Spatiotemporal Variations in Growing Season Exchanges of CO_2, H_2O, and Sensible Heat in Agricultural Fields of the Southern Great Plains

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Abstract

Climate, vegetation cover, and management create fine-scale heterogeneity in unirrigated agricultural regions, with important but not well-quantified consequences for spatial and temporal variations in surface CO_2, water, and heat fluxes. We measured eddy covariance fluxes in seven agricultural fields— comprising winter wheat, pasture, and sorghum —in the U.S. Southern Great Plains (SGP) during the 2001–2003 growing seasons. Land-cover was the dominant source of variation in surface fluxes, with 50–100% differences between fields planted in winter-spring versus fields planted in summer. Interannual variation was driven mainly by precipitation, which varied more than two-fold between years. Peak aboveground biomass and growing-season net ecosystem exchange (NEE) of CO_2 increased in rough proportion to precipitation. Based on a partitioning of gross fluxes with a regression model, ecosystem respiration increased linearly with gross primary production, but with an offset that increased near the time of seed production. Because the regression model was designed for well-watered periods, it successfully retrieved NEE and ecosystem parameters during the peak growing season, and identified periods of moisture limitation during the summer. In summary, the effects of crop type, land management, and water limitation on carbon, water, and energy fluxes were large. Capturing the controlling factors in landscape scale models will be necessary to estimate the ecological feedbacks to climate and other environmental impacts associated with changing human needs for agricultural production of food, fiber, and energy.

1. Introduction

Land-surface exchanges of energy, water, and CO_2 are the dominant factors affecting near-surface air temperatures, boundary-layer CO_2 concentrations, boundary-layer development and structure, cloud development, and precipitation. In the case of energy budgets and surface climate, previous work has shown that spatial complexity and temporal variations in land cover generate variations in climate at the regional scale (Song et al. 1997; Doran et al. 1998; Cooley et al. 2005). Accurately capturing these processes over large scales in agricultural systems is difficult because of spatial heterogeneities driven by land management and large temporal variations (often driven by available moisture). Similar problems exist in capturing variations in the carbon cycle.

Early work focused on quantifying the seasonal variations in surface exchange during growing seasons for individual crop systems (Anderson and Verma, 1986; Baldocchi 1994), whereas later studies explored within-season and interannual variations in sensible heat (H), latent heat (LE), and net ecosystem CO_2 exchange (NEE) in tall-grass prairies, pasture sites, and crop fields (Dugas et al. 1999; Meyers 2001; Suyker and Verma, 2001; Suyker et al. 2003). Recent studies have explored the spatial variations between nearby fields. Initial results from a detailed study of the carbon cycle response to different management strategies demonstrated the large increase in maize production that might be expected under irrigated versus dry-land farming (Suyker et al. 2004). In a two-year study in New South Wales, Australia, flux measurements were made in three sets of paired crop and pasture fields, with the pairs organized along a moisture gradient transect (Leuning et al. 2004). Here, the variations along the moisture gradient and between wet and dry years were all much greater than the differences between the paired crop and pasture fields. However, capturing the effect of moisture in predictive models remains a stubborn problem (Gilmanov et al. 2003; Riley et al. 2003; Hanan et al. 2005, Lai et al. 2006; Inoue and Olioso 2006).

The Southern Great Plains (SGP) region of the United States presents a challenging environment for predicting surface exchanges, because of the frequent chronic and often severe moisture limitations of the region. In the SGP, 80% of the area is managed for agriculture and grazing in a variety of land cover types. Of the agricultural land, about 40% is planted in winter wheat, a C_3 species growing from November to June followed by fallow; 40% is (mostly lightly grazed) pasture containing mixes of C_3 and C_4 grasses that grow from March to October; and the remaining 20% is planted with a mix of C_3 and C_4 crops (e.g., soy beans, grain sorghum, corn) that grow from April through August (Cooley et al. 2005).

In this paper, we describe measurements and analyses that examine the spatial heterogeneity within and across cover types, as well as the interannual variations in growing-season ecosystem-atmosphere exchange for unirrigated agriculture. Within seven unirrigated SGP fields planted with three different crop types, we measured NEE and latent heat, as well as sensible heat exchanges, aboveground biomass, and associated surface meteorological and soil variables. These measurements were made from July 2001 through summer 2003, as part of research conducted by the U.S. Department of Energy Atmospheric Radiation Measurement Program (ARM).

2. Methods

2.1. Site Description

The measurements were performed within 5 km of the ARM central facility (CF), near Billings, North Central Oklahoma (36.61 N, 97.49 W), between July 2001 and August 2003 (Figure 1). We studied three wheat fields (f8, f14, f21), two pastures (f9, f21), two sorghum fields (fP, f101). We note that the field numbers were defined by a preexisting map of the area provided by staff at the ARM site. All fields were level (slopes < 3°) and large enough to provide at least 200 m fetch in the smallest dimension (east or west or north), approximately 400 m fetch in the southern (predominant wind) direction, and at least 200 m fetch in all other directions.

Soils in the area are well drained Kirkland (silt loam; fine mixed thermic Udertic Paleustolls), Renfrow (silty clay loam; a fine mixed thermic Udertic Paleustolls), and Vernon (clay loam; a clayey, mixed, thermic, shallow Typic Ustochrepts) associations. Replicate (n=4) soil cores were collected at 10 and 30 cm depths in fields f8, f21, fP, and fS (see Figure 1) and used to determine soil texture and water retention curves (Carter 1993). The sand:silt:clay ratio was consistent across these fields in proportions 33:22:45 (± 3 on any percentage across fields).

Management of each field was determined by farmers. Table 1 lists the crops planted and nitrogen applications for the fields on which we were able to obtain information; information was unavailable for some fields. Nitrogen was applied as either dry ammonium nitrate or liquid urea. All of the wheat planted was hard-red winter wheat (predominantly KSU Jaeger). Neither of the pastures was fertilized, grazed, or burned during observations or in the three years preceding observations.

2.2. Ecological Measurements

Total (green plus brown) leaf area index (LAI) was measured optically at one time point in each field in July 2001 and at one time point (shortly before harvest) in spring 2002 using a Licor LAI-2000 Plant Canopy Analyzer (LiCor Biosciences; Welles and Norma, 1991). Aboveground plant biomass (AGB) was measured destructively at the same times. In spring 2003, total LAI was measured biweekly and aboveground biomass was measured shortly before harvest. For each date and field, LAI was measured in ten 1 m^2 squares that were placed at approximately 40 m intervals on transects centered on the flux towers. Total AGB was estimated by harvesting biomass within the 10 sampling squares, drying for 24–48 hr at 60˚C, and weighing. The carbon content (which varied from 43 to 46 % by mass) and nitrogen content (which varied from 1% to 4% by mass) of the vegetation was determined from subsamples of whole plant vegetation using a Carlo Erba C&N analyzer. Individual results from the measurements of chemical composition are not reported in this paper.

2.3. Micro-Meteorological Measurements

Surface flux measurements were made with three portable eddy covariance systems. The systems were developed for rapid deployment in agricultural systems (Billesbach et al. 2004). Briefly, each system comprised a sonic anemometer (Gill-Solent WindMaster Pro), an open-path infrared gas analyzer (IRGA LiCor LI-7500), and a set of meteorological and soil sensors that monitor net and photosynthetically active radiation, air temperature, relative humidity, precipitation, soil heat flux, and profiles of soil moisture and temperature. The anemometer and IRGA were located 4 m above the ground, allowing a minimum of ~3 m between the top of the canopy and the instruments for all crops included in this study. During 2002 and 2003, one system was permanently located year round in a winter wheat field (f8), while the other two systems were deployed for shorter periods in combinations (depending on the year) of winter wheat, pasture, and sorghum. Calibrations of the IRGAs were performed prior to and at the completion of each deployment and every six to twelve months in f8.

Turbulent vertical fluxes of CO_2, water, and heat were calculated every 30 minutes using algorithms performing spike removal, coordinate rotation to zero mean vertical wind speed, and block averaging of scalar quantities (Billesbach et al. 2004). Density corrections were applied to the covariances of vertical wind, using CO_2 and H_2O densities obtained with the open-path IRGA (Webb et al.1980). Multiplicative spectral corrections caused by sensor separation and other factors (Moore 1986) were estimated after confirming that the measured co-spectra were consistent with similarity theory, as expected for the systems under study. In general, the corrections were small (<10%) and consistent across the different field sites. Hence, we did not apply the corrections, since they would not affect the primary conclusions of this study concerning cross-site comparisons. Similarly, storage corrections to vertical fluxes from changes in CO_2 concentration below the 4 m measurement height were estimated and found to be negligible compared with turbulent fluxes (except for a small fraction of the measurements in which the friction velocity $u*$ was less than 0.1 m s^{-1}, which were discarded). Hence, NEE was directly estimated as the turbulent flux of CO_2.

The accuracy and precision of the portable systems have been verified through intercomparison experiments. The first portable system produced was compared with existing systems at Ameriflux sites near Shidler and Ponca City, Oklahoma, and to the Ameriflux Closed-Path

Intercomparison system (Billesbach et al. 2004). To verify the other two portable systems, we performed side-by-side measurements with all three in a sorghum field in July 2001, using large daytime CO_2 (NEE ~ -30 μmol C m^{-2} s^{-1}), sensible heat (H ~ 250 W m^{-2}), and latent heat (LE ~ 300 W m^{-2}) fluxes. Comparison of NEE, H, and LE measured by each of the three systems showed no significant differences with RMS deviations of 1.8 μmol C m^{-2} s^{-1}, 12 W m^{-2}, and 11 W m^{-2} respectively. These tests provide sufficiently tight constraints such that the fluxes obtained from the different fields and years of this experiment can be compared confidently.

2.4. Estimation of Gross Uptake and Respiration

We estimated gross primary production (*GPP*, μmol C m^{-2} s^{-1}) and ecosystem respiration (R_{eco}, μmol C m^{-2} s^{-1}) from measured net ecosystem carbon exchange by decomposing NEE as

$$\mathrm{NEE} = R_{eco} - GPP, \tag{1}$$

(Note that negative fluxes imply energy or mass transfer toward the surface, and positive values imply transfer away from the surface.) We estimated R_{eco} from measured nighttime NEE, NEE_n, using an exponential temperature relation:

$$R_{eco}(T_s) = \mathrm{NEE}_n = R_0 \exp(\beta T_s), \tag{2}$$

where R_0 (μmol C m^{-2} s^{-1}) is the soil respiration scaled to a soil temperature of 0ºC, and β (ºC^{-1}) is a constant related to Q_{10} as $\beta = \ln(Q_{10})/10$, so that $\beta = 0.069$ for $Q_{10} = 2$ (Lloyd and Taylor 1994). A mean soil temperature T_s was calculated as the average of data from 5 and 15 cm depths, under the assumption (supported by visual inspection of soil pits dug in all fields) that the 0–15 cm depth interval contains a sufficient fraction of root biomass and soil organic matter to characterize soil respiration. We then estimated daytime soil respiration by applying measured daytime soil temperatures in combination with the functional form and parameters of Equation (2).

Following previous work of Gu et al. (2002), we estimated *GPP* as a simple rectangular hyperbolic function of light:

$$GPP = R_{eco}(T_s) - \mathrm{NEE}_d = G_{max}\,\alpha Q/(G_{max} + \alpha Q), \qquad (3)$$

where NEE_d is daytime measured NEE, G_{max} (μmol C m^{-2} s^{-1}) is the maximum rate of gross assimilation, α (μmol C μmol^{-1} photon) is the quantum efficiency, and Q (μmol photon $m^{-2}s^{-1}$) is incident photosynthetically active radiation flux. Equations (1)–(3) were fit separately to the NEE measured in each field to obtain estimates of R_0, β, G_{max}, and α in 10-day intervals during the active growing season and for 20-day intervals during dormant periods. We expect the parameters to vary during the season as soil moisture and plant and microbial functions vary.

3. Results

3.1. Climate and Vegetation, 2001–2003

3.1.1. Temperature and Precipitation

A summary of surface climate for the sites is shown in Figure 2. A drought affecting much of the central United States began in 2000, continued through the first half of 2002, and then abated in late 2002 and early 2003 (Lawrimore and Stephens 2003). Mean air temperature in winter and early spring 2002 was warmer than the corresponding period of 2003, while summer 2003 was cooler than summer 2002. In this study, precipitation relevant for winter wheat (from previous mid-June to current mid-May) was 380 mm in the 2002 harvest year and 810 mm in 2003. For pasture and summer crops, the situation is different, in that the relevant period for accumulated precipitation is shifted later into the summer, from about September to the following August. In this study, summer crops and pasture received 760 mm for the 2002 harvest, significantly more than the 580 mm received for 2003. In response, soil moisture was low during the wheat-growing season in spring 2002 and again in the summer-crop season of summer 2003.

3.1.2. Aboveground Biomass and Leaf Area

The field with the highest maximum AGB was sorghum, while the field with the lowest maximum AGB was the pasture (Table 1). Winter wheat AGB varied by ~10–20% across fields within a given season, but the interannual variations were large. Maximum winter-wheat biomass was 200 g C m^{-2} in 2002, half as much as the 400 g C m^{-2} in 2003. The large interannual variation in biomass production is consistent with the large increase in precipitation between the 2002 and 2003 growth years. In contrast to winter wheat, peak pasture biomass (f21) was about 50% larger in 2002 than in 2003. As with winter wheat, the interannual variation in pasture biomass production is positively related to the interannual variations in growth-year precipitation.

Total LAI showed within-season and interannual variations similar to those observed for aboveground biomass. Figure 3 shows the 2003 seasonal variations in LAI for winter wheat (f8 and f20), pasture (f21), and sorghum (f101) fields, while Table 1 reports LAI measured at the time of near peak AGB for 2001, 2002 and 2003. Although winter wheat begins growth in the fall preceding a given harvest year, the period of high photosynthesis lasts for only about 30 days in the April to May period, with exact dates dependent on climate. Sorghum, which is a C_4 plant, had a period of active growth that lasted from about mid-June to mid-July. For both winter wheat and sorghum, LAI decreased rapidly at the end of the respective growing seasons. In contrast, LAI persisted for nearly 90 days in pastures, because they contain a mix of C_3 and C_4 species.

3.2. Ecosystem-Atmosphere Exchange

3.2.1. Fluxes of CO_2, Water, and Heat

The temporal patterns of NEE, LE, and H are shown for 2003 in Figure 4a. The largest variations in NEE between fields were caused by the early growth of winter wheat versus the much-later growth of pasture and sorghum. The similarity of fluxes in the wheat fields and differences with other crops is highlighted in Figure 4b, which shows the ratios of NEE, LE, and H of different fields to winter wheat field f8. Measurements made in 2001–2002 (not shown) exhibited similar features, but had some differences. First, a sparse covering of Bermuda grass (LAI and AGB were not measured) grew in the winter wheat field (f8), generating a small but measurable CO_2 uptake in July 2002. Second, although NEE differed by only ~10% between fields f8 and f20 in 2002, NEE in the third winter wheat field (f14) was 20% higher than the other fields.

Latent heat (like NEE) also exhibited the seasonality of the different crops, with the exception that soil moisture evaporation continued into the summer after plant crops were harvested and photosynthesis had stopped (Figures 4a and 4b). For example, LE increased briefly in the winter-wheat fields near day 210 after a rain event (Figure 4b). Sensible heat did not exhibit as strong a difference across the different fields. Sensible heat was small early in the season, when solar input was small, and also during active growth, when LE was reasonably large, owing either to plant transpiration or soil evaporation. The largest differences in H were observed between early and late season crops during early summer, when winter wheat had been harvested, leaving bare, dry soil and stubble while the summer crops were actively growing and generating large LE. *H* was typically large and similar in magnitude for all three fields observed during late summer, when plants had mostly senesced.

3.2.3 Net Ecosystem Exchange, Gross CO_2 Uptake, and Ecosystem Respiration

We separated measured NEE into estimates of *GPP,* R_{eco}*,* and NEE using Equation (1)–(3) and measured *PAR* and T_s. Figure 5 shows that measured NEE is reasonably well represented by predicted NEE for a representative 10-day period at the beginning of the active growing season for winter wheat (f8) in 2003. For the 2003 year of winter wheat data, predicted NEE matched measured NEE closely during periods with active photosynthesis, with $R^2 > 0.9$ and normally distributed RMS residuals of 2-3 μmol m^{-2} s^{-1} (about 10% of peak daytime fluxes). The regression model captured a smaller fraction of the variance in NEE ($R^2 \sim 0.75$) during the summer season, likely because of water stress, plant senescence, and respiration pulses following rain events (Xu and Baldochhi 2004).

Estimates of *GPP* and R_{eco} for three winter wheat fields in 2002 and 2003 are compared in Figure 6. There is a strong positive correlation between *GPP* and R_{eco} when the data are separated into an early period of active growth (before ~Day 130) and a later period of seed production and senescence. During the period of active growth, *GPP* was higher in 2003 than in 2002 for a given value of *Reco*, consistent with the greater photosynthetic uptake in 2003 than 2002. However, the slope, $dGPP/dR_{eco}$, was similar in both years (3.0 ± 0.2) (Xu et al. 2004).

After Day 130, predicted R_{eco} increased by a constant amount independent of *GPP*. This increase in respiration likely reflects increased autotrophic maintenance respiration necessary for flowering and seed production (Baldocchi 1994). Comparisons of *GPP* and R_{eco} for the pasture (f21) yielded an R_{eco} intercept and slope similar to that for actively growing winter wheat. Sorghum also yielded an *R* intercept similar to that of wheat, but with a slope of 4.7 ± 0.8.

3.2.4 Estimated Model Parameters

Model parameters (G_{max}, α, β, and *Ro)* were estimated for each 10- or 20-day interval. The seasonal variations in G_{max} and α showed smooth increases in maximum values at periods of peak growth, followed by decreases toward senescence, as observed previously for crops and grasslands (Gilmanov et al. 2003; Xu et al. 2004). We summarize the parameter values obtained during periods of peak uptake for several of the different fields in Table 2, noting that the period of peak uptake varied between years.

Mean light use efficiency in wheat, pasture, and sorghum were 0.04 ± 0.01, 0.03 ± 0.008, and 0.05 ± 0.004 mol C/ mol photosynthetically active photons, respectively. These values are approximately consistent with previous estimates for similar plant types (Gilmanov et al. 2003; Xu et al. 2004).

Peak growing season values of G_{max} for winter wheat were 20–30 μmol C m^{-2} s^{-1} in 2002 and 40–50 μmol C m^{-2} s^{-1} in 2003, consistent with the interannual difference in LAI. Because G_{max} scaled approximately linearly with LAI, we estimated a maximum uptake rate per unit leaf area, A_{max} (μmol C m^{-2} s^{-1}). Interestingly, A_{max} and α did not vary significantly between years for the winter-wheat fields. Weighted averages of A_{max} for winter wheat, pasture, and sorghum were 16

± 4, 17 ± 6, and 23 ± 3 μmol C m^{-2} s^{-1}, respectively. The respiration coefficients R_0 and β appear to have been greater in 2002 than 2003 for all fields. The temperature dependence of respiration was indistinguishable between the three cover types, with mean values for β in wheat, pasture, and sorghum of 0.066 ± 0.015, 0.069 ± 0.015, and 0.08 ± 0.02, respectively (corresponding to Q_{10} values near 2).

3.2.5 Effect of Moisture Stress

For several periods during the summer with clear-sky conditions, carbon uptake in the afternoon was significantly lower than uptake in the morning. Figure 7 shows a typical example, in which C uptake in the 2003 sorghum crop decreased by a factor of two from mid-morning to mid-afternoon. In these cases, the best fit *GPP* and R_0 sum to a predicted NEE that is consistently larger than measured NEE. This discrepancy could be caused by some combination of a limitation to afternoon uptake or an increase in afternoon respiration not captured by Equations (1)–(3). An increase in afternoon respiration is unlikely, because modeled afternoon R_{eco} was already quite large (see Figure 7), and because afternoon R_{eco} would also likely be limited by diurnal afternoon reductions in soil moisture (Norman et al. 1992; Mielnick et al. 2000). The most likely explanation for the decrease in net uptake and model-measurement mismatch is that the simple expression *GPP* from Equation (2) does not include parameterizations for water stress. Although beyond the scope of this study, this problem requires more detailed modeling. Possible modifications to the model might include parameterizations for stomatal and nonstomatal (e.g., enzyme) impacts of water stress (Colello et al. 1998; Griffiths and Parry 2002).

4. Discussion

Here we discuss how the results described above provide insight into the importance of land cover and moisture availability for spatial and temporal variations in carbon, water, and energy fluxes. To broaden the geographic scope of our findings, we also explore the relationship between moisture and winter wheat production across the Southern Great Plains, using a statistical analysis of historical climate and agricultural data.

4.1. Spatial Variation: Importance of Land Cover

Spatial variations in the magnitude and timing of carbon, water, and heat fluxes across the landscape were controlled primarily by land-cover type, and to a lesser extent, by climate and management. In particular, the largest spatial differences at any time in fluxes are associated with different phonologies of winter wheat versus summer crop or pasture. However, even comparing sorghum (a summer crop) with pasture (a late spring to summer mix), fluxes differ by up to 100% at any time, resulting from differences in plant phenology and management practices such as planting and harvest dates. The pasture growing season was 2–3 months longer than that of the single species crops, because they include cool season C_3 grasses (dominant early in the spring) and hot-dry adapted C_4 grasses (dominant later in the summer) (Still et al. 2003).

These land-cover controls on surface fluxes can impact regional climate. For example, a modeling analysis of the SGP found that spatially coherent differences in the timing of the wheat harvest raise surface temperatures by as much as 5ºC, by changing the balance between latent and sensible heat fluxes (Cooley et al. 2005). For most areas of the Great Plains and globally, there are no readily available maps or data products for land cover or land use that match the temporal resolution of regional model applications (i.e., that are accurate for the modeled period). While it is widely recognized that improved maps specific to season will significantly improve predictions of surface exchanges, we also suggest that they will improve prediction of atmospheric processes such as convection and cloud formation.

As illustrated in Figure 4a, the issue of scaling is expected to be particularly difficult in this highly heterogeneous region. Because of the very different phenological timing of different land cover types, regional estimates of NEE, H, and LE will most likely be multipeaked with very complex shapes. Further, each land-cover type contributing to the overall convolution must be weighted in accordance to its relative abundance. These weighting factors themselves will vary on an annual basis, as individual farmers make decisions about what crops to plant.

4.2. Interannual Variations: Importance of Moisture

The large difference in both growing-season precipitation and winter-wheat productivity from 2002 to 2003 emphasizes the importance of interannual variations in soil moisture. As shown in Figure 8, there was a close correspondence between interannual variation in winter wheat AGB, cumulative growing-season NEE, and growing-season-averaged root-zone soil moisture in 2002 and 2003. In 2002, the near-surface soil moisture was systematically lower than in 2003. Our conclusion that moisture is limiting to NEE in the Southern Great Plains is supported by previous studies in SGP prairies, which found that while NEE in years with average precipitation showed net uptake (approximately 100 g C m^{-2} yr^{-1}), years with drought resulted in a net carbon release of comparable magnitude (Meyers 2001; Suyker et al. 2003).

Finally, we consider how the results of the current study could be used to improve model prediction of NEE in response to varied moisture limitation in individual agricultural plots and the factors that should be considered to capture variations at the landscape-scale. Although the first order factors include the amount and timing of precipitation interacting with crop type and planting date, additional factors include water and residue management, because all of these factors are expected to affect both plant physiology and soil respiration (Gervois et al. 2004; Hanan et al. 2005). Although in our study, the dominant effect was caused by a large interannual variation in precipitation, timing of planting relative to precipitation can be important, because fields need to receive moderate precipitation soon after planting, but heavy precipitation soon after germination can damage small plants. Capturing the effect of management is a challenge at the landscape scale, largely because data on management is not (to our knowledge) collected in a systematic fashion. For example, farmers may attempt to increase soil-water retention before an anticipated drought through alternative tillage or boost production with increased fertilizer application during a year with ample moisture. Although only an anecdotal example, we note that f14 was tilled (according to a private communication with the farmer) in summer 2001 to conserve moisture (by reducing runoff), and subsequently experienced higher soil moisture and greater productivity in 2002. In this study, we could not address the question of differences in fertilizer application. Of the winter-wheat fields that were observed, only f8 in 2002 received a significantly different nitrogen treatment, roughly half of the fertilizer applied to other fields and or years, while both fields f8 and f20 yielded roughly comparable AGB and accumulated NEE in 2002 (a drought year) and 2003 (a nondrought year). In summary, we suggest that a study (or multistudy synthesis) including data covering many years of measurements in fields of different cover types and management strategies, would be valuable for characterizing the response of NEE to varied moisture and management.

5. Conclusions

Based on our surface flux and biomass measurements, land cover dominates the timing and spatial variability of carbon uptake in the Southern Great Plains, because of the distinct and punctuated growing seasons for winter wheat, summer crops, and to a lesser extent, pasture. Within a land-cover type, temporal variability, in the form of interannual differences in productivity correlated with large interannual differences in rainfall, was much larger than spatial variability across fields. Water availability limits carbon uptake and ecosystem respiration for the region in the crop systems we studied. Absorption of solar radiation and the partitioning of net radiation between latent and sensible heat are also strongly influenced by cover type and moisture level. This is largely because they are directly affected by soil moisture, but also because plant cover and transpiration control these fluxes. Because current models do not accurately predict variations in surface exchanges during periods of moisture limitation (Gervois et al. 2004; Hanan et al. 2005), we consider these results motivation for further model development and experimental testing. Providing accurate predictions of regional land-surface exchange is increasingly important for informed policy decisions, because large scale modifications of land cover have the potential to generate ecological feedbacks to climate and affect other environmental services. This will become increasingly relevant as societies consider changes to the balance of agricultural land used for production of food, fiber, and energy.

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Figure Captions

Figure 1. Aerial view of the fields that were measured during the period 2001–2003. Inset map marks the location of the ARM Central Facility (CF) in North Central Oklahoma. The view shows the field conditions in July 2001, with harvested wheat fields (white to beige) and growing summer crops and pastures (green).

Figure 2. Interannual variation in surface climate for sites near ARM Central Facility, 2001-2003. The upper panel shows minimum and maximum (dots), and mean daily (line) air temperature. The middle panel shows the cumulative daily (lines) and monthly precipitation (boxes). The bottom panel shows vapor-pressure deficit and soil moisture at 5 and 25 cm depths. Vertical lines mark the main growth periods for winter wheat (W) and summer crops (S) and pastures.

Figure 3. Leaf area index measured in winter wheat (f8), pasture (f21), and sorghum (f101) fields in 2003 showing the distinct seasonality in LAI for different land-cover types.

Figure 4a. Seasonal variations in daily averaged net ecosystem CO_2 exchange (NEE), latent heat (LE), and sensible heat (H) across fields with different land cover in 2003. Fields are winter wheat (black =f8, green = f20), pasture (red= f21), and sorghum (blue=f101).

Figure 4b. Ratio of fluxes in different fields to the flux measured in field f8. Color scheme is the same as in Figure 4a.

Figure 5. Comparison of measured and predicted—Eq. (1)–(3)—NEE for winter wheat (f8), in April, 2003.

Figure 6. Comparison of 10-day averages of estimated gross primary production *GPP* and ecosystem respiration, *Reco*. Thick lines show best-fit linear regressions (thin lines indicate 95% confidence intervals) separately for the period of plant growth (before Day ~130) in 2002 and 2003 (closed symbols), and for the period of seed production and senescence in 2002 and 2003 together (open symbols).

Figure 7. Illustration of soil-moisture limitation in a sorghum field (f101) during July 2003.

Figure 8. Interannual and across-field variations of peak-growing-season aboveground biomass, cumulative NEE from Day 90 to 140, and season-averaged soil moisture at 5 cm depth in winter wheat fields.

Tables

Table 1. Field management, yield, and leaf area for fields included in study. Unavailable or nonapplicable information is indicated with "-". Standard errors of the mean values are given inside parentheses.

Field	Year	Crop	Variety	Applied Nitrogen (kg N /ha^{-1})	Yield* (bushel acre^{-1})	AGB** (g C m^{-2})	LAI*** (m^2 m^{-2})
f8	2001	Wheat	KSU Jaeger	-	0	-	-
	2002	Wheat	KSU Jaeger	66	32	182 (9)	1.6 (0.2)
	2003	Wheat	KSU Jaeger	116	42	394 (26)	2.8 (0.1)
f14	2001	Wheat	OSU 2174	85	32	-	-
	2002	Wheat	KSU Jaeger	85	35	250 (5)	2.2 (0.2)
	2003	Wheat	KSU Jaeger	85	-	-	-
F20	2001	Sorghum	Pioneer 8500	-	13	-	-
	2002	Wheat	KSU Jaeger	102	34	216 (11)	1.8 (0.2)
	2003	Wheat	KSU Jaeger	91	54	428 (36)	3.1 (0.2)
f9	2002	Pasture	mixed C_3 C_4	0	-	110 (18)	1.5 (0.2)
F21	2001	Pasture	mixed C_3 C_4	0	-	-	-
	2002	Pasture	mixed C_3 C_4	0	-	145 (4)	2.2 (0.2)
	2003	Pasture	mixed C_3 C_4	0	-	119 (4)	2.8 (0.2)
fP	2001	Sorghum	Pioneer 8500	-	0	411 (50)	2.5 (0.3)
f101	2002	Sorghum	Pioneer 8500	82	172	-	-
	2003	Sorghum	Pioneer 8500	82	65	381 (33)	1.7 (0.1)

* Years with 0 entered indicate crop failed to mature and grain was not harvested for grain.

** Carbon content of AGB was calculated assuming 45% carbon by mass

*** LAI is reported as average for 10 day period surrounding peak CO_2 uptake.

Table 2. Coefficients estimated from fits of Equations (1)–(3) for 10-day periods surrounding the period of peak carbon uptake.

Crop	Field	Year	Day	Gmax (μmol C m^{-2} s^{-1})	α x 100 (-)	R0 (μmol m^{-2} s^{-1})	β x 100 (C^{-1})	Amax (μmol m^{-2} s^{-1})
Wheat	F8	2002	102	26 (7)	4.6 (1.9)	1.4 (0.1)	6.8 (0.2)	16 (4)
Wheat	F8	2003	112	47 (8)	3.5 (0.6)	1.0 (0.4)	7.9 (0.2)	17 (3)
Wheat	f20	2002	107	23 (7)	5.0 (0.8)	1.1 (0.3)	7.2 (0.2)	13 (4)
Wheat	f20	2003	112	49 (16)	4.3 (1.0)	0.8 (0.3)	1.1 (0.3)	16 (5)
Wheat	f14	2002	108	34 (10)	6.8 (2.4)	1.4 (0.4)	8.6 (0.4)	16 (5)
Pasture	f21	2002	172	54 (12)	3.4 (1.4)	1.2 (0.3)	7.3 (0.3)	24 (6)
Pasture	f21	2003	178	32 (12)	4.2 (1.3)	0.8 (0.3)	8.3 (0.2)	12 (4)
Pasture	f9	2002	192	52 (18)	2.6 (0.5)	1.5 (0.5)	5.4 (0.2)	34 (12)
Sorghum	f101	2003	178	42 (6)	4.9 (0.4)	1.0 (0.3)	6.0 (0.2)	25 (3)
Sorghum	fP	2001	197	51 (10)	4.7 (0.5)	0.8 (0.3)	9.0 (0.2)	20 (4)

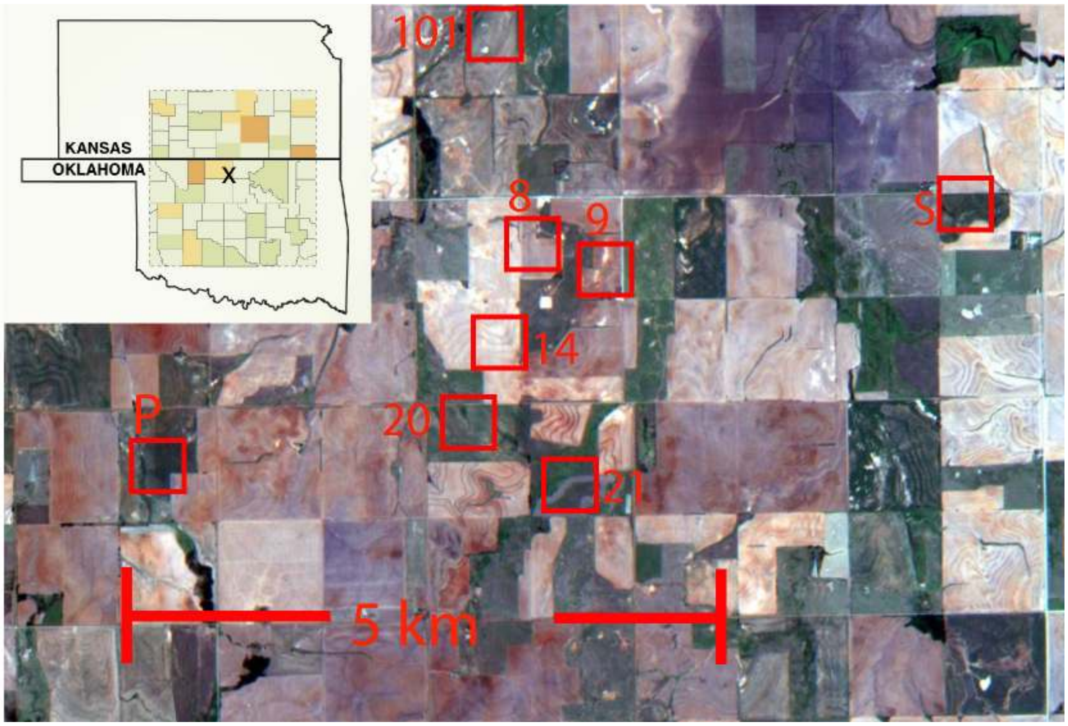


Figure 1.

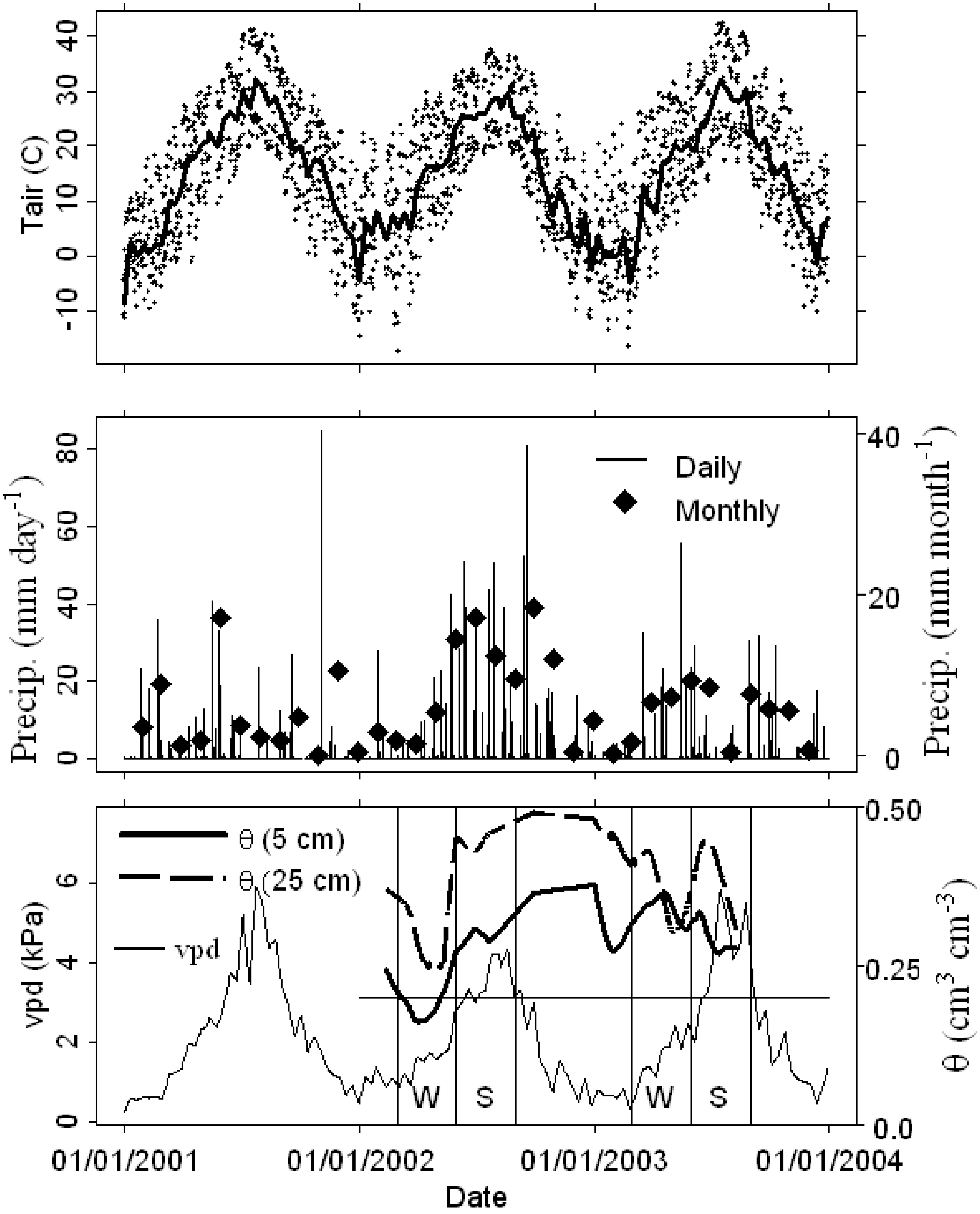

Tair (C)
-10
0
10
20
30
40
Daily
Monthly
Precip. (mm day^{-1})
0
20
40
60
80
Precip. (mm month^{-1})
0
20
40
θ (5 cm)
θ (25 cm)
vpd
vpd (kPa)
0
2
4
6
θ (cm^3 cm^{-3})
0.0
0.25
0.50
W
S
W
S
01/01/2001
01/01/2002
01/01/2003
01/01/2004
Date

Figure 2.

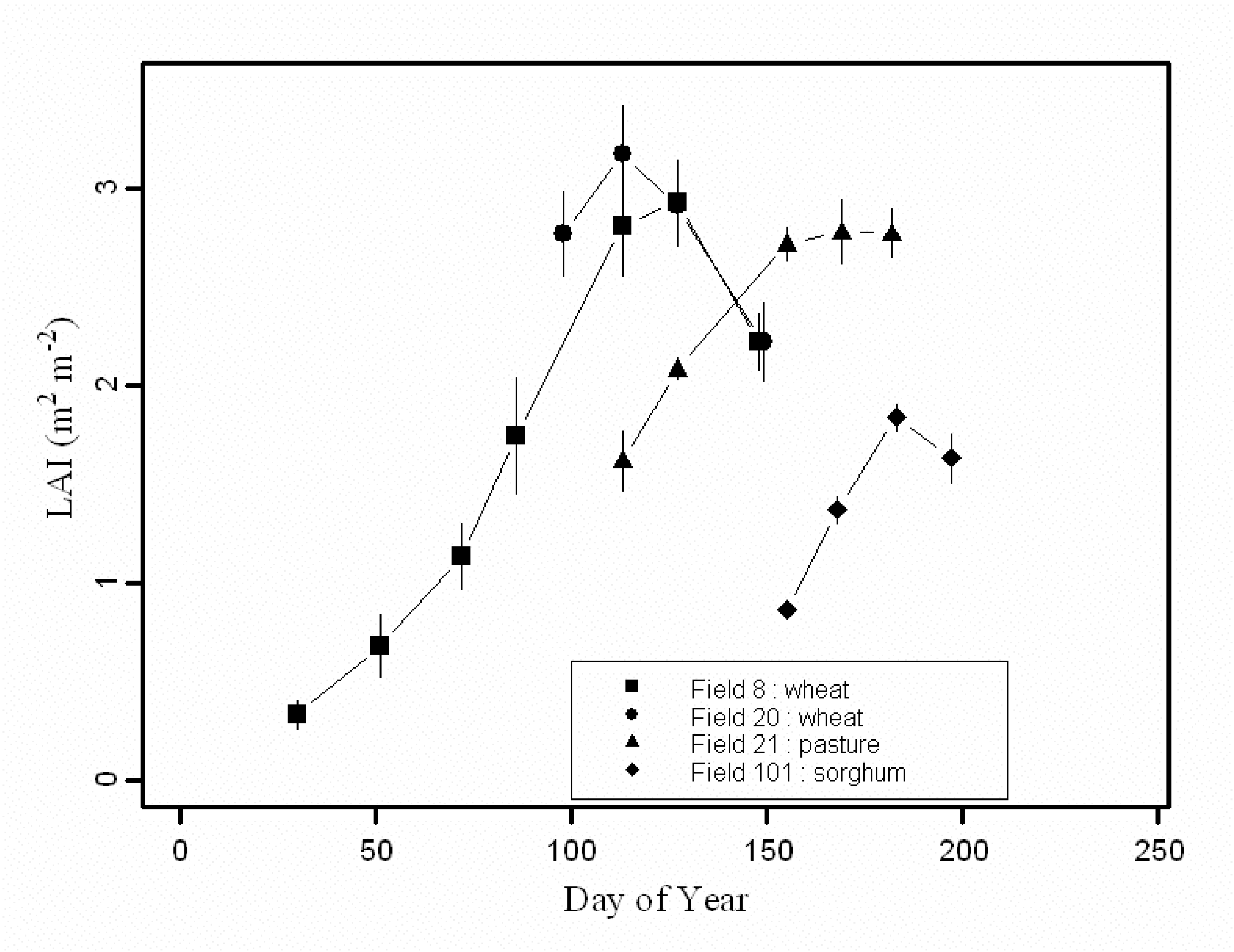
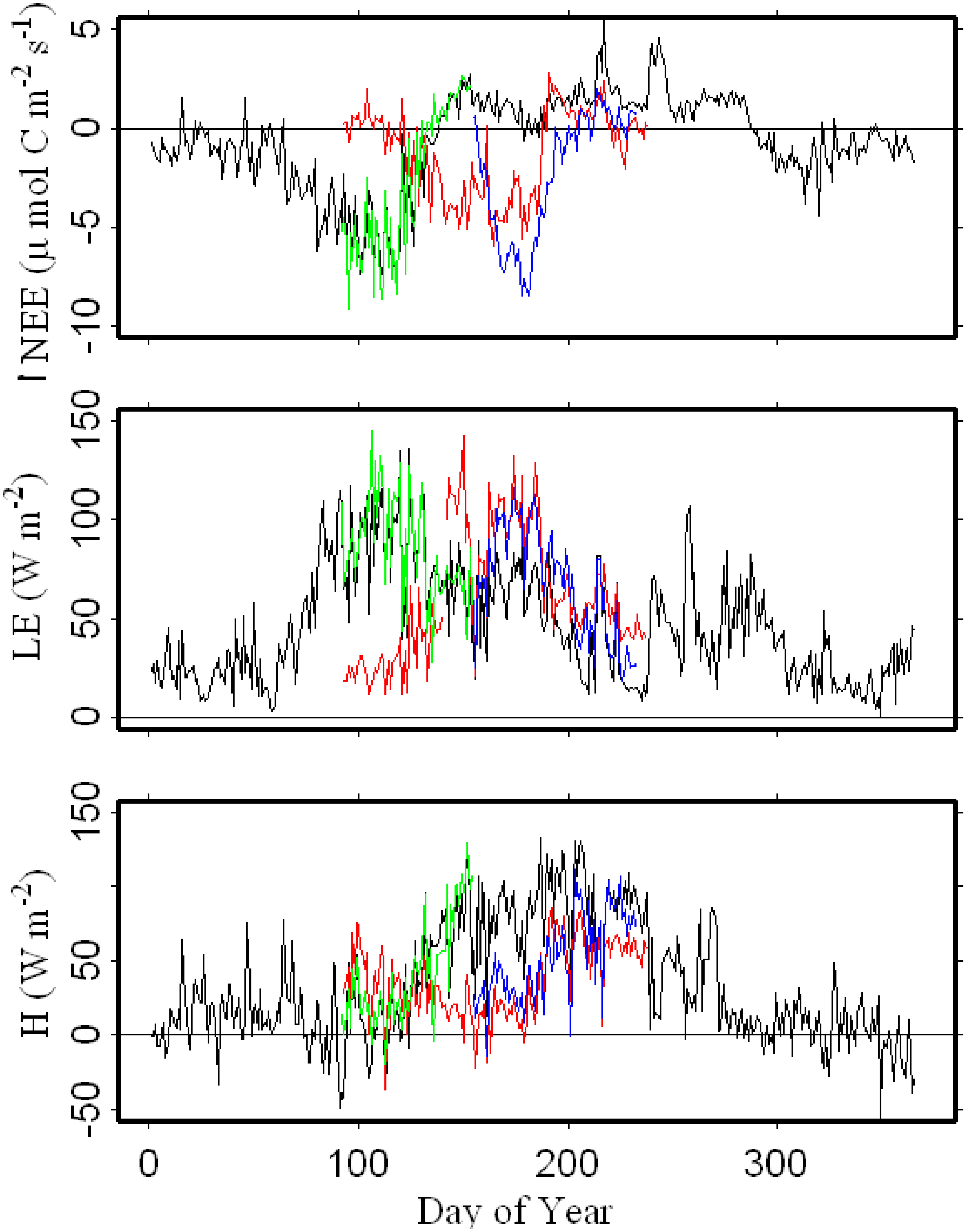

LAI (m^2 m^{-2})
0
1
2
3
Day of Year
0
50
100
150
200
250
■ Field 8 : wheat
● Field 20 : wheat
▲ Field 21 : pasture
◆ Field 101 : sorghum

Figure 3.



1
2 Figure 4a.
3

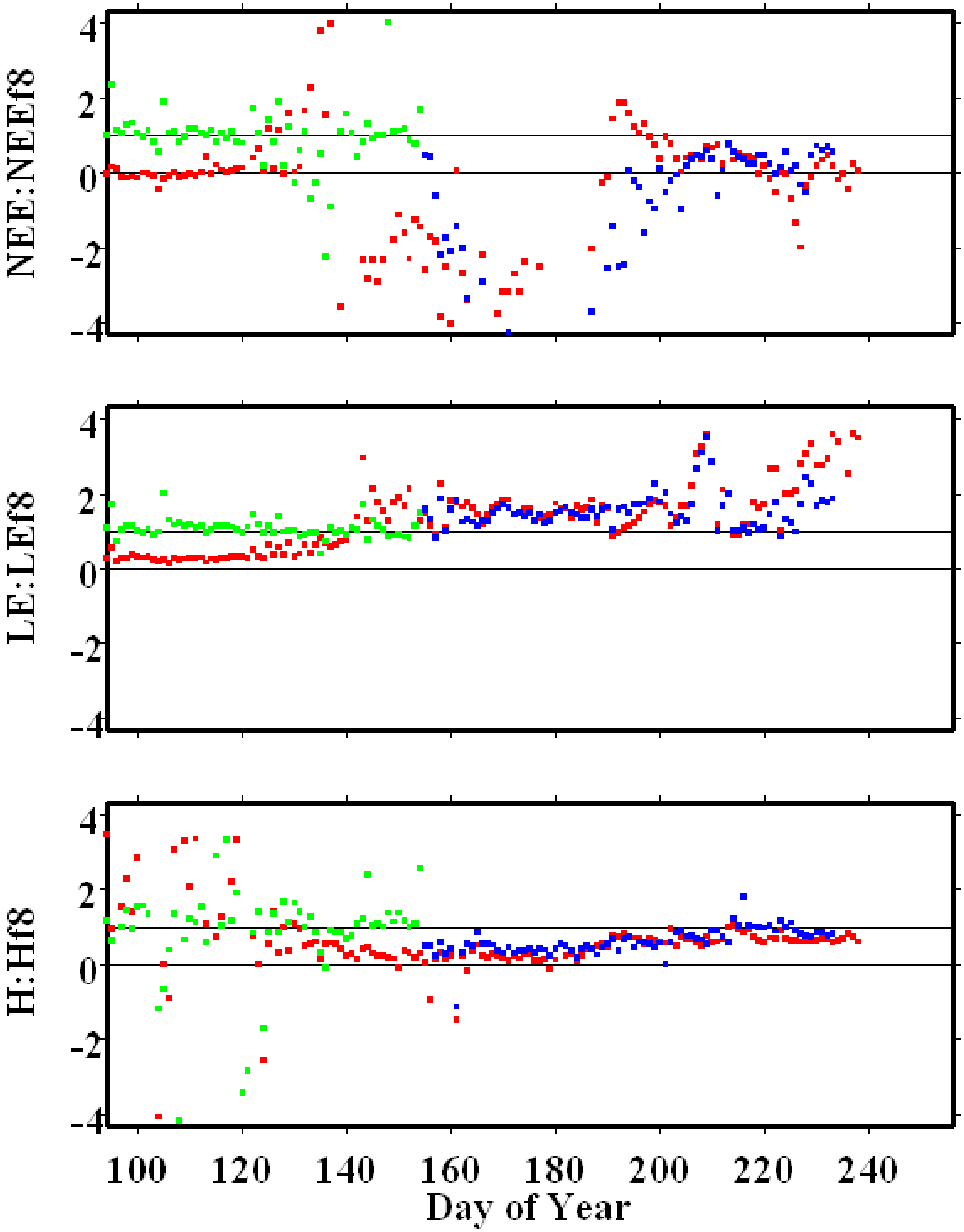

NEE:NEEf8
LE:LEf8
H:Hf8
4
2
0
-2
-4
100
120
140
160
180
200
220
240
Day of Year

Figure 4b.

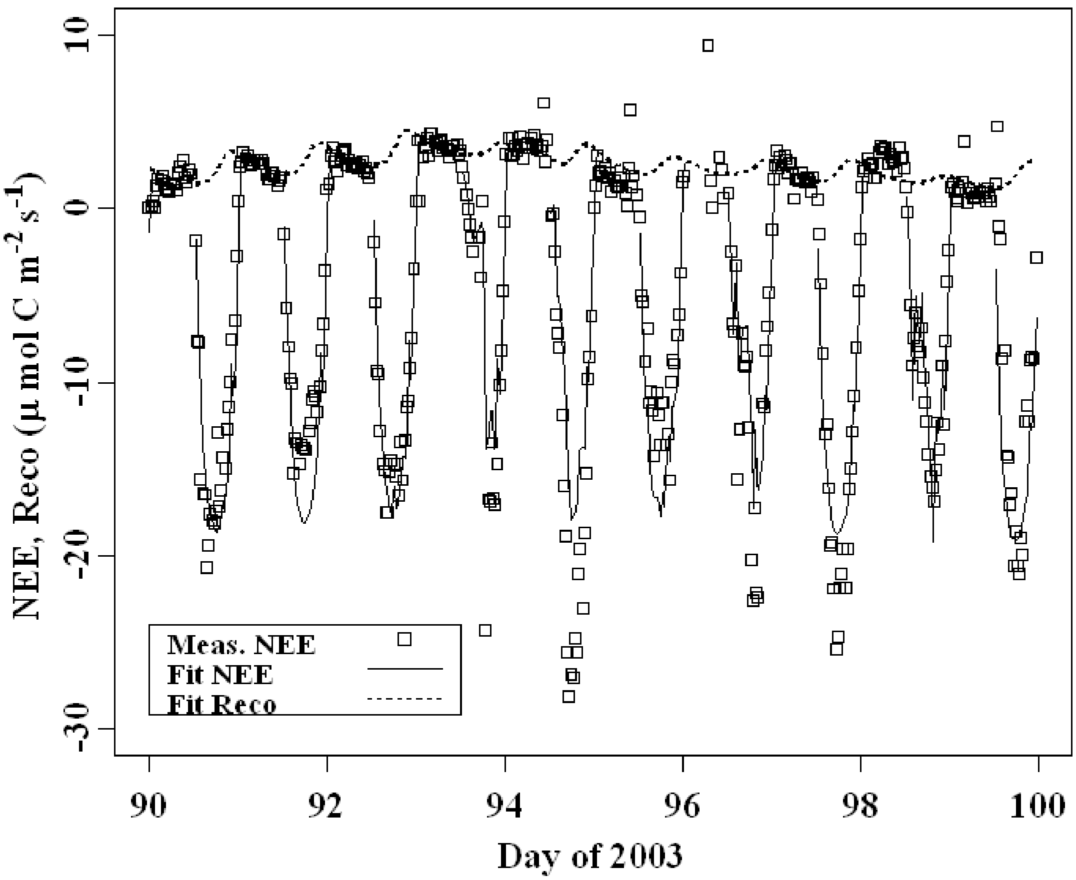

NEE, Reco (μ mol C m^{-2} s^{-1})
10
0
-10
-20
-30
Meas. NEE □
Fit NEE
Fit Reco
90
92
94
96
98
100
Day of 2003

Figure 5.

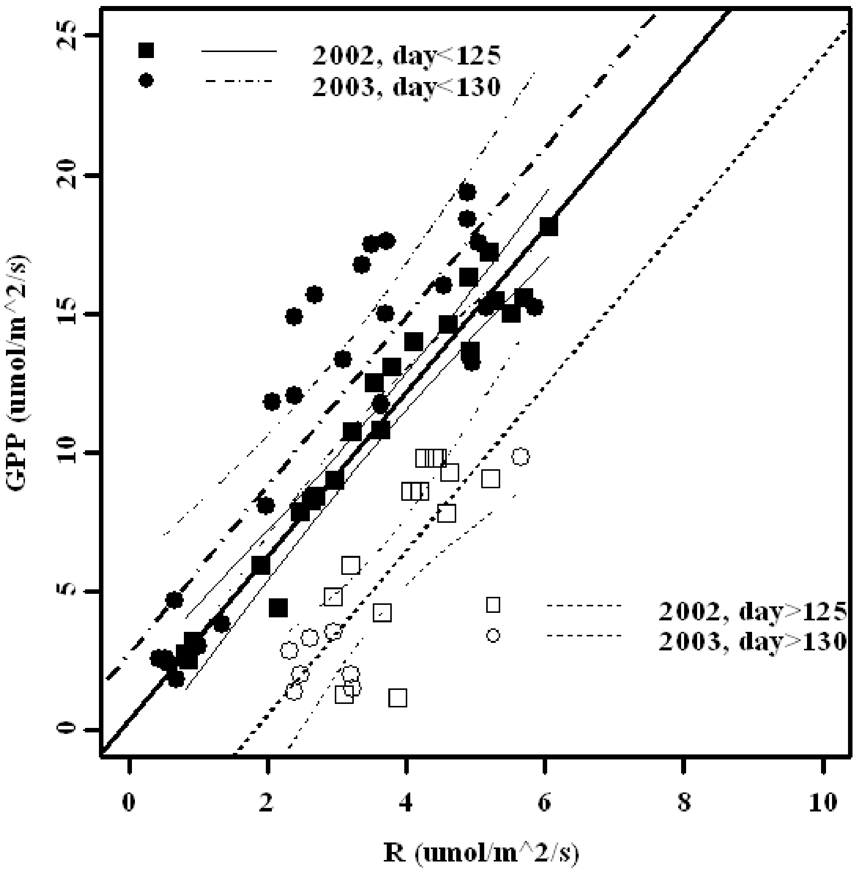

■ 2002, day<125
● 2003, day<130
□ 2002, day>125
○ 2003, day>130
GPP (umol/m^2/s)
R (umol/m^2/s)
0
5
10
15
20
25
0
2
4
6
8
10

Figure 6.

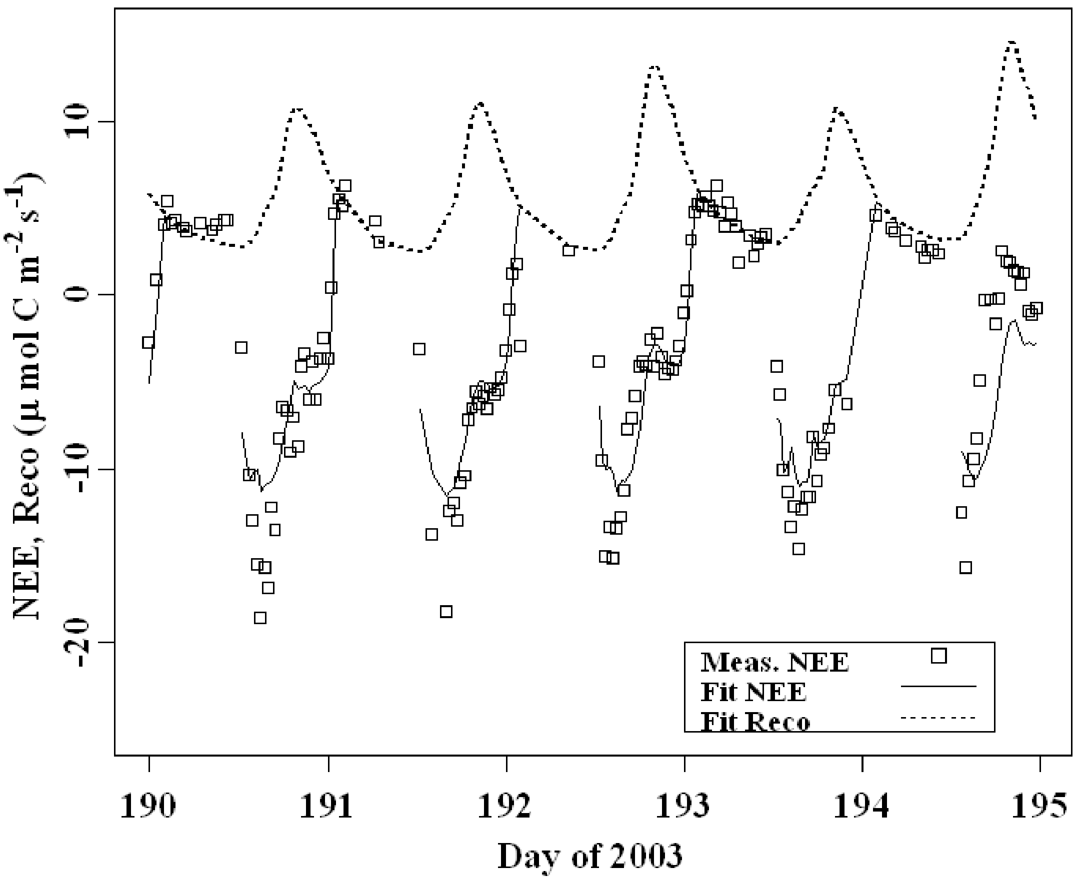

NEE, Reco (µ mol C m^{-2} s^{-1})
10
0
-10
-20
Meas. NEE □
Fit NEE
Fit Reco
190
191
192
193
194
195
Day of 2003

Figure 7.

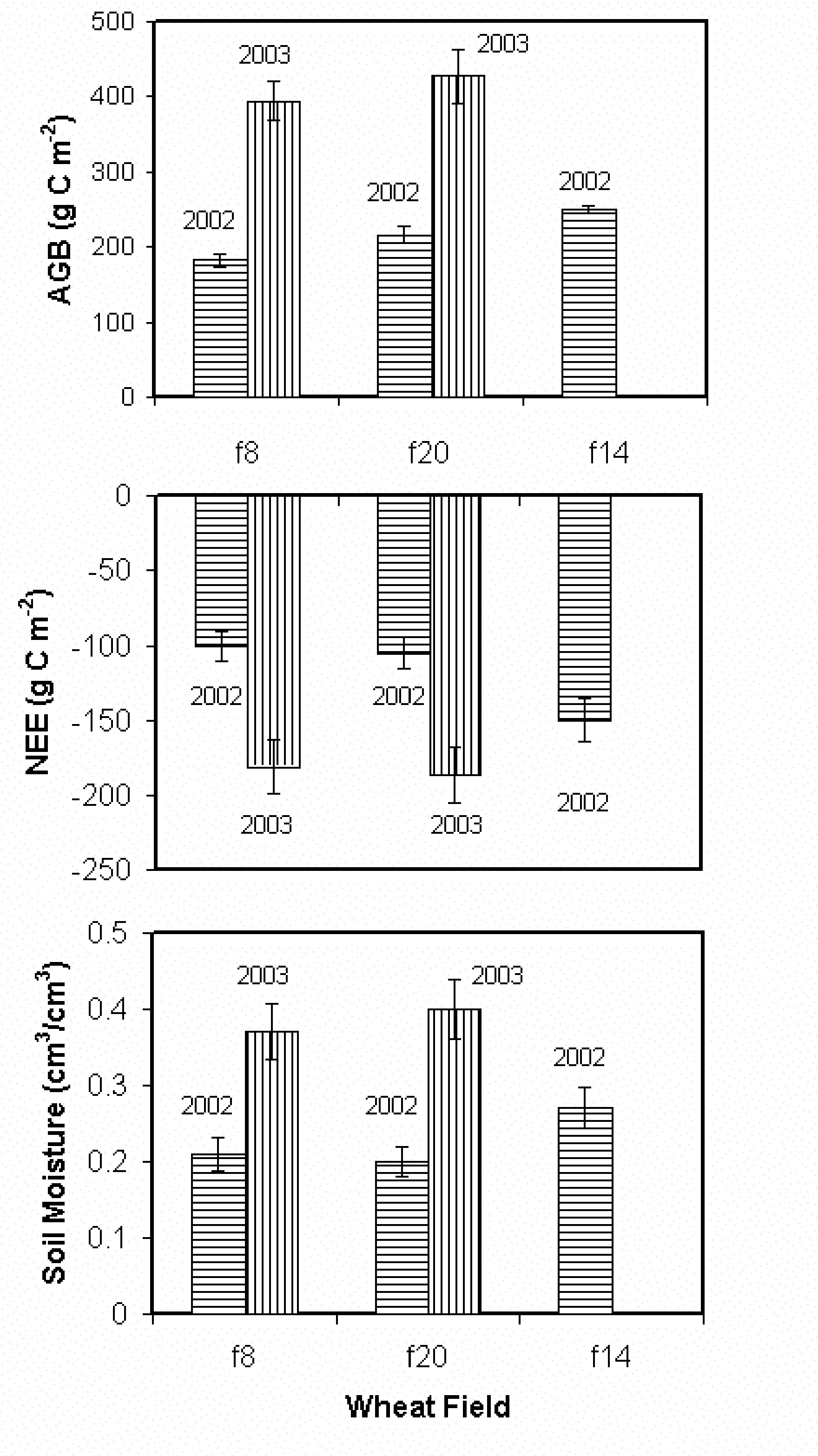

AGB (g C m^{-2})
500
400
300
200
100
0
2003
2003
2002
2002
2002
f8
f20
f14
NEE (g C m^{-2})
0
-50
-100
-150
-200
-250
2002
2002
2003
2003
2002
Soil Moisture (cm^3/cm^3)
0.5
0.4
0.3
0.2
0.1
0
2003
2003
2002
2002
2002
f8
f20
f14
Wheat Field

Figure 8.