Final Report
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Project Objective

The overall objective of this research is to improve our basic understanding of the biophysical processes that govern C sequestration in major rainfed and irrigated agroecosystems in the north-central USA.

Summary of Key Results

A field research facility, consisting of three study sites, was established at the University of Nebraska Agricultural Research and Development Center near Mead, NE. Two sites are equipped with center-pivot irrigation systems while the third site relies on rainfall. We focused on three major cropping systems: (1) irrigated continuous maize (Site 1), (2) irrigated maize-soybean rotation (Site 2), and (3) rainfed maize-soybean rotation (Site 3). Landscape-level fluxes of CO_2, water vapor and energy were measured using tower eddy covariance flux systems (for details on such systems, see Verma, 1990; Baldocchi, 2003, 2008) at the three study sites. Within each site, six small measurement areas (intensive measurement zones, IMZs), each 20 m x 20 m, were established for detailed process-level studies of soil C dynamics, crop growth and dry matter partitioning, soil moisture, canopy and soil gas exchange, and crop residue decomposition. The locations were selected using fuzzy-k-means clustering (De Gruijter and McBratney, 1988) applied to six layers of previously-collected, spatially-dense (4 m x 4 m cells) information (elevation, soil type, electrical conductivity, soil organic matter content, digital aerial photographs, NIR remotely sensed imagery). The IMZs represent all major occurrences of soil type and crop production zones within each site and allow accurate upscaling of ground measurements to the landscape level. Prior to the initiation of the study, in 2001, the irrigated sites (Sites 1 and 2) had a 10-year history of maize-soybean rotation under no-till. The rainfed site (Site 3) had a variable cropping history of primarily wheat, soybean, oats and maize grown in 2-4 ha plots with tillage. All three sites were uniformly tilled by disking prior to the beginning of the study to homogenize the top 0.1 m of soil and incorporate P and K fertilizers as well as previously accumulated surface residues. Since initiation in 2001, all fields have been under no-till (except Site 1 since 2005). Crop management practices (e.g., plant populations, herbicide and pesticide applications, irrigation) have been employed in accordance with the standard best management practices prescribed for production-scale maize-soybean systems. Results from the first 4 years documented declining yields with continuous irrigated maize (Site 1) because of difficulties in achieving uniform and adequate plant populations due to a heavy litter layer that impeded the sowing operation, greater immobilization of fertilizer N reducing fertilizer N use efficiency, and increasing incidence and severity of insect and disease damage. The latter is a common problem in continuous maize that is worsened when large amounts of crop residue litter remain on the soil surface (e.g., Steffey et al., 1999, Handbook of Corn Insects, APS Press, St. Paul, MN.). To address these constraints in our continuous irrigated maize system (Site 1), we began to utilize a conservation-plow in autumn 2005-06 and a mulch-tiller since 2007. This conservation tillage technique reduces soil disturbance compared to other tillage methods.

Atmospheric CO_2 Flux Measurements (Using Tower Eddy Covariance Flux Systems)

Daily values of net ecosystem production (NEP) at the three sites are shown in Figure 1 (NEP is equal in magnitude but opposite in sign to NEE, the net ecosystem CO_2 exchange). These data show the seasonal pattern of strong CO_2 uptake during the growing season and low CO_2 emission (respiration) during the fall/winter/spring “nongrowing” season. Generally, the ecosystems became net sinks of CO_2 in the second or third week of June. The maize fields remained CO_2 sinks for 100 to 110 days. The soybean fields were CO_2 sinks for shorter periods (70 to 85 days) before returning to sources of CO_2 in September to early October. The peak NEP was 15-20 g C $m^{-2}d^{-1}$ for maize and 5-7 g C $m^{-2}d^{-1}$ for soybean. Cumulative daily gain of C by the crops (from planting to physiological maturity), determined from the measured eddy covariance CO_2 fluxes and estimated heterotrophic respiration, compared within ± 15% of measured total plant biomass (Verma et al., 2005).

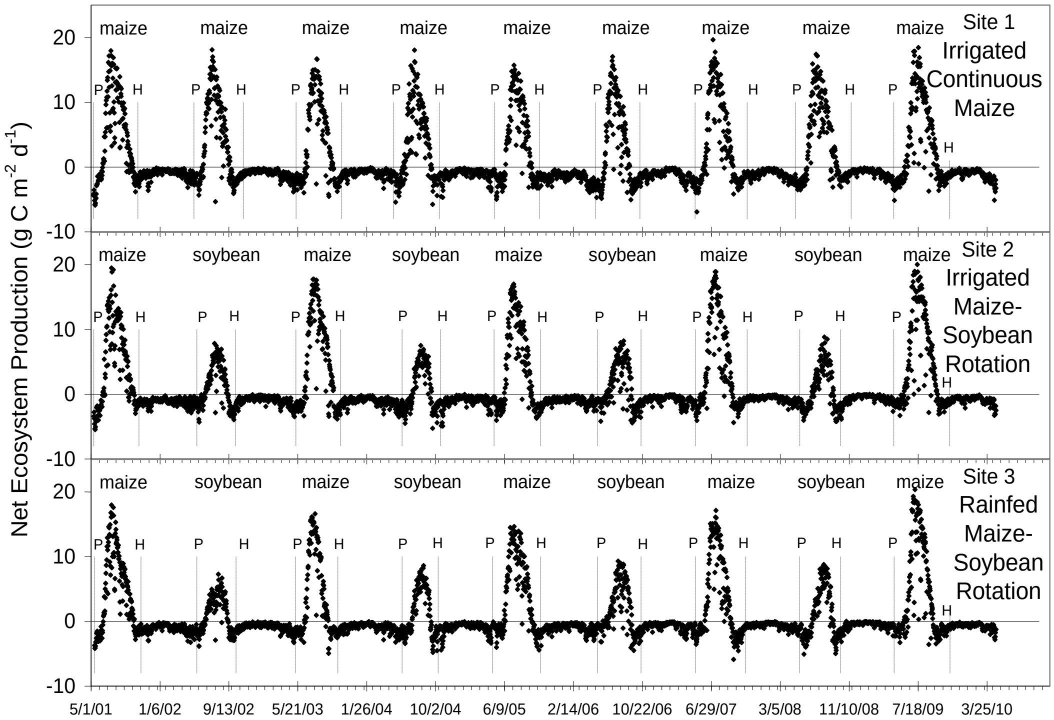

Figure 1. Daily values of net ecosystem production (NEP) at the three study sites. Dates of planting (P) and harvest (H) are indicated with dashed lines.

Gross primary production (GPP) and ecosystem respiration (Re) were calculated (e.g., Xu and Baldocchi, 2003) from CO_2 flux measured at the three sites. Maize (both irrigated and rainfed), had a much larger GPP (about twice) than soybean. The interannual variability in the growing season GPP at all sites (Fig 2) was closely related to the yield (R^2 = 0.95) and aboveground biomass (R^2 = 0.94). The growing season Re in relation to GPP for soybean was higher than that for maize: the growing season Re/GPP ratio for soybean generally ranged 0.81 ± 0.05, whereas the growing season Re/GPP for maize was around 0.61 ± 0.04. This is consistent with our previous observations (Verma et al., 2005). Carbon input to soil from the relatively large amount of maize residues (compared to the amount of soybean crop residues) in previous cropping cycles likely contributed to the high Re/GPP ratio of soybean. The nongrowing season Re was about 0.17 ± 0.04 of the Re during the growing season. Generally the nongrowing season Re values were higher after maize harvest than after soybean harvest.

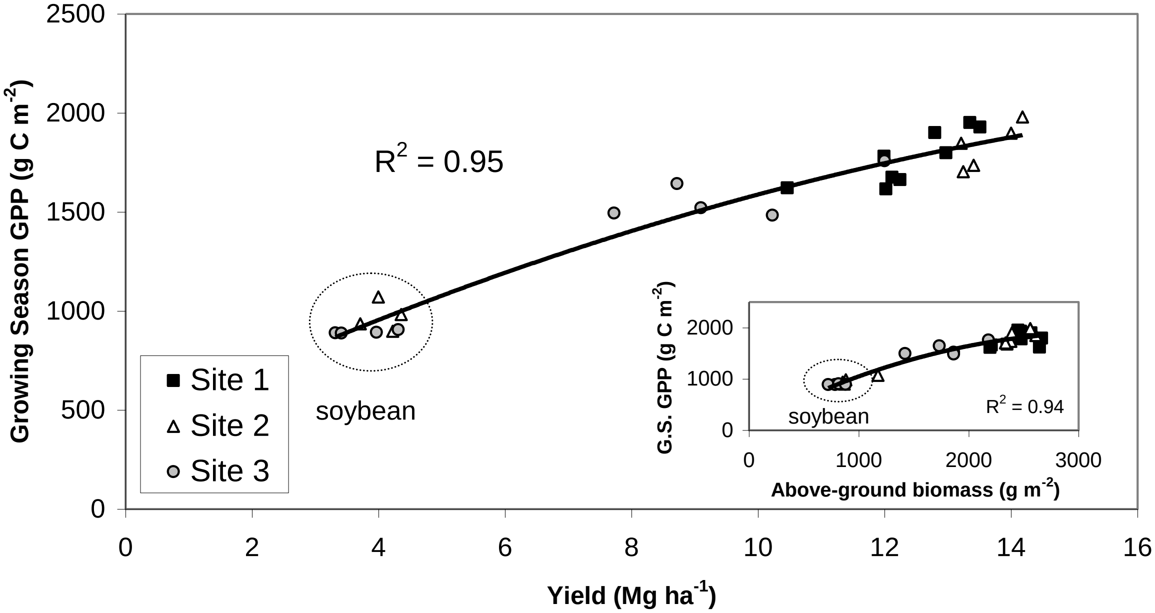

Figure 2. Growing season gross primary production (GPP) vs. yield; Inset: Growing season GPP vs. aboveground biomass.

Soil Surface CO_2 Flux

We have measured soil surface CO_2 fluxes with portable gas exchange systems (LI-6200 and LI-8100, LiCor Inc., Lincoln, NE). Typically, a total of 36 measurements are used to characterize site-specific surface CO_2 fluxes. During the non-growing season, the site-averaged surface emissions were characterized by low fluxes (minima were near 0.02-0.04 mg CO_2 m^{-2} s^{-1}); conversely, the growing season exhibited relatively high fluxes. For example, maize in 2008 exhibited maximum fluxes near 0.35-0.40 mg CO_2 m^{-2} s^{-1} in mid- to late July (DOY 185-210). In soybean maximum fluxes were smaller, near 0.22-0.26 mg CO_2 m^{-2} s^{-1} during late July and August (DOY 210-240), i.e., slightly later than the maxima in maize. The magnitudes of these fluxes were positively correlated with soil temperatures. Spatial variability in soil surface CO_2 fluxes was high. Proximity of the measurement to an existing plant row appeared to have the largest spatial effect. Fluxes measured at within-row positions were almost always higher than fluxes measured at between-row positions. Some of this spatial variability can be explained by the presence of active plant roots, i.e., the root length density and, hence, root respiration, tended to be highest nearest the rows. However, the amount of residue from the previous crop confounded this relationship at times since there was often (especially with soybean following maize) higher residue at the within-row positions. Temporal effects on surface CO_2 fluxes included seasonal changes due to soil temperature, soil water content, and presence of live plants, as well as significant diel changes related to both soil temperature and plant activity. Empirical equations have been fit to the surface CO_2 fluxes to provide an independent estimate of site-level net ecosystem CO_2 exchange, NEE (see next section).

Plant Carbon Assimilation

A portable gas exchange system (LI-6400, LiCor Inc., Lincoln, NE) has been used to quantify single leaf gas exchange properties. In general, maize and soybean leaves exhibited typical C_4 and C_3 responses, C_4 responses (maize) showed less light saturation and lower internal CO_2 concentrations than C_3 responses (soybean). Maximum rates of CO_2 assimilation, i.e., rates in full sunlight at moderate temperatures and vapor pressure deficits, were affected significantly by leaf nitrogen content in both species. Leaf nitrogen content typically peaked early in the season and decreased thereafter. Rates of net CO_2 assimilation in the absence of light (i.e., dark respiration rates) were exponentially related to leaf temperature with Q_{10} near two. Dark respiration rates were also positively correlated with leaf nitrogen content. We estimated canopy photosynthesis by scaling the single leaf responses to the canopy level by quantifying canopy architecture (leaf area index and leaf angle distribution) and predicting interception of direct beam and diffuse radiation. We then combined the canopy photosynthesis estimates with our hourly soil surface CO_2 flux interpolations to estimate NEE. Our results showed, in most cases, a promising agreement with NEE measured by eddy covariance (Arkebauer et al., 2009).

Integration of Results: Carbon Balance

We calculated the net biome production (NBP) of the three cropping systems (Table 1) using the tower flux eddy covariance measurements of the annual NEP, the amount of carbon removed with harvested grain (C_g) and CO_2 released (I_c) from irrigation water (NBP = Annual NEP – C_g + I_c: for details, see Verma et al., 2005). For the irrigated sites, a range of values for NBP is given to reflect the possibility that not all of the CO_2 released from the irrigation water was sensed by the tower eddy covariance sensors. During maize years, the rainfed site was a C sink with a NBP of 95 to 224 g C m^{-2} yr^{-1}. The NBP of irrigated maize varied from -188 to 257 g C m^{-2} yr^{-1}. Both the rainfed and irrigated soybean fields were a significant source of C with a NBP ranging from -282 to -118 g C m^{-2} yr^{-1}.

Examination of two-year averaged NBP values in Table 1 indicates that the rainfed maize-soybean rotation system is approximately C neutral. This result is consistent with other studies of C exchange in rainfed maize-soybean systems that are also based on eddy covariance measurements or direct measurements of soil C stocks that account for changes in soil bulk density (Baker and Griffis, 2005; Wander et al., 1998). The irrigated maize-soybean rotation began as a moderate source of C; however, more recently, it appears to be nearly C neutral. In the first three years, irrigated continuous maize was nearly C neutral. This cropping system was a moderate source of C in the latter three years, perhaps because of the heavy litter layer that reduced GPP by impeding the sowing operation and increasing incidence and severity of insect and disease damage. In response, conservation tillage was initiated starting in autumn 2005. Measurements during the seventh, eighth and ninth years in this system indicate a tendency toward positive NBP, potentially as a consequence of the conservation tillage which is intended to help move crop residues deeper into the soil profile to improve soil C sequestration. Additional measurements are needed to clearly establish whether significant carbon sequestration is achieved, and sustained, in this “modified” irrigated continuous maize system.

Table 1. Carbon balance (g C m^{-2} yr^{-1}): A. Year-by-year results on NBP (net biome production) and B. 2-year averaged NBP.

A. Year-by-year results	Year 1 2001-02	Year 2 2002-03	Year 3 2003-04	Year 4 2004-05	Year 5 2005-06	Year 6 2006-07	Year 7 2007-08	Year 8 2008-09	Year 9 2009-10
Site 1	Maize	Maize	Maize	Maize	Maize	Maize	Maize	Maize	Maize
Annual NEP	515	440	409	346	256	205	468	472	544
C_g	521	503	470	470	447	401	487	447	501
I_c	43	39	49	30	43	35	35	31	14
Annual NBP	5 to 26	-53 to -34	-49 to -24	-116 to -101	-180 to -159	-188 to -171	-10 to 7	33 to 48	47 to 54
Site 2	Maize	Soybean	Maize	Soybean	Maize	Soybean	Maize	Soybean	Maize
Annual NEP	523	-47	593	-116	495	-5	634	-53	780
C_g	518	183	538	171	488	199	496	188	531
I_c	41	26	45	21	40	16	34	28	10
Annual NBP	15 to 36	-224 to -211	66 to 89	-282 to -271	17 to 37	-200 to -192	147 to 164	-234 to -220	252 to 257
Site 3	Maize	Soybean	Maize	Soybean	Maize	Soybean	Maize	Soybean	Maize
Annual NEP	518	-37	395	-20	482	78	481	18	649
C_g	335	153	297	157	340	196	386	178	425
Annual NBP	183	-190	98	-177	142	-118	95	-160	224

B. 2-yr avg.	NBP (2002-2004)	NBP (2004-2006)	NBP (2006-2008)	NBP (2008-2010)
Site 1	-51 to -29	-148 to -130	-99 to -82	40 to 51
Site 2	-79 to -61	-133 to -117	-27 to -14	9 to 19
Site 3	-46	-18	-12	32

Refereed Publications Stemming from This Project

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