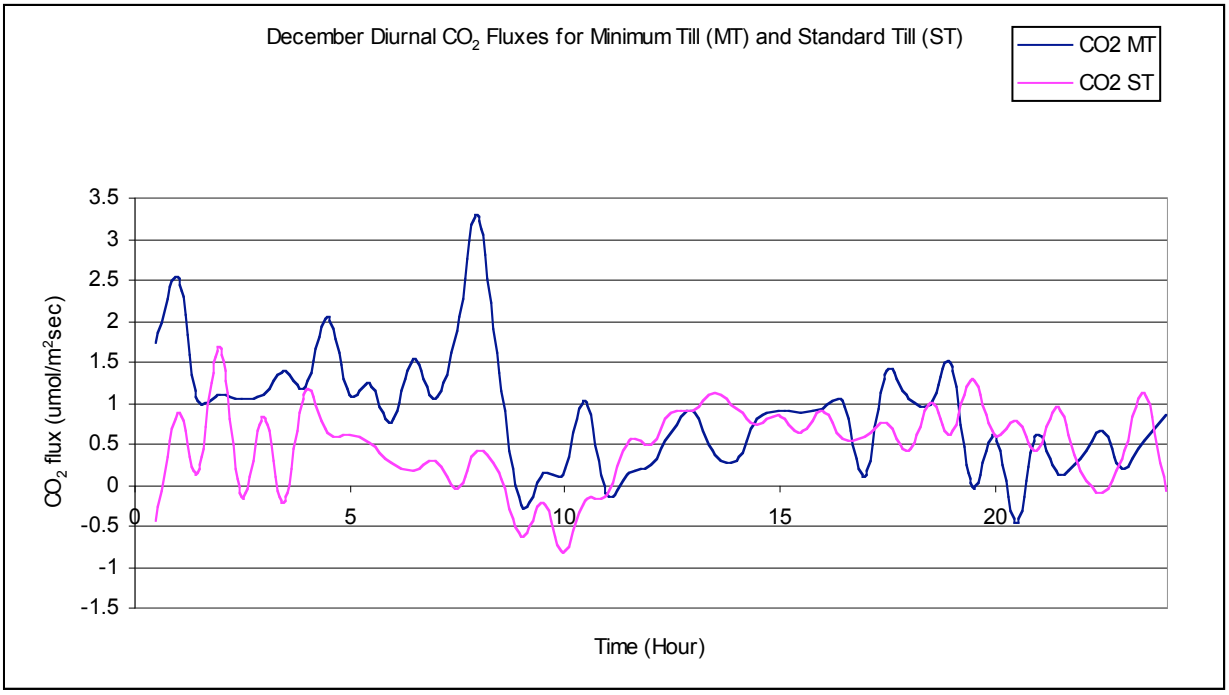

Figure 9. Mean carbon dioxide flux for December 2004 versus time of day using the eddy-covariance method.

There was no observable emission of N_2O for most of fall 2003, with the exception of the Dec. 2 sampling date, when minor surface flux was recorded. These preliminary N_2O data also show higher flux on the MT (no-till) side.

The flux from all three CO_2 flux measurement methods (eddy co-variance, automated chambers, and portable chambers) was compared for Nov.21, 2003. The flux values from the three methods are all reasonably close to each other (*table 2*). A comparison between the eddy-covariance method and the automated chambers over three days in early September 2003 also showed a comparable flux of about 1 μ mole m^{-2} s^{-1}.

Table 2. *Mean CO_2 flux in μ moles CO_2 m^{-2} s^{-1} for three measurement systems on Nov. 21, 2003. Standard deviations are in parentheses.*

	n	12-8 pm	2-4 pm	3-4:30 pm
No-till tower	1	1.36 (0.55)	1.36 (0.4)	
Till tower	1			1.36
No-till auto chamber	1	1.31	1.47	
Till auto chamber	2	2.51	3.11	
No-till portable chamber	4		1.33 (0.51)	
Till portable chamber	4		1.19 (0.17)	

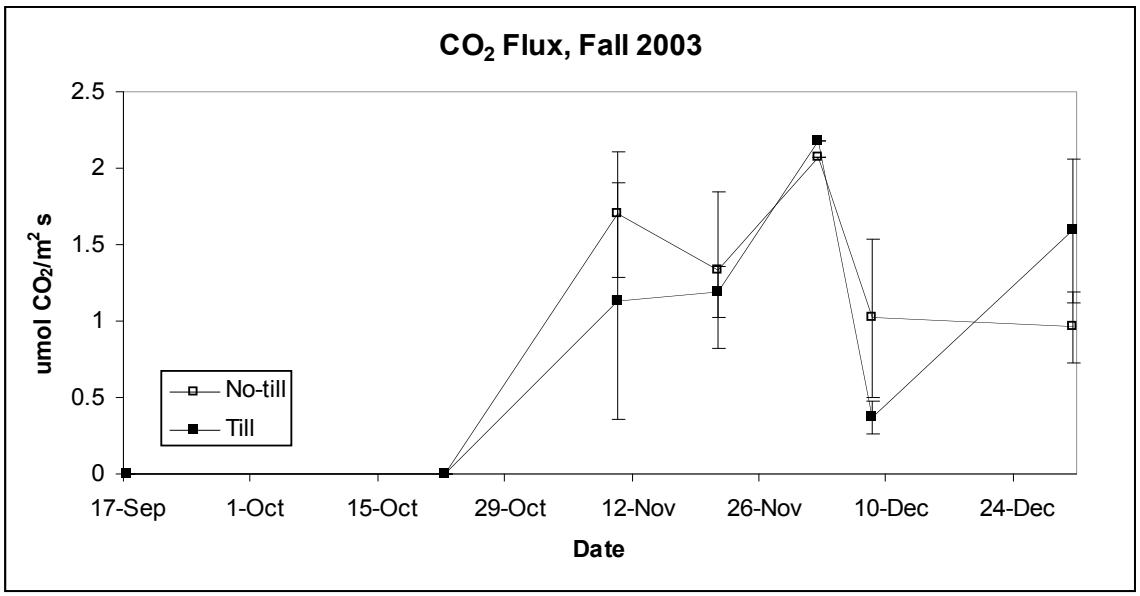

Figure 10. Carbon dioxide emission from the soil surface measured with the 0.35-m^2 chambers (n=4 for each treatment).

Figure 11 gives CO_2 emission from the soil surface using the automated chambers for the period of July 28 to Aug. 5, 2004. Soil temperature at the 8-cm depth is also given. It is seen that the CO_2 efflux from the field was periodic and tracking the periodic behavior of the diurnal soil temperature. The efflux was highest in the middle of the day, and declined in late afternoon and after sunset. For this period, the ST field appeared to have slightly larger emissions than the MT field. The peaks in CO_2 emission occurred earlier in the day than the peaks of soil temperature at the 8-cm depth indicating that much of the CO_2 seemed to be produced near the surface (<8 cm). The surface CO_2 flux values during this time period ranged from about 5-10 μ mole m^{-2} s^{-1}, which is in the same range of the CO_2 nighttime emissions as measured by the eddy-covariance approach for July.

Figure 12 gives the average CO_2 flux as determined from the small chambers located throughout each field area of 15.4 ha from January through November 2004. Due to high standard errors of the mean, there were no consistent differences in mean flux between the ST and MT systems. The ST had higher mean flux in April than the MT and these fluxes compared well with the fluxes measured by the eddy-covariance approach. The CO_2 fluxes showed a general increasing trend as soil temperatures increased from January through July. However, measurements in April show slightly lower fluxes than in March, most likely due to drying of the upper part of the soil profile (confirmed by gravimetric sampling and TDR) prior to maize planting. The first irrigation after planting was a small sprinkler irrigation. The fluxes began to increase again as the soil was periodically furrow irrigated and soil temperatures continued to increase. After harvest in September 2004, the flux gradually decreased due to drying of the soil profile and decreasing temperature. The increase in flux at the late October sampling occurred one day after the first major rain (27 mm) of the season.

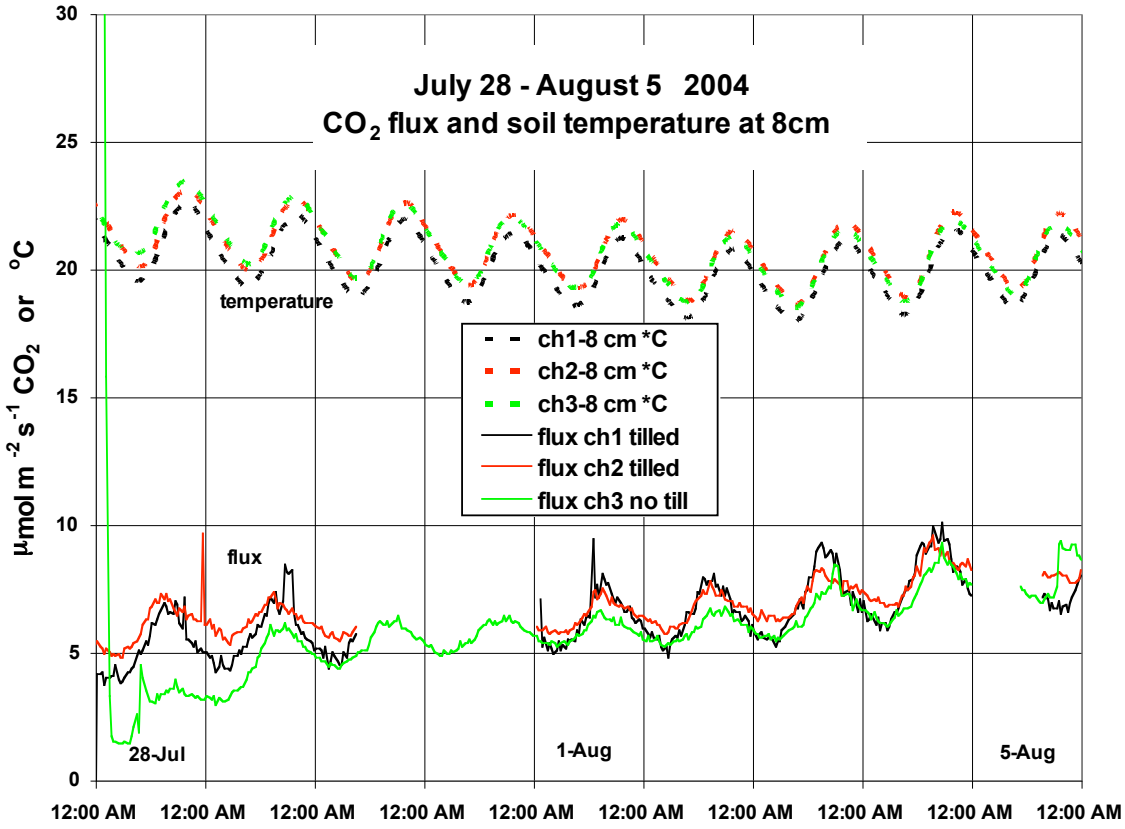

Figure 11. Carbon dioxide surface flux and soil temperature from July 28 to August 5, 2004, using the automated chambers.

Analyses of CO_2 flux data were made from chambers placed in the bed, in the corn row, over the fertilizer side-dressed band, and in the furrow. Overall, there was little or no difference in flux for the various sampling locations with a couple of exceptions. The flux for the furrow location of the MT field during winter 2004 was much higher than in the furrows of the ST field. This difference was likely due to the presence of crop residue in the furrows of the MT field and no residue in the furrows of the ST field. The moist residue on the soil surface of the furrows was apparently producing CO_2 during times when temperatures became sufficient to promote microbial activity. Another exception was that the fluxes in the corn row were higher than those at other locations during June 2004 for both the ST and MT fields. This result may be due to concentrated root mass (and thus root respiration) beneath the row during this stage of plant growth.

Overall, similar magnitudes and patterns of fluxes were measured with the chambers and the eddy covariance method, although the chambers appear to be giving slightly smaller fluxes (measured during the middle of the day) than the nighttime CO_2 exchange as measured by the eddy covariance approach. This difference can be partly explained by nighttime plant respiration. Flux data from the automated chambers and smaller chambers were also similar in magnitude and corresponded to the diurnal patterns and flux values determined with the eddy-covariance

approach. Simple correlation analysis indicated that CO_2 flux is primarily correlated with soil surface temperature.

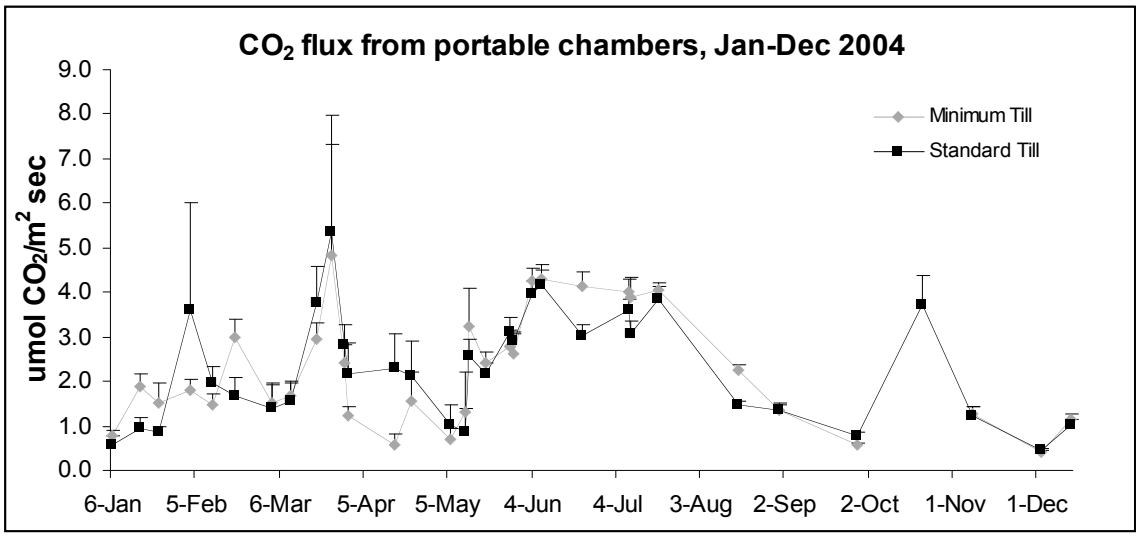

Figure 12. Carbon dioxide fluxes for 2004 as measured with portable chambers. Bars are the standard error of the mean.

NO, N_2O, and CH_4 Emissions as Measured by Field Chambers and Lab Incubations

The CH_4 emissions were nearly all negative, indicating that the soil was, as expected, a small sink for CH_4. Very little or no emission of NO and N_2O occurred from October 2003 until April 2004. Soon after planting of the corn and fertilization, emissions for both gases increased. Emission of NO occurred mostly at sampling locations directly over the fertilizer bands, and there was a trend for more emissions on the standard till locations (data not shown). The mean monthly N_2O fluxes (excluding fluxes from the side-dressed areas) increased gradually from March through June (0.2 mg N m^{-2} h^{-1}) and then decreased to about half the peak values in July and remained nearly zero for the remainder of 2004 (*fig. 13*). Only minor differences are apparent in N_2O fluxes between the two tillage treatments. The largest differences occurred between fluxes over the side dressed fertilizer band and the rest of the area. As expected, large emissions occurred directly over the fertilizer band. The smallest emissions tended to be from the furrow locations. This large spatial variability not only across the field but also within the bed and furrow, represents a challenge in calculating field scale fluxes because of the uncertainty in determining the area of the emission.

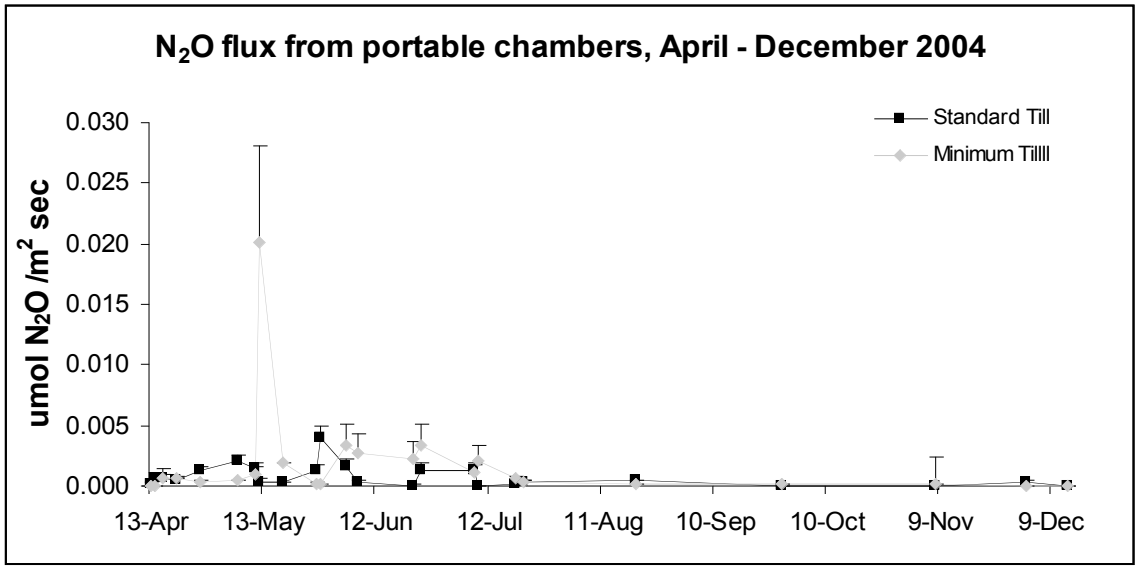

Figure 13. Nitrous oxide fluxes for 2004 as measured with portable chambers. Bars are the standard error of the mean.

Incubation Studies

In 2004, 40 soil cores were taken to a depth of 0 to 15 cm at regular spatial intervals along two 360-m transects, which represented a range of variation in soil texture and moisture. The cores were incubated at 25°C at field moist state for 10 days, and then were wetted to 60% of water holding capacity (WHC) and incubated again for additional 10 days. At field moist state, the global warming potential (GWP) was, on average, greater in the ST than MT soil cores, and CO_2 production rates were greatest contributor to the GWP of both the ST and MT soils. However, spatial variability of GHG emissions was large at the field scale, masking tillage-induced differences in the emissions. Upon wetting the soil cores to 60% WHC, both CO_2 production rates and N_2O accumulation rates drastically increased, but more in the MT than ST cores. Compared to the ST soils, the MT soils with low clay content lost relatively more C and N in the form of GHG as moisture content increased. Most of the spatial variability was primarily explained by differences in tillage and soil texture (e.g., clay content) and to a lesser degree by differences in soil C and N content as well as moisture, indicating an interaction between tillage, soil texture, and moisture content in determining GHG emissions. Microbial biomass, mineral N, and dissolved organic C were also key controlling factors for N_2O accumulation rates.

New Particulate Organic Matter (POM) C Input

The surface samples (0-15 cm) taken in August 2003 and April 2004 at 140 locations were analyzed for C, N, and $\delta^{13}C$ associated with POM fractions (53-250, 250-1,000, and 1,000-2,000 μm) in order to quantify C pools that are sensitive to tillage-induced changes in C input and decomposition. The spatial and temporal variability of new POM-C in the surface samples (0-15 cm) was great at the field scale (*table 3*). As the size of POM fraction decreased, new POM-C content tend to increase but mean residence time decreased. On average, new POM-C was greater in the MT soils than ST soils, indicating tillage effects on C input. More importantly,

fine (53-250 µm) POM-C in the MT soils was greater than the ST soils, showing that MT could effectively enhance the stabilization of soil organic C under Mediterranean climate conditions. The preliminary data collected prior to the implementation of MT showed that soil organic C in the top 15 cm were positively related to silt and clay content. This indicates that silt and clay contents are key factors, which control the storage and sequestration of soil C across the fields. However, clay was a poor indicator for the spatial distribution of new POM-C (*fig. 14*). But, there was, partly in space, still a negative correlation between new POM-C input and clay content. This indicates that soil organic C distribution at the landscape scale is likely to be controlled by a set of controlling factors rather than by a single factor.

Table 3. *Comparison of wheat-derived new C input into POM fractions and corresponding mean residence time (MRT) (ST = standard tillage, MT = conservation tillage)*

		New POM-C (g C m^{-2})			MRT (yr)		
	Fraction size	Mean	Max	Min	Mean	Max	Min
ST	>1000 µm	4.18	11.05	0.97	0.77	2.10	0.25
	250-1000 µm	10.01	25.38	0.67	0.98	3.77	0.36
	53-250 µm	20.27	51.82	3.95	0.81	2.49	0.39
MT	>1000 µm	5.63	16.78	0.65	1.32	5.35	0.31
	250-1000 µm	15.95	38.49	2.18	2.06	10.89	0.38
	53-250 µm	27.69	71.84	0.01	1.55	6.85	0.42

Yield

Based on the observed depression in plant height for the corn during the growing season of 2004 for the MT treatment and the decreased photosynthetic uptake for the MT field during the early part of the growing season, it was expected that the grain yield at harvest may also be depressed for the MT field. This was indeed correct with the yield for the MT field to be 8,630 kg/ha compared to 11,809 kg/ha for the ST field. Analysis of the hand harvest of total biomass and grain yield is still underway.

Preliminary Modeling Results

Initial results show that the model can simulate fairly well the yield measured under standard tillage, but has difficulty reproducing the slower growth under minimum tillage. Despite simulating yield well, the model does not appear to simulate ecosystem (non-plant) respiration well, either before or during the growing season (*fig. 15*). Throughout the winter, CO_2 efflux measured by eddy covariance and closed chambers show much greater respiration than was modeled. Although respiration is not directly measured by eddy covariance, the chamber measurements indicate that true respiration is much greater than modeled respiration throughout the growing period. The sources of this discrepancy are not obvious, although greater respiration during the growing period may reflect a higher carbon allocation to roots than was parameterized (the majority of ecosystem respiration in the model comes from roots), and the wintertime respiration observations indicate that there is a higher non-root (i.e., soil) respiration throughout the year which is not captured by the model. The cause of a model underestimation of soil respiration may also be due to soil temperature or moisture regimes, to residue input and quality,

or to decomposition kinetic parameters. Comparisons of the model temperature and moisture regime with measured temperature and moisture will help identify problems with the model specification or the model physics.

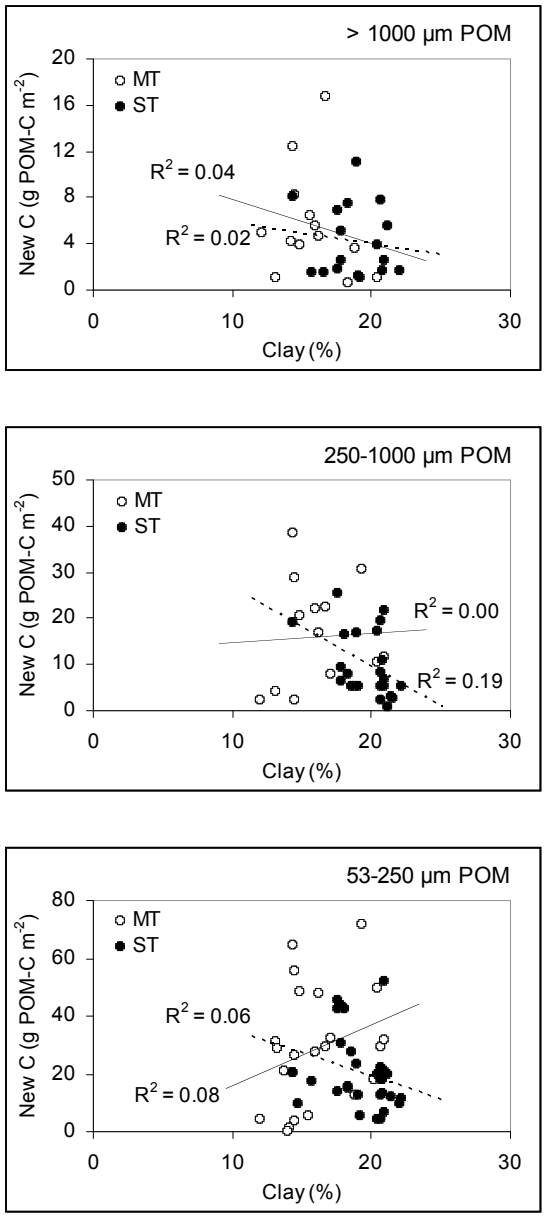

Figure 14. New POM-C input by clay content (ST = standard tillage, MT = minimum tillage)

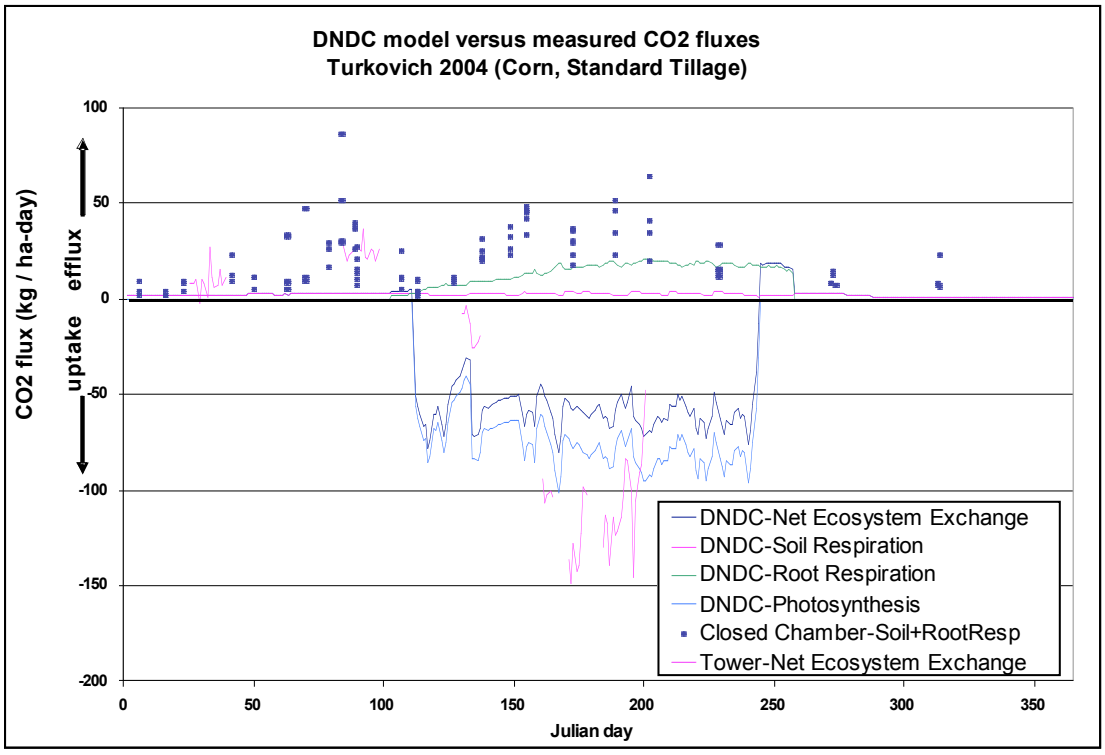

Figure 15. Measured and simulated CO_2 fluxes for 2004. The simulations using DNDC are for net ecosystem exchange, soil respiration, root respiration, and photosynthesis. The measured values are from the eddy-covariance method and closed chambers.

Model estimates of nitrous oxide (N_2O) emission are apparently well corroborated by the chamber measurements. Although N_2O efflux peaks are very ephemeral (as judged by the simulated efflux, *fig. 16*), the measurements match up well with both the baseline flux magnitude as well as the peaks. This is heartening, because it shows that the model can reproduce the N_2O fluxes well even if its respiration estimates are biased. On balance, the model indicates that the Greenhouse Warming Potential (GWP, in CO_2 units) of N_2O efflux is a bit higher than for CO_2: 1151 kg CO_2 equivalents for CO_2 versus 4886 kg CO_2 equivalents for N_2O. (For CO_2, this figure represents complete removal of residue from the system and is the upper boundary for greenhouse contribution. If a small fraction of residue remains as soil carbon, the GWP of CO_2 would be closer to zero.)

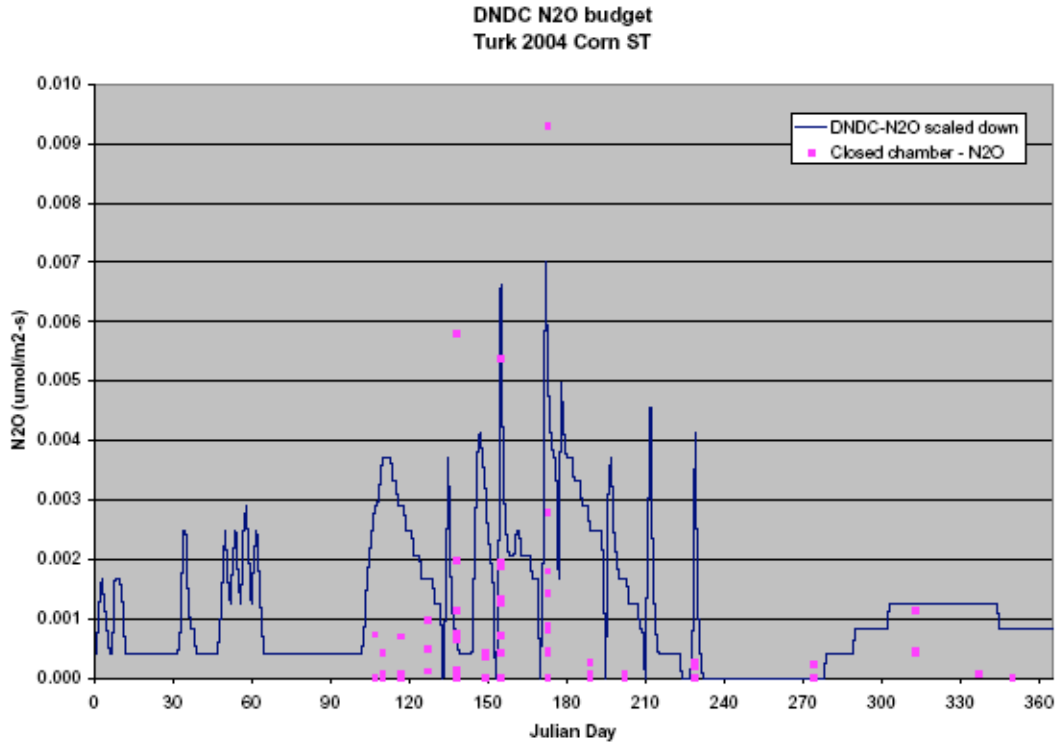

Figure 16. Measured and simulated N_2O fluxes for 2004.

Organic C in Irrigation and Return Flow Water

For the two irrigation events sampled during 2004, no differences in applied irrigation and tail water volumes and water quality measures were found between the two tillage treatments. However, it was found that tail water had about three times higher DOC concentrations than the irrigation water. The enrichment of DOC in the tail water may be explained by exchange between irrigation water and plant residue or surface soil (Lundquist et al. 1999). Although tail waters were generally concentrated with DOC, the total field DOC balances indicated a net addition of 4.2 and 2.7 kg C ha^{-1} for the first and second irrigation, respectively. These additions of DOC with the irrigation water may be insignificant compared to total organic soil C, but are not insignificant in relation to the potential amounts of C sequestered nor are they insignificant versus the levels emitted to the atmosphere via soil and root respiration.

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