Winter Cover Crops in Illinois: Evaluation of Ecophysiological Characteristics of Corn

Fernando E. Miguez and German A. Bollero*

ABSTRACT

Understanding ecophysiological characteristics of corn (*Zea mays* L.) under winter cover crops (WCCs) can improve management and farmers' acceptance by increasing the positive effects and decreasing the negative effects associated with their use. This study was conducted to quantify the effects of WCC on corn development, growth, and yield through the evaluation of ecophysiological characteristics. No-till corn planted after hairy vetch (*Vicia villosa* Roth), cereal rye (*Secale cereale* L.), and hairy vetch–cereal rye biculture and with four levels of N fertilizer (0, 90, 180, and 270 kg ha^{-1}) was evaluated in 2002 and 2003 at Urbana, IL. Number of leaves, height, leaf area, chlorophyll meter readings (CMRs), light interception (LI), leaf carbon dioxide exchange rate (CER), grain yield, and yield components were measured. At 0 kg ha^{-1}, rye had significant detrimental effects on corn ecophysiological characteristics. However, most of the detrimental effects were overcome by adding 90 kg N ha^{-1}. Overall, hairy vetch provided benefits to corn that resulted in higher corn grain yield and was significantly better than all other treatments when no N fertilizer was used. Corn yield following hairy vetch–rye was intermediate between no cover and rye. As long as N rates are at least 90 kg ha^{-1}, incorporating WCC in a corn–soybean [*Glycine max* (L.) Merr.] rotation in Illinois does not affect corn ecophysiological characteristics and yield potential.

INTEGRATING WINTER COVER CROPS in a cropping system provides benefits that can result in enhanced crop yield (Snapp et al., 2005). Although it is important to recognize that WCC can increase corn yield and provide environmental benefits, management practices need to be adapted to specific regions and cropping systems to increase the positive effects of WCC on corn yield and the environment. Correspondingly, in cropping systems where use of WCC may result in lower corn yields, possible negative effects need to be decreased.

In Illinois, a statewide average of 4 300 000 ha of corn were planted annually between 1993 and 2002, and each year at least 175 kg ha^{-1} of N fertilizer was used in 94% of the planted area (National Agricultural Statistics Service, 2004). Although WCCs have been recognized as an effective strategy for reducing potential N leaching and maintaining N within the cropping system (Dinnes et al., 2002), until recently very little information was available in this region. Bollero and Bullock (1994) showed that corn yield increase due to hairy vetch did not compensate economically for the cost of the seed, planting operations, and herbicide application. Further research showed that hairy vetch and/or rye alone do not provide sufficient N to optimize corn grain yields (Ruffo and Bollero, 2003a, 2003b). However, the previous studies

indicated that management tools such as fertilization and WCC kill date need to be adapted to a specific region and cropping system. Ruffo and Bollero (2003b) concluded that in this region killing cereal rye 1 wk before planting corn was not optimal for adequate synchronization between N release from the residue and N demand for corn. Crandall et al. (2005) evaluated kill date and fertilization strategies with the goal of improving the synchronization of N demand for corn and supply from the cropping system while minimizing N losses. They concluded that applying N fertilizer at planting and killing cereal rye 2 wk before planting corn produced yields comparable to corn following no cover. Most importantly, Crandall et al. (2005) showed that, through adequate management practices, crop productivity can be maintained and negative effects to the environment can be reduced, thus suggesting that these are not conflicting goals.

Many studies have focused on describing the decomposition of WCC residues (Wagger, 1989a, 1989b; Ruffo and Bollero, 2003a, 2003b) and quantifying N pools in the cropping system (Varco et al., 1989). However, there is little information about the effects of WCCs on corn beyond grain yield data. Evaluating ecophysiological characteristics of corn under WCCs can lead to improved management decisions that maximize positive effects and minimize negative effects associated with the use of WCCs. In the future, this may promote a greater acceptance of WCCs among Illinois farmers who may need to comply with state laws to reduce the use of fertilizer, address soil erosion, and/or reduce the use of other agrochemicals (Dinnes et al., 2002). The objective of this study was to examine corn development, growth, and yield through the evaluation of ecophysiological characteristics (i.e., morphological characteristics, development, LI, carbon exchange, chlorophyll readings, and yield components) of corn following WCC and a no-cover control.

MATERIALS AND METHODS
Field Site and Methods

This 2-yr field experiment was conducted at Urbana, IL, during 2002 and 2003. The soil is a Drummer silty clay loam (fine-silty, mixed, superactive, mesic Typic Endoaquoll). The experiment was conducted using no-till practices in plots that have been previously in corn–soybean rotation for at least 7 yr. Winter cover crops were drilled on soybean stubble in adjacent fields each year. Corn was planted using 76-cm row spacing on 1 May 2002 and 29 Apr. 2003. The experimental design was a split-plot arrangement in a randomized complete block with four replications. Whole-plot treatments were WCC (rye, hairy vetch, and hairy vetch–rye biculture) and no cover (control).

Dep. of Crop Sciences, Univ. of Illinois, 1102 S. Goodwin Ave., Urbana, IL 61801. Received 8 Sept. 2005. *Corresponding author (gbollero@ uiuc.edu).

Abbreviations: CER, carbon dioxide exchange rate; CMR, chlorophyll meter reading; GDD, growing degree days; LI, light interception; NFR, nitrogen fertilizer rate; PAR, photosynthetic active radiation; PPFD, photosynthetic photon flux density; SED, standard error of the differences of means; WCC, winter cover crop.

Whole-plots were 9 m wide by 20 m long. Subplot treatments were four levels of N fertilizer (0, 90, 180, and 270 kg ha^{-1}) applied as ammonium sulfate (21–0–0) at planting. Subplot size was 4.5 by 10 m and accommodated six rows of corn.

Planting dates for WCCs were 31 Oct. 2001 and 25 Sept. 2002. Seeding rates were 90 kg ha^{-1} for rye, 34 kg ha^{-1} for hairy vetch, and 68 kg ha^{-1} of rye + 28 kg ha^{-1} of hairy vetch for the biculture. Hairy vetch was inoculated every year with *Rhizobium leguminosarum* var. *viciae* (Urbana Labs, St. Joseph, MO). Kill dates were based on previous research by Crandall et al. (2005) and Ruffo and Bollero (2003b). Rye was killed approximately 2 wk before planting corn. Hairy vetch–rye biculture was killed 1 wk before planting corn and hairy vetch was killed at planting. Glyphosate (N-[phosphonomythyl] glycine) at 1.1 kg a.i. ha^{-1} was sprayed with a backpack to kill WCCs. Weeds were controlled when necessary with additional applications of glyphosate.

Winter cover crop dry biomass was estimated before killing by sampling an area of 0.25 m^2 in each whole plot. Two sub-samples of plant biomass were cut at ground level, then dried at 65°C to a constant dry weight (48 h) and weighed. Rye and hairy vetch in the biculture were separated in the field and dried separately.

Morphological Characteristics

In 2003, selected morphological characteristics of corn were recorded: height (from the ground to the base of the uppermost fully expanded leaf), number of fully expanded leaves, and area of the uppermost fully expanded leaf. The area of the uppermost fully expanded leaf was calculated as maximum leaf length × maximum leaf width × 0.75 (McKee, 1964). Two plants per plot were randomly selected in each subplot for these measurements. Corn growth stages were determined according to Ritchie et al. (1997). Corn dry biomass was estimated by harvesting two plants per plot at V6, V9 (2003 only), and R1. Samples were dried at 65°C to constant weight (48 h) and weighed. The corn stand was determined before harvest by counting the number of plants in the two center rows.

Chlorophyll Meter Readings

Corn-N status was evaluated using a chlorophyll meter (SPAD-502, Konica Minolta Holding, Inc.). Readings were taken on the uppermost fully expanded leaf with a visible collar during vegetative growth and from the ear leaf during reproductive growth (Binder et al., 2000). A subsample of 10 corn plants was measured around R1 in each subplot.

Light Interception

The photosynthetic active radiation (PAR, μmol m^{-2} s^{-1}) intercepted by the crop was recorded using a 0.8-m-long Sunfleck PAR Ceptometer (Decagon Devices, Pullman, WA). Measurements were taken on cloudless days between 1100 and 1400 h when the external sensor read at least 1400 μmol m^{-2} s^{-1} photosynthetic photon flux density (PPFD). Light interception (LI) is reported as percentage of the PAR intercepted by the corn crop over the PAR recorded by an external sensor.

$$\text{LI} (\%) = \left[1 - \left(\frac{\text{PAR below canopy}}{\text{PAR above canopy}} \right) \right] \times 100 \quad [1]$$

Leaf Carbon Dioxide Exchange Rate

Leaf CER (μmol CO$_2$ m^{-2} s^{-1}) was measured using a portable, open-flow gas exchange system LI-6400 (LI-COR, Lincoln, NE). An area of 6 cm^2 that did not include the midrib was chosen on a sun-lit fully expanded leaf. The CO$_2$ concentration in the reference was set at 350 μL L^{-1} using 6400-01 CO$_2$ injector (LI-COR, Lincoln, NE). The flow rate of air through the chamber and sample was maintained at 500 μmol s^{-1} to stabilize the measurements. The light source was kept at 2000 μmol m^{-2} s^{-1} PPFD. The temperature was kept within 1°C for measurements taken in each block. Leaf CER was calculated by the LI-6400's operating system, which follows the method of von Caemmerer and Farquhar (1981). Two plants per plot were selected, and CER was recorded between 10 and 20 times after CER and conductance were stable.

Yield and Yield Components Methods

The two and four central rows of each plot in 2002 and 2003, respectively, were mechanically harvested. Yield was corrected for moisture at 155 g kg^{-1}. Three corn plants were collected before harvest (avoiding the center rows) to determine yield components. Plants were dried to a constant weight at 65°C and stems, leaves, and kernels were weighed. Kernel number and weight was also determined for each sample.

Statistical Analysis

The linear model used for the statistical analysis was

$$y_{ijk} = \mu + b_i + \alpha_j + w_{ij} + \beta_k + \alpha\beta_{jk} + e_{ijk}$$

where y_{ijk} = observation in the *i*th BLOCK, receiving *j*th level of factor COVER (α_j) and *k*th level of factor NITROGEN FERTILIZER RATE (β_k); μ = overall mean; b_i = random effect due to the *i*th level of factor BLOCK(*i* = 1, 2, 3, 4), N(0, σ_b^2); α_j = fixed effect due to the *j*th level of factor COVER (*j* = no cover, rye, hairy vetch, hairy vetch–rye); w_{ij} = whole-plot error effect assumed identically and independently distributed N(0,σ_w^2); β_k = fixed effect due to the *k*th level of factor NITROGEN FERTILIZER RATE (*k* = 0, 90, 180, 270 kg ha^{-1}); $\alpha\beta_{jk}$ = fixed interaction effect due to the *j*th level of factor COVER and *k*th level of factor NITROGEN FERTILIZER RATE; e_{ijk} = is the subplot error effect, assumed identically and independently distributed, N(0,σ^2); w_{ik} and e_{ijk} are assumed to be independent of one another.

The random factor *year* and interactions with other terms were also incorporated in the model for analysis using the MIXED procedure of SAS (SAS Institute, 2000). Dependent variables that were measured several times on the same experimental units were analyzed using a repeated measures approach, modeling the variance–covariance matrix of the residuals. For this approach, the REPEATED statement in the MIXED procedure was used. The Akaike's Information Criterion and the Schwarz's Bayesian Criterion were used to select the variance–covariance matrix model and degrees of freedom were adjusted using the Kenward-Roger correction (Littell et al., 2002). All pairwise mean comparisons were done using appropriate standard error of the differences (SED) and appropriate degrees of freedom. The variable time was expressed as days after planting or growing degree days (GDD) using 8°C as the base temperature for corn development (Hesketh and Warrington, 1989; Ritchie and NeSmith, 1991). These variables were used as independent variables in the polynomial regression analysis for CER and LI. The relationship between nitrogen fertilizer rate (NFR) and corn grain yield was investigated using polynomial regression in the MIXED procedure of SAS (SAS Institute, 2000). In all statistical analyses, normality of the residuals was evaluated using the UNIVARIATE procedure of SAS (SAS Institute, 2000).

RESULTS AND DISCUSSION

Weather Conditions

The precipitation during 2002 and 2003 was 922 and 915 mm, respectively. Soil moisture conditions at WCC planting were optimum for seed germination. Although the total amount of precipitation was similar between years, the patterns were different (Fig. 1). An important difference was the precipitation received in July (60 mm in 2002 vs. 162 mm in 2003). This month is critical for corn development and yield determination since silking (R1) occurred around 17 July in both years.

Winter Cover Crop Biomass

Biomass production of WCCs differed substantially between years (Table 1). A possible reason for this difference was planting dates. Because of weather conditions, in 2001 WCCs were planted a month later than in 2002. These differences in biomass production show the widely reported importance of early fall planting for successful WCC establishment and biomass production (Bollero and Bullock, 1994; Clark et al., 1997). This is especially true for hairy vetch, which is more susceptible to winterkill than rye (Reeves, 1994). Although hairy vetch winterkill was not specifically measured in this
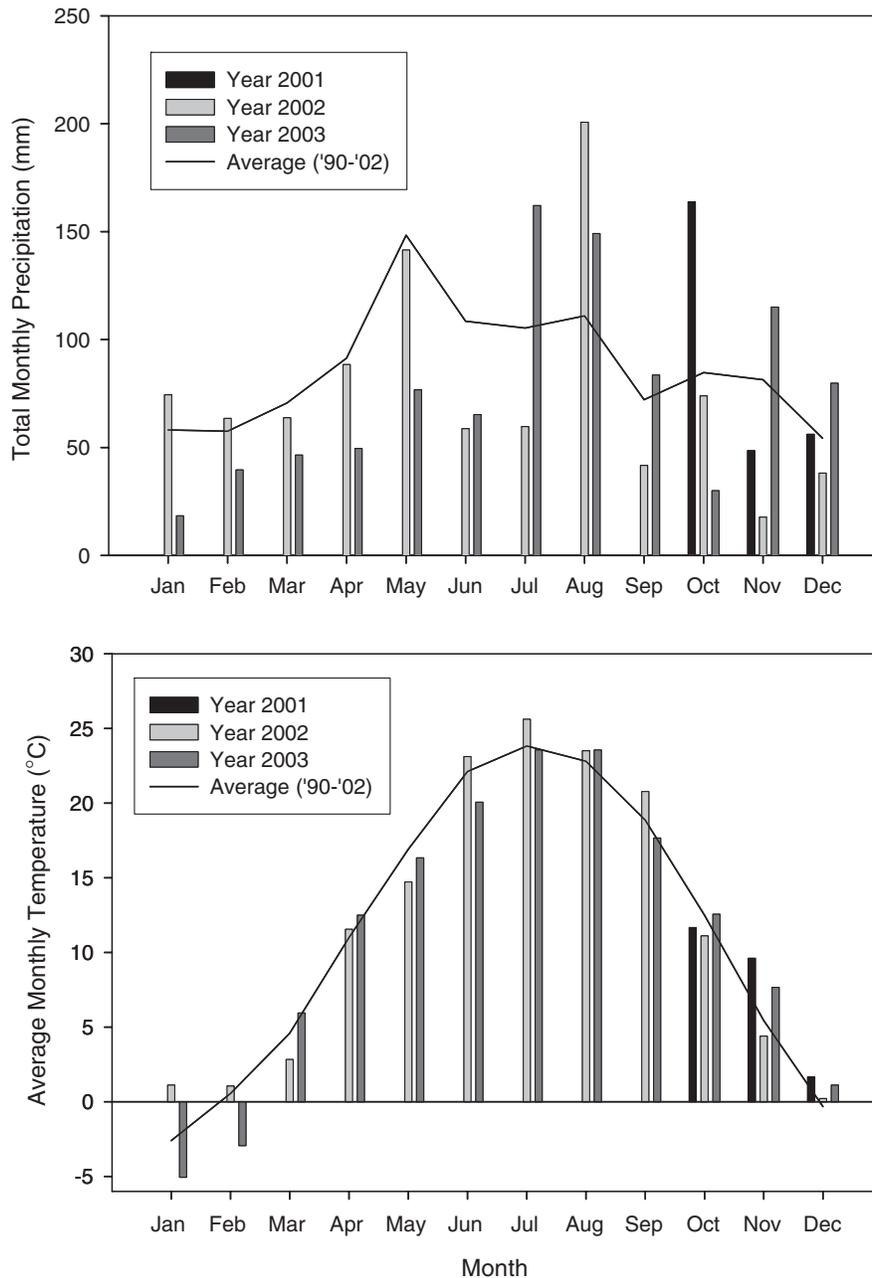

Fig. 1. Weather conditions for 2002 and 2003 growing seasons and 12-yr average at Urbana, IL.

Table 1. Winter cover crop (WCC) aboveground dry biomass and C/N ratio before killing at Urbana, IL.†

Year	R	RB	HV	HVB	SED
			WCC biomass		
			Mg ha^{-1}		
2002	0.61	0.81	0.12	0.02	0.07
2003	2.43	3.17	2.20	0.95	0.23
			C/N		
2002	15.62	10.59	10.28	10.44	1.29
2003	16.76	18.16	10.80	9.87	0.60

† R = rye, RB = rye in biculture, HV = hairy vetch, HVB = hairy vetch in biculture, SED = standard error of the difference.
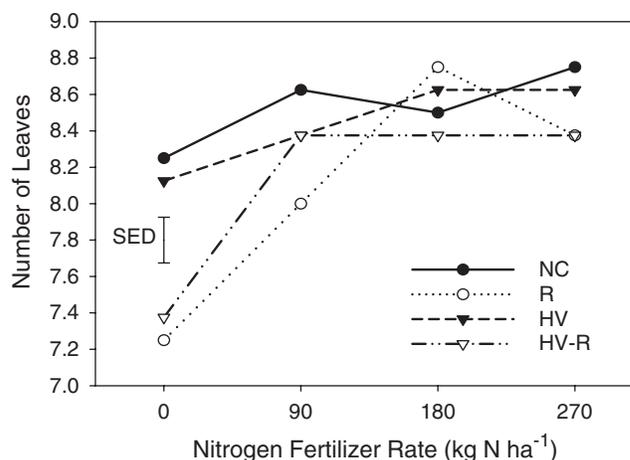

Fig. 2. At corn stage V$_9$, number of leaves for corn following no cover (NC), rye (R), hairy vetch (HV), and hairy vetch–rye biculture (HV–R) with four nitrogen fertilizer rates at Urbana, IL. SED = standard error of the difference.

study, the low biomass production indicates that plants were lost. However, the biomass for the other WCCs was also low, suggesting that conditions were not ideal for WCC growth. Biomass production for rye in biculture for 2003 was similar to that reported by Ruffo and Bollero (2003b). Rye biomass in monoculture was similar to that reported by Crandall et al. (2005) for kill dates 2 and 3 wk before planting corn. As suggested by Crandall et al. (2005), rye was killed 2 wk before planting corn to optimize rye biomass and subsequent corn yields. Hairy vetch biomass showed a similar range compared with other studies in Illinois (Ruffo and Bollero, 2003b; Ruffo et al., 2004).

In this study, the average C/N ratio was 12 and 14 for 2002 and 2004, respectively. These values are lower than the average 17 reported by Ruffo and Bollero (2003a) for Illinois. The C/N ratio of the rye in monoculture and biculture is lower than the values reported in Ruffo and Bollero (2003b), probably as a result of the different management. Killing rye 2 wk earlier is a compromise between the biomass produced and the lower C/N ratio. A lower C/N in the rye in monoculture reduced the negative effects due to immobilization. Probably, if rye were killed 2 wk later, the C/N ratio would be much higher and closer to 25. The low C/N ratios reported here are similar to those in Ruffo et al. (2004) for the higher NFR.

Corn Morphological Characteristics

There was a significant WCC × NFR interaction for the number of corn leaves at growth stages V6 and V9. Rye and hairy vetch–rye biculture significantly reduced the number of leaves at lower NFR (Fig. 2, data for V6 not shown). However, application of 90 kg N ha^{-1} was sufficient to overcome most of these negative effects.

Winter cover crops had a significant effect on the height of corn plants. Corn following rye and hairy vetch–rye biculture was shorter than corn following hairy vetch or no cover (Table 2). However, the significant WCC × NFR interaction ($P < 0.01$) revealed that the effect of WCCs on height was greatly dependent on NFR. For example, at R1 with 0 kg N ha^{-1} corn plants following rye and hairy vetch–rye biculture were significantly shorter than corn plants following hairy vetch and no cover (Table 3). This effect was overcome by application of 90 kg N ha^{-1} for hairy vetch–rye biculture and 180 kg N ha^{-1} for rye.

As early as V6, the uppermost fully expanded leaf of corn following rye had a smaller area than corn fol-

lowing any other treatment, but this difference was not significant at this stage (Table 4). At R1, the difference was greater in magnitude and statistically significant ($P < 0.001$). Rye in monoculture significantly decreased leaf area more than hairy vetch–rye biculture.

The results of the analysis of corn morphological characteristics demonstrate that rye in monoculture had detrimental effects on corn development. The differences found in leaf number, height, and leaf area indicate that corn following rye resulted in a smaller plant and consequently a reduced canopy, which probably led to lower efficiency in intercepting solar radiation. However, most of the detrimental effects were observed at 0 kg N ha^{-1}, and these negative effects were partially or completely overcome by adding 90 kg N ha^{-1}. There were no negative effects at higher NFR. This suggests that rye in monoculture not only did not effectively supply N to corn but rather caused immobilization of N and consequently N deficiency (Wagger and Mengel, 1993). In eastern Canada, Tollenaar et al. (1993) reported reduced height and dry biomass for corn following rye. These authors suggested that the negative effects of rye on corn growth were due to the presence of allelochemicals, the quantity of dry biomass produced by rye, and N deficiencies caused by N immobilization. We hypothesize that, in this study, allelopathic effects were

Table 2. Height and dry biomass of corn plants at different corn developmental stages at Urbana, IL.†

Stage	NC	R	HV	HV–R	SED
			Winter cover crop		
			Height, cm		
V6	17.4	16.0	18.3	16.7	0.8
V9	48.6	38.1	49.9	44.2	1.7
R1	188.5	164.2	190.4	178.3	6.0
			Dry biomass, g plant^{-1}		
V6	6.3	5.4	5.8	5.6	0.3
R1	102.3	97.4	103.5	99.5	2.4
H	252.4	229.2	270.6	247.9	4.2

† NC = no cover, R = rye, HV = hairy vetch, HV–R = hairy vetch–biculture. SED = standard error of the difference.

Table 3. Chlorophyll meter readings and height of corn following winter cover crops and nitrogen fertilizer rate (NFR) at Urbana, IL, averaged across 2002 and 2003.†

| | NFR | Winter cover crop | | | | SED |
		NC	R	HV	HV–R	
	kg N ha^{-1}	cm				
Height	0	190	131	190	167	12
	90	192	162	188	185	
	180	192	185	199	186	
	270	180	178	185	175	
		CMR units				
Chlorophyll meter reading	0	42	38	45	40	2.8
	90	55	52	56	53	
	180	57	57	57	57	
	270	58	59	58	59	

† NC = no cover, R = rye, HV = hairy vetch, HV–R = hairy vetch–rye biculture, SED = standard error of the difference.

not the main reason why rye had detrimental effects on corn development because rye in monoculture was killed 2 wk and rye in biculture 1 wk before planting corn, and negative effects were clearer for rye in the monoculture. We would expect to encounter larger negative effects due to allelopathy where more rye biomass was present and less time for compounds to leach was available. It is possible that belowground biomass, which was not measured in this study, was responsible for the negative effects of rye on corn growth (Tollenaar et al., 1992). In a study by Kuo et al. (1997), the belowground dry biomass of rye was 2.61 Mg ha^{-1}, representing 36% of the total dry biomass and the C/N ratio was 63. It is generally accepted that a C/N ratio > 25 is likely to result in N immobilization and consequently N deficiency to the following crop (Wagger and Mengel, 1993). The high C/N ratio of the roots suggests that N immobilization might be one process by which rye can cause N deficiency and therefore affect corn development. Thus, we propose that in this study the negative effects of rye were partially due to the root system.

The effect of hairy vetch–rye biculture on corn development was intermediate to the effects of rye and hairy vetch in monoculture or no cover. It is likely that the detrimental effects of hairy vetch–rye biculture on

Table 4. Area of the uppermost fully expanded leaf of corn plants at different nitrogen fertilizer rates (NFRs) and corn developmental stages at Urbana, IL.†

| Stage | NFR | Winter cover crop | | | | SED |
		NC	R	HV	HV–R	
	kg N ha^{-1}	cm^2				
V6	0	128	102	139	134	10
	90	155	142	160	144	
	180	160	158	136	167	
	270	158	150	139	150	
V9	0	456	278	503	362	22
	90	545	451	532	517	
	180	531	491	569	516	
	270	507	467	526	514	
R1	0	605	395	622	540	13
	90	627	542	678	678	
	180	674	672	690	680	
	270	680	677	718	668	

† NC = no cover, R = rye, HV = hairy vetch, HV–R = hairy vetch–rye biculture, SED = standard error of the difference.

corn development can be attributed to the negative influence of rye as discussed above. However, the different management (i.e., later kill date) for the hairy vetch–rye biculture provided a greater dry biomass for both components of the biculture. The contribution of hairy vetch to the biculture probably resulted in a greater N supply and a more balanced C/N ratio of the combined residue, and consequently a lower potential for N immobilization (Ranells and Wagger, 1997). Ideally, a hairy vetch–rye biculture can provide corn with benefits associated with both components, but in this study, corn development following hairy vetch–rye was not optimal compared with the response to no cover or hairy vetch in monoculture. In Illinois, management of hairy vetch–rye biculture will require a minimum of 90 kg N ha^{-1} to minimize the negative effects that are likely associated with rye. However, as shown in other states, the inclusion of rye in the biculture can be desirable because rye is more effective than hairy vetch in taking up residual N, and thus better reduces the potential for N loss from the cropping system (Shipley et al., 1992).

Corn Biomass

Dry biomass of corn was affected by the preceding WCC for the combined analysis of years. Small differences in corn dry biomass early in the season, as shown for the morphological characteristics, were more pronounced at later stages of corn development (Table 2). Corn following hairy vetch achieved a larger dry biomass than corn following other WCCs or no cover, but these differences were statistically significant only at harvest. The magnitude of this difference was 21 g plant^{-1} ($P <$ 0.10) between corn following hairy vetch and corn following no cover. This difference was even larger between corn following hairy vetch and corn following rye (41 g plant^{-1}). The difference between corn following hairy vetch and corn following no cover at harvest cannot easily be explained by any of the morphological variables analyzed. However, these variables focused on the early development of corn, and the observed differences might be a result of ecophysiological changes that occurred later in corn development.

Chlorophyll Meter Readings

Chlorophyll meter readings were made around R1, giving an indication of the N status of corn plants during a critical period for yield determination (Binder et al., 2000). Since CMRs provide an indication of corn N status, it is not surprising that when no N fertilizer was applied, CMRs were lower regardless of WCC (Table 3). However, CMRs of corn fertilized with 0 kg N ha^{-1} following hairy vetch was higher than either hairy vetch–rye biculture or no cover ($P <$ 0.10), and corn following rye had the lowest reading ($P <$ 0.05). These results agree with the patterns observed for the morphological characteristics, and thus support the hypothesis that the process by which rye negatively affected corn development was through N immobilization. Additionally, with 90 kg N ha^{-1}, CMRs were substantially increased for all

treatments and there were no significant differences at higher NFRs. One of the implications of higher CMR is greater absorptance of PAR by the crop (Earl and Tollenaar, 1997). According to the relationship found by Earl and Tollenaar (1997), the predicted absorptance in this study was 0.86 for corn following hairy vetch at 0 kg N ha^{-1} and 0.83 for corn following rye at 0 kg N ha^{-1}. This suggests that the higher N status of corn following hairy vetch may allow for a greater absorptance, possi-

bly contributing to higher growth rate, but this may not be as important as the effects on LI and CER.

Light Interception

Light interception predictions show that the largest differences for corn following WCCs or no cover were observed at 0 kg N ha^{-1}. No significant differences were observed at 90 kg N ha^{-1} or 180 kg N ha^{-1}. Because
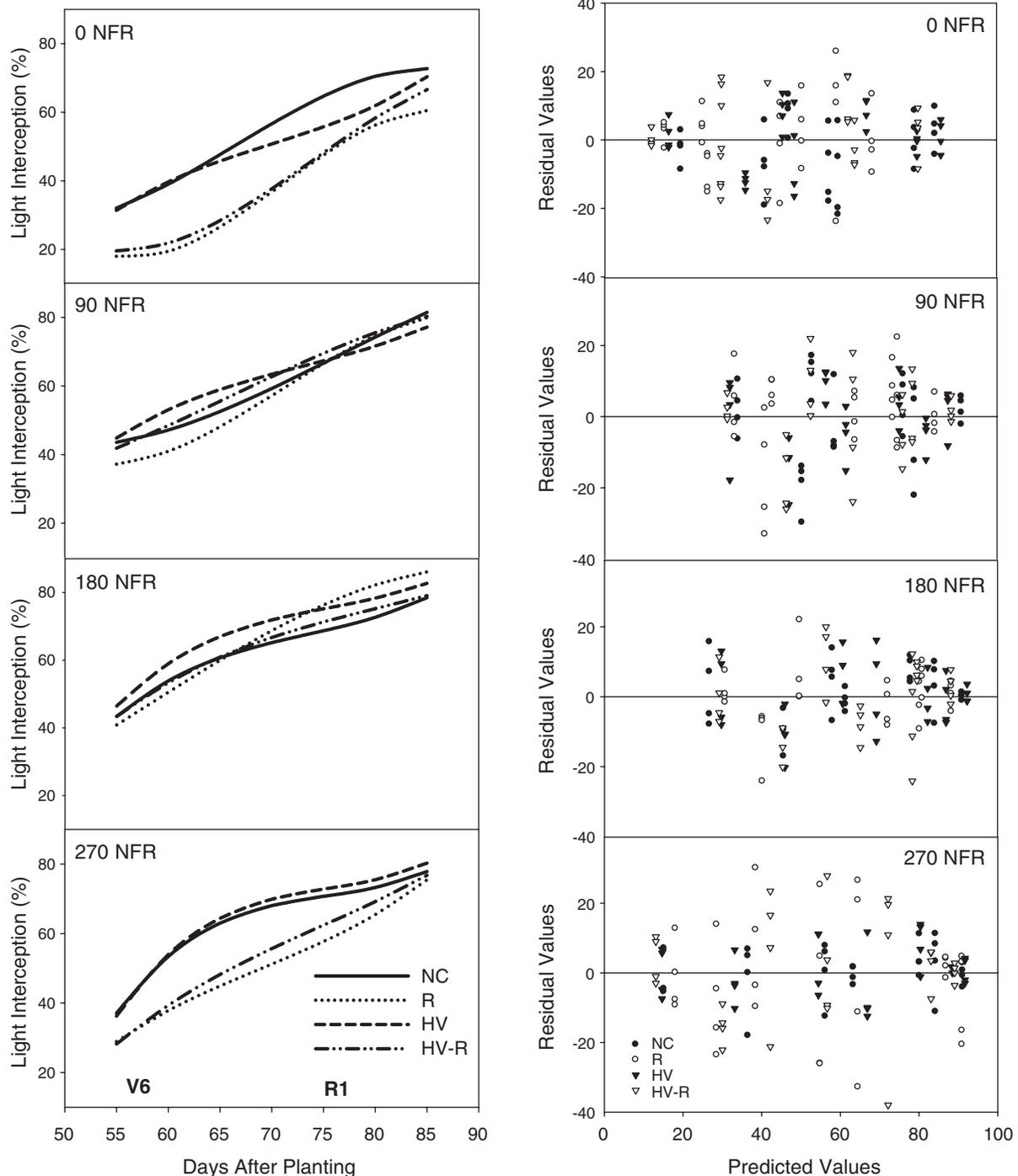

Fig. 3. Relationship between light interception for corn following no cover (NC), rye (R), hairy vetch (HV), and hairy vetch–rye biculture (HV–R) against days after planting with four nitrogen fertilizer rates (NFR) at Urbana, IL. A plot of raw residuals and predicted values is included.

there were significant differences in the area of the uppermost fully expanded leaf at R1 (Table 4), it is expected that corn following rye had lower LI at this stage. The detrimental effect of rye or hairy vetch–rye biculture observed in most of the morphological characteristics, combined with the analysis of biomass, agree with the observation that PAR intercepted by corn was greatly reduced for these treatments in the period between V6 and R1 (Fig. 3). Additionally, plant population

was uniform across treatments (data not shown), suggesting that the main reason for a decrease in LI was a negative effect on crop growth and leaf area, which in turn led to reduced light intercepted by the whole canopy (Andrade et al., 2002). Although CMR indicated that absorptance was reduced for corn following rye and hairy vetch–rye biculture, the main reason for a lower growth rate was less light intercepted at early stages of development.
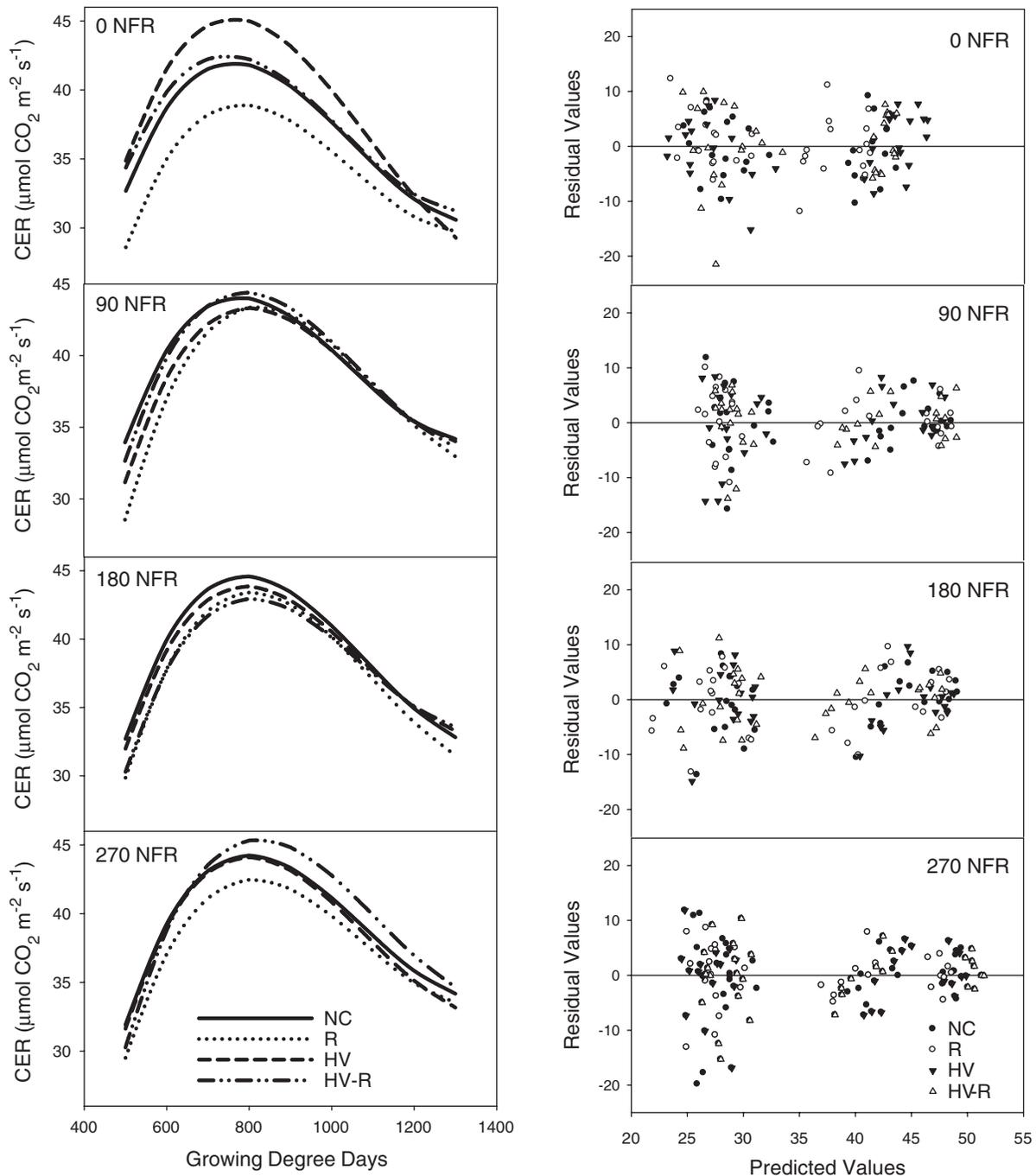

Fig. 4. Relationship between carbon dioxide exchange rate (CER) and growing degree days for corn following no cover (NC), rye (R), hairy vetch (HV), and hairy vetch–rye biculture (HV–R) with four nitrogen fertilizer rates (NFR) at Urbana, IL. A plot of raw residuals and predicted values is included.

Carbon Dioxide Exchange Rate

The results of corn development and LI raise the question of how corn growth rate responded to WCCs. As for LI, statistical differences and differences in magnitude in CER were mainly found for corn that received no N fertilizer (Fig. 4). At 0 kg N ha^{-1}, corn following hairy vetch maintained CER comparable with higher NFR, while corn following rye had significantly reduced CER at 0 kg N ha^{-1}. Corn following no cover and hairy vetch–rye biculture achieved intermediate CER. These results reflect the growth rate of corn in the period before silking ($\approx$1100 GDD), which has been recognized as a critical period for kernel set, which is in turn closely associated with corn grain yield (Andrade et al., 2000). The higher values of LI (Fig. 3), combined with higher CERs, provided corn following hairy vetch an advantage over corn following any other WCC or no cover. Although corn following hairy vetch at 0 kg N ha^{-1} had CER comparable with higher NFR, LI measurements were lower than at higher NFR. These results agree with
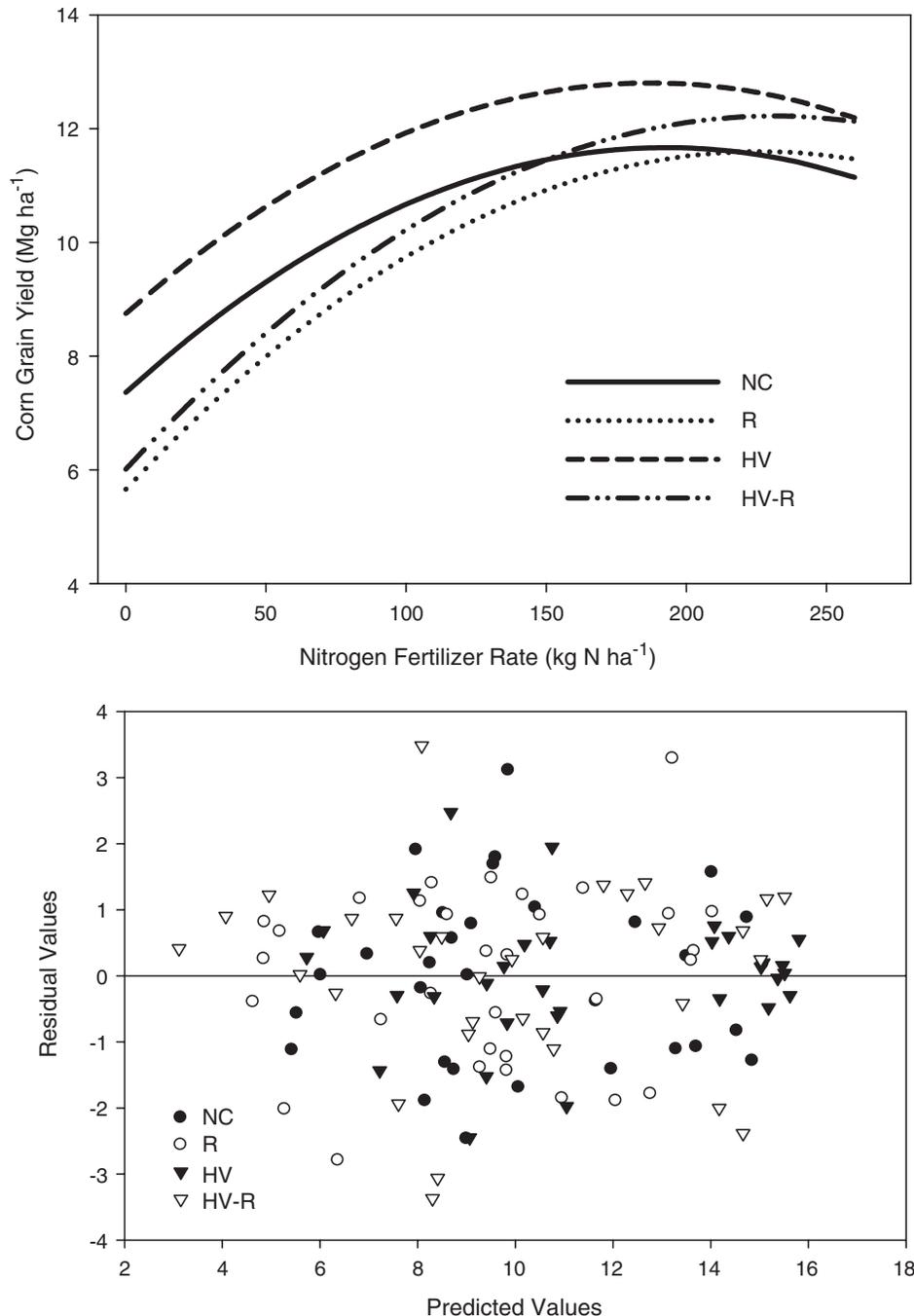

Fig. 5. Relationship between corn grain yield and nitrogen fertilizer for corn following no cover (NC), rye (R), hairy vetch (HV), and hairy vetch–rye biculture (HV–R) at Urbana, IL. A plot of raw residuals and predicted values is included.

Table 5. Regression analysis for corn grain yield following winter cover crops (WCCs) and nitrogen fertilizer rates (NFR) at Urbana, IL, averaged across 2002 and 2003.†

Covariance parameter estimates			ANOVA					Contrasts			
Covariance parameter	Estimate	Ratio to the residual	Effect	d.f.	Error d.f.	F	P value	Intercept		Linear parameters	
Year	4.5897	2.4884	WCC	3	3	1.52	0.3687	NC vs. R	ns‡	NC vs. R	*
Block (year)	0	0	NFR	1	1	16.23	0.1549	NC vs. HV	ns	NC vs. HV	ns
Year × WCC	0.4106	0.2226	WCC × NFR	3	83.1	4.91	0.0034	NC vs. HV–R	ns	NC vs. HV–R	**
Block (year) × WCC	1.1552	0.6263	NFR × NFR	1	83.1	61.54	<0.0001	R vs. HV	*	R vs. HV	**
Residual	1.844	1	NFR × NFR × WCC	3	83.1	0.86	0.4634	R vs. HV–R	ns	R vs. HV–R	ns
			NFR × NFR × NFR	1	83.1	2.33	0.1304	HV vs. HV–R	*	HV vs. HV–R	**
			NFR × NFR × NFR × WCC	3	83.1	0.86	0.4679				

* Significant at the 0.05 level.
** Significant at the 0.01 level.
† NC = no cover, R = rye, HV = hairy vetch, HV–R = hairy vetch-rye biculture.
‡ ns = not significant.

much of the evidence in the literature in which leaf area is more sensitive to N deficiencies than CER (Bloom et al., 1985; Sinclair and Horie, 1989; Grindlay, 1997; Gastal and Lemaire, 2002). Thus, although hairy vetch increased soil N availability to corn, it was not enough to provide the entire N needed for achieving high levels of LI. This is in agreement with Roberts et al. (1998), given that the best recommendation for farmers interested in replacing synthetic N fertilizer with hairy vetch is that additional N fertilizer should be applied to optimize leaf area and consequently light intercepted by the corn crop.

Corn Yield and Yield Components

The predicted equations for corn grain yield for years combined as anticipated by the analysis of ecophysiological characteristics show that the largest differences were found at lower NFR (Fig. 5). Although nonsignificant, the magnitude of the difference in corn grain yield following hairy vetch and no cover was 1.1 Mg ha^{-1}. Moreover, there were no significant differences between the intercept and the linear parameter of the regression equations for corn following hairy vetch and no cover (Table 5). Even though differences in corn yield for corn following hairy vetch at low NFR could be a result of higher LI and CER, it is not entirely clear what mechanisms are responsible for the difference observed between corn following hairy vetch and no cover at higher NFR. Clark et al. (1997) found that hairy vetch residue was more effective in conserving soil moisture than no cover. Therefore, it is possible that in this study some of the beneficial effects attributed to hairy vetch are associated with improved soil moisture conservation.

There were differences in corn grain yield between years since the grand mean yield was 8.1 Mg ha^{-1} for 2002 and 12.3 Mg ha^{-1} for 2003. The variance component for the random effect of year was 2.5 times larger than the residual. It is clear that 2 yr do not provide a reliable estimate for this variance component (Littell et al., 1996), and that much of the variability in this study is due to factors that differed between years. Probably the two factors that varied the most were the precipitation in July and the dry biomass production by WCCs. More years of experimentation are needed to estimate the effects of highly variable annual weather patterns.

In addition, a better approach to this issue is combining the results of studies which considered similar treatments using appropriate statistical methods (Miguez and Bollero, 2005).

Kernel number and weight increased with N fertilizer (Table 6). As with previous variables, kernel number and weight only differed among WCCs when no N fertilizer was applied and as NFRs increased differences among WCCs were nonsignificant. Also, corn following hairy vetch had the highest mean for kernel number and weight and corn following rye had the lowest.

In summary, the analysis of ecophysiological characteristics of corn following WCCs and no cover revealed that corn following hairy vetch was superior to all other treatments when no N fertilizer was applied. The fact that most observed differences disappeared with N fertilizer suggests that most of the beneficial effects of hairy vetch are due to an improved soil N availability. However, in the regression analysis for grain yield, although the parameters were not statistically different, corn following hairy vetch yielded more than following no cover, suggesting that there might be beneficial effects associated with hairy vetch that are not solely due to N supply. On the other hand, rye and hairy vetch–rye biculture had detrimental effects on corn, and this was almost always true when no N fertilizer was applied. No N fertilizer is an unrealistic scenario for most farmers, and there were very few cases in which the negative effects were not overcome by application of 90 kg N

Table 6. Corn yield components following winter cover crops and at different nitrogen fertilizer rate (NFR) at Urbana, IL, averaged across 2002 and 2003.†

Yield Component	NFR	Winter Cover Crop				SED
		NC	R	HV	HV–R	
	kg N ha^{-1}	—— no. kernels plant^{-1} ——				
Number of kernels	0	445	313	510	400	48
	90	529	533	542	506	
	180	564	531	571	547	
	270	658	599	641	618	
		—— g plant^{-1} ——				
Weight of kernels	0	102	74	121	88	13
	90	145	146	162	140	
	180	158	150	159	159	
	270	181	172	193	183	

† NC = no cover, R = rye, HV = hairy vetch, HV–R = hairy vetch–rye biculture, SED = standard error of the difference.

ha^{-1}, which is below the average NFR used by farmers in Illinois (Bollero and Bullock, 1994). It is encouraging that the management practices used in this study did not cause negative effects on corn development and yield as long as at least 90 kg N ha^{-1} were applied. Thus, incorporating WCCs in a corn–soybean rotation in Illinois could provide environmental services without affecting corn yield potential. Furthermore, if hairy vetch is incorporated, the yield potential of corn might even increase above what would be expected under the prevalent cropping system in Illinois in which WCCs are not used.

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