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ABSTRACT

Changes in government farm programs and the introduction of new technology offer wheat producers in the western Great Plains a variety of management practices to alleviate biotic and agronomic constraints inherent in a wheat monoculture. Producers have adopted alternative tillage systems, crop diversification, and insect-resistant varieties in response to the hot, semiarid growing conditions and increased pest pressure. The objective of this study was to determine if those practices generated positive impacts on wheat yield and corresponding net returns. Panel data collected from a group of 141 producers over a four-year period (N = 564) were analyzed using econometric models. The most significant impacts were from crop diversification, which on average more than doubled returns from $29 to $69 per acre compared to a wheat monoculture. Pest-resistant varieties increased returns by 59%, from $32 to $51 per acre. The use of no-till reduced returns by an average of $13 per acre, but when combined with a modest level of crop diversity, returns approached breakeven. Stakeholders should aspire to increase the profitability of no-till to increase its adoption in this environmentally sensitive region.

KEY WORDS

cereal aphids, crop diversity, greenbugs, pest-management practices, tillage, Russian wheat aphids, winter wheat

INTRODUCTION

Wheat has traditionally been one of the most important crops in U.S. and global agriculture. In 2018, 1.9 billion bushels of wheat were produced in the United States, generating $9.5 billion in revenue and ranking only behind corn and soybeans (U.S. Department of Agriculture National Agricultural Statistics Service [USDA NASS], 2001–2010). In typical years, U.S. wheat production satisfies domestic demand and also provides substantial export earnings. The Great Plains is the largest wheat-producing region in the United States. Of specific interest to this essay is the western Great Plains of the United States,[1] where more than 50 million acres of wheat are planted annually. The hot and dry conditions in the region limit cropping opportunities, resulting in a wheat monoculture. Recent changes in government farm programs have, however, initiated an increased level of crop diversity.

Monocropping and the geographic concentration of crop species are often associated with the buildup of persistent insects, weeds, and foliar disease (Brewer & Elliot, 2004; Men, Feng, Erdal, & Parajulee, 2004). Common wheat pests in the western Great Plains region include a variety of cereal aphids and other winged insects such as Hessian fly. Russian wheat aphids (*Diuraphis noxia*, RWAs) and greenbugs (*Schizaphis graminum*, GBs) are two of the most common aphids in the western Great Plains (Giles, Jones, Royer, Elliott, & Kindler, 2003; Mornhinweg, Brewer, & Porter, 2006; Keenan, Giles, Burgener, & Elliott, 2007a; Keenan et al., 2007b). Aphids damage wheat by sucking phloem fluids from plant tissue as well as injecting toxins into plants. GBs transmit barley yellow dwarf virus, a vicious wheat disease that often causes significant losses (Webster et al., 1994; Brewer, Nelson, Ahern, Donahue, & Prokrym, 2001). Aphids typically do not cause serious crop losses every year. Sudden outbreaks, however, occur when temperature, humidity, and wind speed are favorable, enabling aphid populations to flourish (Archer & Bynum, 1992; Archer, Johnson, Peairs, Pike, & Kroening, 1998; Peairs, 2006; Keenan et al., 2007a, 2007b). In a relatively short period of time, about 7–10 days, RWAs can destroy an entire wheat crop. GB outbreaks are common within a 5- to 10-year cycle and can be equally damaging to wheat (Giles, Hein, & Peairs, 2008).

When outbreaks occur, RWA and GB infestations can have substantial economic impacts on wheat production. Placing economic values on crop losses is difficult, since estimates of pest damage are not routinely monitored by the USDA or other crop reporting agencies. However, Starks and Burton (1977) estimated that a 1976 GB outbreak inflicted damages of $80 million (valued in 1976 dollars) in Oklahoma. Webster et al. (1994) reported that 20% of dryland winter wheat and 60% of irrigated wheat was infested by RWAs in 1993. Dryland yield loss was estimated to be 3.3 million bushels, with a corresponding economic loss ranging from $0.5 million to $135 million (Webster et al., 1994). Further losses in 1993 were reported from GBs, which infested an estimated 41% of dryland wheat and 93% of irrigated wheat, resulting in substantial economic losses across the entire Great Plains that would reach $405 million per year (Giles et al., 2008).

Integrated pest management (IPM) is a systems-based approach to control pest infestations. By coordinating a range of complementary practices, IPM can provide alternative, less environmentally intrusive approaches to chemical spraying. The purposeful use of natural enemies is an IPM tool to maintain pest populations below economic injury levels. In some growing seasons, RWA and/or GB populations can be controlled by naturally occurring enemies such as lady beetles, nabids, green lacewings, and parasitic wasps. In the 1990s entomologists released an introduced parasitoid, *Aphidius colemani*, in several locations throughout the western United States to control RWAs (Jones, Giles, Berberet, Royer, Elliott, & Payton, 2003). When the GB and/or RWA populations exceed economic injury levels, the use of a labeled broad-spectrum insecticide is prescribed as the most effective method to reduce pest population. However, insecticides can have unintended consequences, including reducing the populations of natural enemies, that can limit their effectiveness over the long run.

Planting wheat varieties known to be resistant to the hosting and development of pest populations is another IPM approach. Wheat breeders have developed a line of wheat varieties that include resistance to RWAs and GBs, including those that are resistant to both RWA and GB biotypes. Although RWAs and GBs still infest fields planted with resistant varieties, they inflict less damage on resistant varieties. Breeding insect resistance into wheat varieties is challenging, because biotypes with variable levels of virulence have simultaneously evolved alongside the RWA- and GB-resistant varieties (Burd & Porter, 2006; Randolph, Peairs, Weiland, Rudolph, & Puterka, 2009; Weng, Perumal, Burd, & Rudd, 2010; Nicholson & Puterka, 2014). Certain genes may provide resistance to one or more biotypes, but to date it has not been possible to successfully address all biotypes with a single resistant variety. Compounding the problem is that the efficacy of emerging biotypes is unknown until field testing assesses whether resistant varieties reduce populations of the more common biotypes.

Other wheat varieties include genes that provide resistance to some biotypes but are not designated as resistant. Wheat breeders are reluctant to designate a variety as resistant if it is not resistant to all known biotypes, since producers could overstate the control of a resistant-labeled variety, disincentivizing the need to scout and leaving fields more susceptible to pest damage. USDA surveys from 2000 to 2016 found that varieties listed as RWA-resistant were seeded on less than 5% of the wheat acres across the surveyed region, with use in Colorado reported at 14%. Acreage seeded to varieties listed as GB-resistant ranged from 0% to 5%. High-yielding nonlabeled resistant wheat varieties remain popular among producers. Benefits from high-yielding varieties are more frequently captured compared to resistant varieties, which provide a substantial payoff only in the less frequent years when heavy infestations occur (Doye & Sahs, 2014). In noninfested years, resistant-variety yields generally underperform high-yielding varieties and generate lower economic returns (Kansas

State University, 2008–2016; Colorado State University 2008-2016).

Crop diversification and rotation are important IPM practices that limit the long-term buildup of pest populations by removing host plant material and introducing natural enemies. Andow (1991) found that parasitoid populations are more abundant and effective in controlling targeted pests in fields where crops are rotated rather than being monocropped. Gardiner et al. (2009) found that increasing plant diversity in the areas bordering soybean fields influenced both the level of pest suppression and plant damage inflicted by soybean aphids.

Employing the most appropriate tillage system is another component of IPM that can complement crop rotation and diversification as deterrents to the buildup of pest populations. When performed properly, tillage can control weed populations and eliminate the potential hosting of pest communities, particularly early in the growing season when populations can multiply exponentially. Plant residue can either provide protection or act as a catalyst for pest population depending on the crop and pest species. Burton and Krenzer (1985) found that GB populations were often greater in conventionally tilled fields with little surface residue than in adjacent no-till fields with substantial surface residue. Hesler and Berg (2003) also found that conventional tillage was associated with greater infestations of cereal aphids and a greater incidence of barley yellow dwarf virus than plots on which substantial surface residue was maintained. Royer, Edwards, and Giles et al. (2009) postulated, however, that increases in Hessian fly infestations in Oklahoma are correlated with an increase in the use of no-till for growing wheat.

In continuous wheat (monoculture) production systems, increased levels of disease inoculum are present on the wheat residue left above the soil surface with no-till compared to conventional tillage. With a disease common to wheat such as take-all root rot, increased residue left on no-till fields results in increased amounts of inoculum because the fungus that causes take-all survives on the wheat residue (Edwards et al., 2006; Decker, Epplin, Morley, & Peeper, 2009). By turning over the soil, conventional tillage provides better protection from surface-borne diseases. Foliar diseases such as tan spot and stagonospora glume blotch are also more common in no-till plots and also reduce grain yield potential (Edwards et al., 2006). For some pests, no-till may be classified as an IPM technique. However, for other pests and diseases, conventional tillage serves as an IPM tool.

IPM requires, by its own definition, evaluating the combination of two or more techniques. Estimates of the aggregate value and economic consequences of IPM practices for wheat have not been produced. While the economics of IPM production practices have been evaluated in standard experiment station–replicated trials, the consequences of combinations of these practices on net returns at the farm level have not been determined. The working hypothesis of this essay is that the bundling (combined packaging) of discrete technologies into IPM strategies generates higher economic returns.

The objective of this essay is thus to determine if individual pest-management practices result in greater yield and economic benefits when combined as an IPM approach to pest control. The specific pest-management practices to be evaluated include tillage systems, resistant-variety selection, crop diversification, and insecticide use. Econometric modeling is used to test whether IPM bundles generate significantly higher yields and returns compared to the individual. Our findings and implications contribute to interest of entomologists, pest-management practitioners, and wheat producers by identifying the effectiveness and profitability of IPM for wheat producers in the western Great Plains.

FARM SURVEY DATA

Data were obtained from a series of face-to-face interviews conducted with 141 wheat producers over four years (2002–2005) generating panel data with 564 observations per variable. Our study area includes the portion of the western Great Plains where RWA and GB pest infestations are of economic importance to producers. Three zones were identified and grouped based on similarity of agroecological conditions. The northern zone encompasses southeast Wyoming, the Nebraska panhandle, and northeast Colorado. The main pest of wheat in this area is RWA. The southern zone includes both the Texas and Oklahoma panhandles and neighboring southeast Colorado.

Wheat's primary pests in this zone are RWA and GB. The eastern zone extends through both central Oklahoma and Kansas, where GB is the main pest of wheat.

Within each zone, survey participants were selected by a panel of experts including cooperative extension service county educators, managers of farmer-owned cooperatives, and executives from producer organizations. The panel of experts identified corresponding pairs of farms in nearby locations, with one farm primarily defined by a wheat monoculture and the other farm utilizing a diversified wheat production system. Criteria were included in the decision-making process to ensure as representative a sample as possible. This included selecting farms with management, agronomic, and topographic conditions that were representative of conditions in each zone. Diversified farms were chosen so that alternative crops rotated with wheat were consistent with standard choices within each zone. The northern zone's alternative crops included sunflower, maize, barley, and proso. Sorghum is an alternative crop in both the southern and central zones. Cotton, canola, and soybean are also rotated in the southern zone with wheat. Participants were included from six states: 35 from Colorado, 12 from Kansas, 14 from Nebraska, 42 from Oklahoma, 24 from Texas, and 14 from Wyoming. Comprehensive on-farm interviews were conducted annually to obtain detailed information on farming operations.

Farm Classification and Variable Definitions

Farms are classified in this essay based on their use of insect-resistant wheat varieties, insecticides, tillage practices, and extent of crop diversification. Farms that planted 10% or more of their wheat acres of a resistant variety (for RWA or GB) were classified as adopters of resistant varieties. About half of farms included in the "more than 10% (more than 130 acres on average) plant-resistant variety" category plant less than resistant varieties every year but showed substantial variation across the four years. Similarly, farms that applied insecticides on more than 130 acres during the four years were classified as adopters of insecticides. Both insect-resistant variety and insecticide-use categories showed substantial variation from one year to the next, as many producers shifted back and forth in their efforts to protect against pest infestations.

Tillage was defined based on reported number of tillage operations conducted in the field. Based on tillage practices defined in current farm management literature, producers were separated into three discrete groups: no-till, minimum till, and conventional till (Mitchell et al., 2009; CTIC, 2002). A farm was classified as no-till if the land was never tilled over the four years. A farm was classified as conventional till if the producer reported three or more tillage passes prior to seeding a crop. Farms that did not fit into the no-till and conventional till categories were designated as minimum till.

Producers were classified into three groups according to their level of cropping diversity based on the proportion of total wheat acres relative to total cropped acres summed over the four-year study period (2002–2005). Fallow acres were included in both the numerator and denominator, resulting in the following equation for crop diversity:

$$\text{Crop diversity ratio} = \frac{\text{wheat planted acres} + \text{fallow acres}}{\text{total crop planted acres} + \text{fallow acres}} \text{ over four years.}$$

Nearly all of the surveyed farms (92%) produced winter wheat in either a monoculture or rotation with alternative crops that varied by zone. Classification of the diversity ratio was based on quartiles. Farms that fell in the upper 25% of the diversity ratio, with most of their land in wheat, were classified as wheat-only. Alternatively, farms that fell in the lower 25% of the diversity ratio were classified as full diversity, and the remaining farms in the middle 50% were classified as some diversity.

The diversity ratio and the previous classifications on tillage and resistant variety use enabled statistical testing of whether management practices had a significant effect on wheat yield and net economic returns. Interaction terms were also considered. Statistical significance of each management practice among groups such as state and varying types of management groups were tested (Table 1). Pearson's chi-square test (null hypothesis is that grouped variables are independent) were used for frequency data, or Median and Wilcoxon

Table 1. Management Practice Categories

Management Practices	Categories
Planting resistant in wheat varieties	More than 10% planted in resistant varieties Less than 10% planted in resistant varieties
Insecticide use	More than 10% insecticide use Less than 10% insecticide use
Diversity	Wheat only (monoculture) Some diversity Full diversity
Tillage	No-till Minimum till Conventional till

tests (no significant difference in means) were used for continuous data.

Computation of Net Returns

Data provided by the producers were used to prepare enterprise budgets that detail revenue and costs on a per crop basis (AAEA Task Force, 2000). Net return per acre was calculated by summing returns across all crops produced on the farm. This aggregate approach is considered to be the most appropriate measure of economic performance, since wheat management practices affect wheat as well as the other crops grown on the farm and vice versa. Total revenue and total cost were computed based on farm survey data. Total revenue included the sum of gross returns from all crops (yield times price), government payments (direct payments, countercyclical payments, and loan deficiency payments), and crop insurance payouts when indemnity occurred.

Total costs included labor, fuel, repairs, seed, fertilizer, herbicide, hired custom operations, crop insurance premiums, overhead, operating interest (variable cost items) and depreciation, interest, taxes, housing, and insurance (fixed cost items). Overhead cost was included to account for shop utilities, supplies, tools, and pickup truck expenses and was computed by multiplying variable cost before interest by 0.04. Operating interest was charged to account for the opportunity cost of annual operating capital. Labor cost included the cost of hired labor as well as the opportunity cost of family labor used to conduct machinery field operations. Machinery and truck costs for hauling were computed based on agricultural machinery management engineering and cost parameters (AAEA Task Force, 2000; American Society of Agricultural Engineers, 2002). Land costs were excluded.

The sample of farms included in the study was drawn by the panel of experts, who identified farms considered representative of conditions in the western Great Plains. Since survey respondents were not selected in an ideal (i.e., random) manner, estimates obtained from the survey were compared to those reported by the USDA. The USDA conducts random surveys to produce estimates of wheat production costs and returns. The estimates of wheat cost and returns for the USDA Prairie Gateway region for 2002–2005 are reported in Table 2. The Prairie Gateway region includes parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, and Texas. Average values for selected items obtained from these three states are also reported in Table 2. A t-test was conducted to determine if the mean values were different between the two samples. The hypotheses of no difference were not rejected for cost of custom operation, fertilizer, revenue from wheat grain, and total gross revenue. However, farm size was statistically significantly different between the two samples. The sample of farms included in this study planted significantly more acres per year to wheat (1,380) than the farms in the USDA sample (395 acres per year). Based on these findings, production practices on the sample farms are assumed to be representative of wheat farms in the region. However, the sample farms are substantially larger.

METHODOLOGY: YIELD RESPONSE AND NET RETURN MODELS

Wheat yield response is modeled as a function of several independent variables: year, state, tillage (no-till, minimum till, and conventional till), insecticide use (use vs. not use), planting wheat varieties resistant to RWAs and/or GBs (plant vs. not plant), crop diversity (wheat only, some diversity, full diversity), and an interaction term between year and insecticide use.[2] The yield response model's error structure contains both fixed and random effects to accommodate the panel nature of the

Table 2. **Comparison of Findings from USDA Estimates of Wheat Cost and Returns for the USDA Prairie Gateway Region, 2002–2005, to Average Findings from the Study Survey for States Included in Both Estimates**

		USDA COP Estimates[a]				Survey[b]			
Item	Units	2002	2003	2004	2005	2002	2003	2004	2005
Revenue from wheat grain	$/acre	65.49	100.23	101.32	98.27	54.64	104.73	88.48	94.96
Revenue from straw/ grazing	$/acre	2.78	2.54	6.72	7.33	11.37	11.78	10.95	11.17
Total gross revenue from production	$/acre	68.27	102.77	108.04	105.60	66.01	116.51	99.43	106.13
Seed cost	$/acre	4.53	5.25	5.42	5.70	7.75	7.79	7.81	7.78
Fertilizer cost	$/acre	14.18	18.54	19.84	23.24	18.41	21.55	25.20	24.59
Chemicals cost	$/acre	3.15	3.16	3.75	3.81	5.22	4.75	5.73	5.96
Custom operations	$/acre	6.61	8.05	6.24	6.29	5.74	7.51	7.20	7.85
Hired labor cost	$/acre	2.06	2.15	2.27	2.34	2.70	3.03	2.94	2.66
Wheat yield	bu/acre	22.20	35.20	29.20	31.70	20.30	34.0	31.20	32.70
Wheat acres	acres	347	347	443	443	1,314	1,447	1,298	1,463

[a] Estimates produced by the USDA Cost of Production surveys. The Prairie Gateway region includes parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, and Texas.
[b] Estimates produced by the current study.

data (Greene, 2010). All the explanatory variables were designated as fixed effects in the regression model. The farm-specific effect, $u_{i,}$ was included as a random effect for considering heterogeneities across the farms. The response model for winter wheat yield is expressed as:

$$Q_{it} = \alpha + \sum_{l=1}^{3} \beta_l Y_{lt} + \sum_{k=1}^{5} \delta_k Z_{ks} + \sum_{m=1}^{2} \eta_m T_{mi} + \gamma_1 I_{it} + \gamma_2 Vr_{it} + \gamma_3 Vg_{it} + \sum_{j=1}^{2} \gamma_j D_{ji} + \sum_{n=1}^{3} \lambda_n Y_{nit} I_{it} + u_i + \varepsilon_{it} \tag{1}$$

where the index i denotes farms; t refers to the four years included in the sample; s denotes the six states; m includes the set of three tillage categories; j includes the set of three levels of crop diversity; Q_{it} is winter wheat yield from farm i in year t; Y_{lt} is a dummy variable for year t; Z_{ks} is a dummy variable for count s; T_{mi} is a dummy variable for tillage m; I_{it} is a dummy variable for insecticide use; Vr_{it} is a dummy variable for planting wheat varieties resistant to RWA; Vg_{it} is a dummy variable for planting wheat varieties resistant to GB; D_{ji} refers to the dummy variables for crop diversity; $Y_{ni} I_{mit}$ is an interaction term between year and insecticide use; α, β_l, δ_k, η_m, $\gamma_1 - \gamma_3$, γ_j, λ_n are parameters to be estimated; u_i is a farm random effect with distribution N $(0, \sigma_u^2)$; and ε_{it} is a random error term with distribution N $(0, \sigma_t^2)$ and $\text{cov}(u_i, \varepsilon_{it}) = 0$.

A log-likelihood function was used to estimate equation (1). Misspecification tests were conducted and revealed that the random errors were not normally distributed but were autocorrelated among years (McGuirk, Paul, & Jeffrey, 1993). To correct for autocorrelation, the state variable was further refined by denoting farm locations using county h dummy variables, and random error terms were specified as first-order autocorrelated. The generalized linear MIXED (GLIMMIX) procedure in SAS was used to estimate the regression model. Although the MIXED procedure could account for the panel data with a flexible error structure, it assumes random error terms are normally distributed. Alternatively, the GLIMMIX procedure was chosen. It conserves most of PROC MIXED characteristics and corrects the standard deviations of the estimated coefficients using empirical (sandwich) estimation. Empirical estimators are useful for obtaining inferences that are not sensitive to the choice of the covariance model (Breslow & Lin, 1995; Booth & Hobert, 1998; SAS Institute, 2010). Statistical tests (Tukey-Kramer) were conducted to determine if the predicted means differed across the extent of each practice.

The model for net return is similar to equation (1), with net return ($/acre) rather than yields used as the dependent variable. A misspecification test revealed that the model for estimating net returns was heteroskedastic. To correct for heteroskedasticity, a square root transformation of net return (dependent variable) was conducted, and the state dummy variables were replaced with the county average wheat yield (Wooldridge, 1991; Manning, 1998) as reported by the National Agricultural Statistics Service (USDA NASS, 2001–2010). Two interaction terms, tillage by diversity and diversity by planting wheat varieties resistant to GB, were also added to test whether the effect of diversity on net return would be different for different value of tillage and planting wheat varieties resistant to GB. These added terms also enabled passage of the misspecification tests and strengthened the regression model's explanatory power. The following equation was estimated for net returns:

$$\begin{aligned}(NR_{it})^{1/2} = \alpha &+ \sum_{l=1}^{3} \beta_l Y_{lt} + \delta ACY_{it} + \sum_{m=1}^{2} \eta_m T_{mi} \\ &+ \gamma_1 I_{it} + \gamma_2 Vr_{it} + \gamma_3 Vg_{it} + \sum_{j=2}^{2} \gamma_j D_{ji} \qquad (2) \\ &+ \sum_{n=1}^{4} \lambda_n T_{ni} D_{ni} + \sum_{n=5}^{6} \lambda_n D_{ni} Vg_{nit} + u_i + \varepsilon_{it},\end{aligned}$$

where NR_{it} is net return across all crops grown on farm i in year t ($/acre/year), ACY_{it} is average wheat yield as reported by NASS for the county where farm i is located (bushels/acre [bu/acre]), $T_{ni}D_{ni}$ is a tillage by diversity interaction term, and $D_{ni}Vg_{nit}$ is a diversity by planting wheat varieties resistant to GB interaction term. Other variables and indices are as previously defined in equation 1.

RESULTS

Data Summary

Tillage

Data summary statistics are provided in the appendix. No-till was used in each of the four years by 16% of the farms (see Table A1). All crops seeded on the no-till farms were directly seeded into residue in each of the four growing seasons. There was considerable variability across states and zone. In Colorado, 97% of the surveyed farms reported using no-till or minimum till. However, 76% of Oklahoma producers reported using conventional tillage. Conventional tillage was used on only one Colorado farm. It was a relatively smaller farm (3,800 acres) with 87% of its area cropped to wheat or in fallow. The average Colorado farm cropped more total acres and planted more acres to wheat than producers in any of the other states. The average Colorado no-till farm included in the survey cropped 7,520 acres with 79% cropped to wheat or in fallow each year.

In Oklahoma and Kansas, farms that primarily produced wheat were associated with conventional tillage, while more diversified farms were associated with no-till. For conventional tilled farms in Oklahoma, 84% of total cropland was seeded to wheat, while only 68% of cropland on Oklahoma no-till farms was seeded to wheat. Experiment station studies conducted in Oklahoma found that grain yield is often reduced on continuous wheat due to wheat residue from the previous wheat crop retained on the surface (Epplin & Al-Sakkaf, 1995). This may explain why Oklahoma producers who produced primarily continuous wheat predominately use conventional tillage to better manage crop residue.

Crop Diversity

Table A2 reports findings relative to crop diversity, which was defined in terms of the proportion of crop acres seeded to wheat and fallowed relative to total crop acres. The least diversified quartile was classified as wheat-only. Across states, a range of 94–98% of the crop acres on these farms were either seeded to wheat or fallowed. The middle 50% of the farms, in terms of diversity, were categorized in the "some diversity" group. On these "some diversity" farms across the six states, 73–81% of crop acres were either seeded to wheat or in fallow. The most diversified quartile was classified as "full diversity." On these farms, 42–56% of cropland was either seeded to wheat or in fallow. Cropping is most diversified on the Kansas farms, with 75% (9 farms) included in the full diversity group. Wyoming was least diversified,

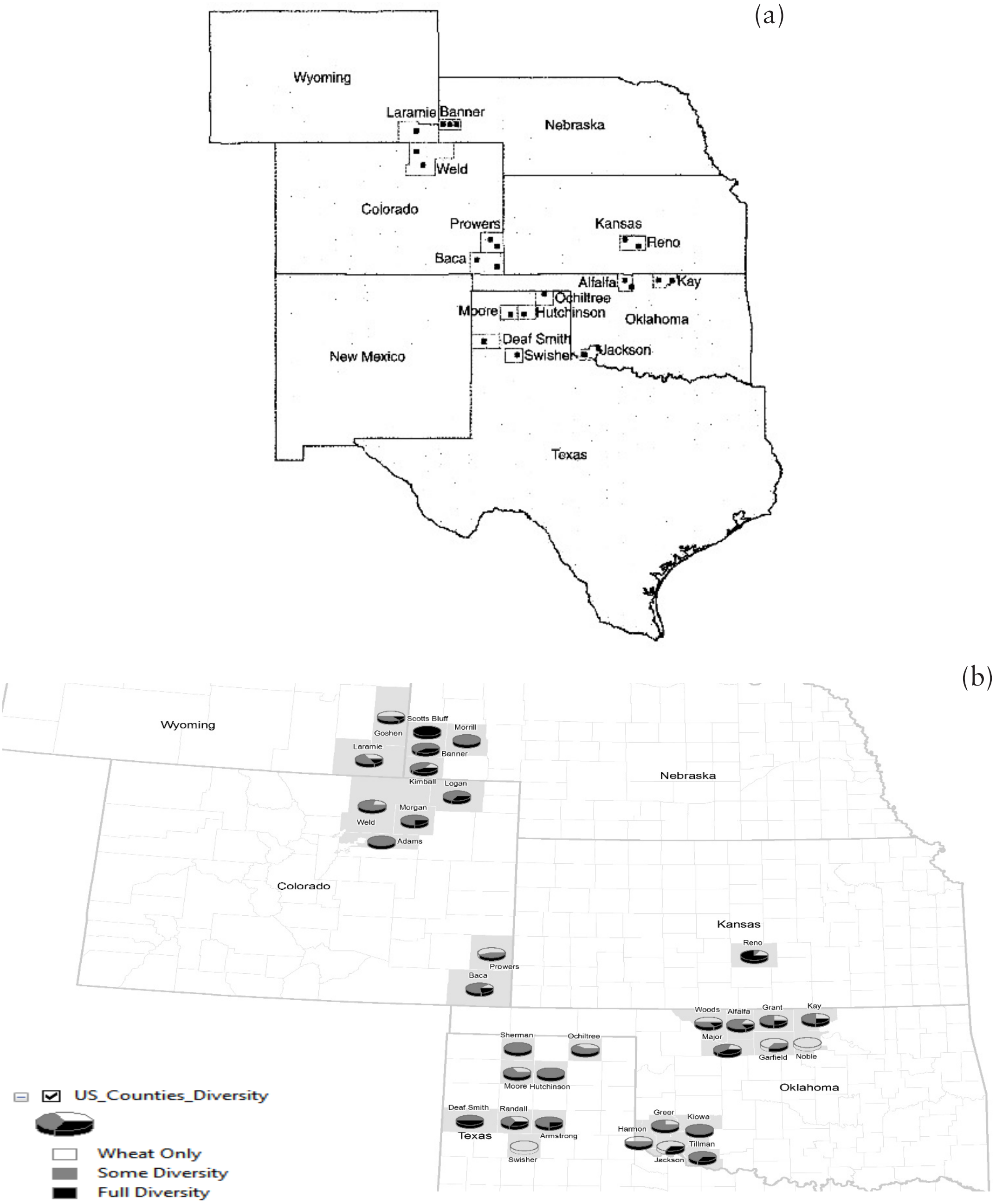

Figure 1. **(a) Location of the Producers by County and State and (b) Pattern of Cropping Diversity across Study Area. Source (a): Giles et al. (2008)**

with 43% (6 farms) included in the wheat-only group. Because of differences in weather and soils, Figure 1 shows that there is no pattern among states from our survey region, but producers in some counties within the region have more economically viable cropping alternatives compared to other producers.

Wheat Varieties Resistant to RWA and/or GB

Across all states in the survey, 18% of the producers (15% of the total observations, since each producer did not use them in each year) planted wheat varieties resistant to RWA on one or more acres (see Table A3). More than half of Colorado producers planted wheat varieties resistant to RWA. Among those producers who planted varieties resistant to RWA, the average area planted to the resistant varieties was 68% in Colorado and 26% (15% of the observations) in Nebraska. Across all states, 21% of the producers planted GB-resistant varieties on one or more acres. Over the four-year survey period, 17–31% of Colorado producers and 33–50% of Texas producers planted wheat varieties resistant to GB on one or more acres. The proportion of total wheat acres planted to GB-resistant varieties on these farms was 79% in Texas, 68% in Colorado, and 26% in Wyoming. None of the Oklahoma and Kansas producers used varieties that were listed as GB- or RWA-resistant.

Insecticide Use

Over the four years and across the 141 surveyed farms, there were 564 opportunities for RWA and/or GB infestations. Insecticide was used for 17% of the total potential outbreaks (see Table A4). However, not every acre was treated on these farms. Producers who used insecticide treated more than 64% of their wheat-planted acres (see Table A4). The Pearson chi-square test indicates that use of insecticide among states was significantly different. None of the Nebraska producers reported insecticide use to protect wheat during any of the four years, while none of the Kansas producers reported insecticide use specifically managing for RWA and/or GB. Insecticide use was more common on Texas farms than elsewhere.

Insecticide Cost by Planting Wheat Varieties Resistant to RWA and/or GB

Planting insect-resistant wheat varieties to either RWA or GB lowered insecticide costs, but the difference was not significant (P > 0.05) according to the Median and Wilcox test. Insecticide costs for wheat planted using insect-resistant varieties were $0.35 per acre on average compared to $0.67 per acre on fields with conventional wheat varieties (see Table A5).

Wheat Yield and Net Return by State

Wheat yields varied from 19 to 44 bushels per acre, with an average field size of 1,341 acres among all six states (see Table A6). Net economic returns for wheat varied from $42 to $75 per acre. Net economic returns across total crops grown varied from $66 to $388 per acre per farm, with an average farm size of 2,619 acres. The farms in the study region grew different crops with fallow rotation. Table A7 shows net economic returns of each crop grown and fallow[3] for four years from 141 farms. All farms grew winter wheat, with number of observations 561, but a few farms did not grow every year, and 316 farms used fallow. Sorghum (grain), millet (proso), and corn were the most popular crops grown in this region. Alfalfa generated the highest net return, with $248.67 per acre, while oats and barley generated the two lowest net returns of $7.21 and $13.93 per acre (see Table A7). Fallow generated negative economic returns, although it provides future benefits since fallow periods serve to reduce soil erosion, conserve soil moisture, and replenish nutrient stocks.

Summary

Management practices varied across farms and across states. Colorado producers had a greater propensity to use no-till and plant wheat varieties resistant to RWA. However, they had less crop diversity and had greater use of insecticides. Kansas producers had more diversified cropping systems and were less likely to use insecticides for managing RWA and/or GB, and most Kansas producers did not plant resistant wheat varieties. Use of conventional tillage was most common in Oklahoma, where none of the survey participants reported planting wheat varieties resistant to RWA and/or GB, and they used significantly greater quantities of insecticide than producers in other states. Texas producers had a greater propensity to plant wheat varieties to GB but applied insecticides to a higher percentage of their wheat acreage. Wheat yield and net return varied across states. Most farms rotated their crops—winter wheat, sorghum, and corn—with fallow. Wheat yields and net returns also varied by state. Kansas had the highest wheat yield and net return of total crops grown across the states.

Model Results

The regression models for both yield and economic returns identified zone as having a significant fixed effect (Pr(F) < 0.01) in both the yield and economic returns equations (Tables 3 and 4). Parameter estimates for the zone variable were significant (P < 0.01) and indicated that Zones 1 and 2 had overall lower yields of 13.5 and 19.3 bu/acre compared to Zone 3 (see Table 3). Individual regression equations were then regressed for each zone using the same regression variables (see Tables 3 and 4). In the yield regression, each of the farm management practices had a significant effect (F-test) in at least one of the zones except for GB (see Table 3). Year also had a significant effect on yields in each zone (F-test), including significant interaction terms with tillage, diversity, and RWA.

Results suggest that in 2002 and 2004, insect infestations reached economic threshold levels in Zones 1 and 2. Insecticide use and the planting of RWA-resistant varieties had positive and significant effects on yields in 2002 and 2004 in both of those zones (see Table 3). While the main effect of insecticide was significant (P < 0.05) only in Zone 1, insecticide had significant interactions with years 2002 and 2004 in both Zones 1 and 2 (see Table 3). The marginal effects[4] of insecticide use were nearly identical in the first two zones, with a slightly larger positive effect of 7.72 bu/acre in Zone 1 compared to 7.09 bu/acre in Zone 2 (see Table 3).

The planting of RWA-resistant varieties also had a significant effect on wheat yields that varied more substantially by zone compared to insecticide use. In Zone 1, RWA had a significant interactive effect with year, increasing yields by 10.81 bu/acre in 2002 and by 9.79 bu/acre in 2004, further suggesting that insect infestations had reached economic threshold levels in Zone 1 (see Table 3). In Zone 2 RWA had significant and negative effect on yields, with a main effect estimated at -5.59 bu/acre (see Table 3). The marginal effect was positive in 2003, however, as RWA-resistant wheat had a significant interaction with year in 2003 that resulted in a yield increase of 10.00 bu/acre. The negative effect of RWA-resistant wheat in the other two years (2002 and 2004) could be explained by the presence of secondary insects (i.e., not RWA or GB) or perhaps due to different agronomic conditions in those years that the RWA-resistant varieties responded to poorly. In Zone 3, neither insecticide nor RWA-resistant wheat had any significant effects on yield (see Table 3). The GB variable was not significant in any of the zones. This could be explained by minimal levels of GB populations in the study zone coupled with the GB varieties performing commensurate with noninsect-labeled varieties.

Crop diversity had a positive and significant effect in each zone that was much greater in the first two zones (see Table 3). In Zone 1, yields on farms in the traditional wheat monoculture were 13.9 bu/acre lower compared to the most diversified farms (see Table 3). According to the model results, conditions were particularly favorable to the wheat monoculture in 2004, a year that had a positive and significant interaction with the wheat monoculture that increased yields by 8.33 bu/acre (see Table 3). The interaction with 2004 resulted in a substantially more modest yield reduction of 5.55 bu/acre compared to the other years (see Table 3). A modest level of crop diversity lowered yields by 7.76 bu/acre compared to the most diversified farms, substantially better performance than the wheat monoculture. Model results also identified a positive and significant interaction with tillage that increased yields by 11.4 bu/acre on modestly diversified farms that practiced no-till (see Table 3). Model results also suggest that conditions in 2002 were particularly favorable on modestly diversified farms that increased yields by 7.16 bu/acre compared to the other years (see Table 3). This resulted in an overall effect of a 10.9 bu/acre yield increase on no-till farms in 2002 (see Table 3).

The general effects of crop diversity in Zone 2 were similar to that of Zone 1 with some differences in the interaction terms (see Table 3). The main effect of the wheat monoculture was reduced yields by 9.87 bu/acre in Zone 2 compared to the most diversified farms (see Table 3). The yield losses were worsened with the wheat monoculture's significant interaction with no-till, which further reduced yields by 7.85 bu/acre (see Table 3). The model results suggest that conditions in 2003 were favorable to the wheat monoculture–no-till farming system, as diversity's significant interaction in 2003 increased yields by 14.4 bu/acre, resulting in an overall yield loss of –3.29 bu/acre (see Table 3). In Zone 2 there was no significant main effect of modestly diversified farms, but there were significant interactions with year. According to the model, conditions in 2002 and 2004 were unfavorable to modestly diversified farms that reduced

Table 3. **Effects of Management Practices on Wheat Yield (bu/acre/year)**

Variables	Levels of Variables	Western Great Plains (All Zones)	Subregion		
			Zone 1	Zone 2	Zone 3
Intercept		49.4077	27.329***	21.5373***	45.7866***
Year	2002	–7.6727	10.2226	-9.3253	–10.4786**
	2003	–4.0383	21.4826**	-3.4431	3.9009
	2004	0.9636	16.0533**	2.0696	2.0277
Location[b]	33 counties	***	***	***	***
Zone (Zone 3 = 0)	1	–13.5351	N/A	N/A	N/A
	2	–19.274	N/A	N/A	N/A
Tillage (conventional = 0)	No-till	–5.3866**	–11.6337**	18.4807***	–7.7063
	Minimum till	–2.4539	–3.1115	13.6104***	–4.3221
Crop diversity (full = 0)	Wheat only	–6.3426***	–13.872**	–9.8727**	–8.6698***
	Some diversity	–5.1545**	–7.7613**	–2.8564	–7.4429**
RWA resist. var. (>10% = 0)	<10% RWA planted	–0.2559	5.2723	5.5949*	0
GB resist. var. (> 10% = 0)	<10% GB planted	–1.9509	–3.4806	–2.2964	0
Insecticide use (> 10% = 0)	<10% used	–3.4297	5.3909**	–2.3354	–3.2165
Tillage x crop diversity	No-till x wheat only	–11.831	11.4477***	–7.8453***	0
	No-till x some diversity	–1.7143	0	–3.3629	0
	Min. till x wheat only	0	3.7526	0	7.4827
	Min. till x some diversity	8.2539	0	–6.6934	5.2743
Year x tillage	2002 x no-till	–0.7153	1.6745	–20.1017***	8.0602
	2002 x min. till	–5.9666**	0.7558	–10.0864*	–2.1389
	2003 x no-till	0	2.1098	–9.8386	–2.0952
	2003 x min. till	–3.1908	–1.2425	–9.7502	–2.5244
	2004 x no-till	–10.378**	0.8626	–14.5066***	5.5963
	2004 x min. till	0	–2.3725	–7.9176**	1.4147
Year x diversity	2002 x wheat only	4.9223	6.8202	7.3834	8.4114*
	2002 x some diversity	5.4208**	7.1599*	8.8206**	5.875
	2003 x wheat only	0	–4.3381	14.4331**	–4.2957
	2003 x some diversity	–1.1212	–4.0252	16.1944***	–3.6904
	2004 x wheat only	–0.5409	8.3275*	4.5413	–0.9427
	2004 x some diversity	0	4.7221	11.2604***	–2.2287
Year x RWA resist. var	2002 x <10% RWA planted	–4.4882*	–9.7924**	–3.544	0
	2003 x <10% RWA planted	0	–5.2214	–15.5976***	0
	2004 x <10% RWA planted	–9.999*	–10.8132***	–4.4994	0
Year x GB resist. var.	2002 x <10% GB planted	0	–2.2371	2.8764	0
	2003 x <10% GB planted	–5.0154	–6.3487	2.3159	0
	2003 x <10% GB planted	–4.4882	3.2398	2.0863	0
Year x insecticide use	2002 x <10% used	–4.3757	–13.1128***	–7.5424**	–3.4016
	2003 x <10% used	0	–2.1745	0.9224	10.9443***
	2004 x <10% used	6.5871	–12.4843**	–10.3285***	3.141

Note. The intercept term reflects the value for conventional tillage, full diversity, planted RWA- and GB-resistant varieties, and insecticide use.

[a] * is significant at the 10% level, ** is significant at the 5% level, and *** is significant at the 1% level.

[b] County location variable was highly significant, with F value 225.59.

yields by 10.1 bu/acre in 2002 and by 7.92 bu/acre in 2004 (see Table 3). In Zone 3, crop diversity had negative and significant effects for both wheat monoculture and modestly diversified farms, reducing yields by 8.67 and 7.44 bu/acre, respectively, compared to the most diversified farms (see Table 3). The only significant interaction in terms of zone was between the wheat monoculture and year, which identified 2002 as a year favorable to the wheat monoculture. Wheat yields were increased by 8.41 bu/acre in 2002, resulting in an overall effect that reduced yields by 0.26 bu/acre (see Table 3).

The importance of tillage on wheat yields was greatest in Zone 2, where both no-till and reduced-till had significant main effects that were both positive, 18.5 and 13.6 bu/acre, respectively (see Table 3). Their negative interactions with diversity and year, however, turned their overall (i.e., marginal) effects negative in several instances, resulting in tillage having an overall mixed effect on yields in Zone 2 (see Table 3). The marginal effects of no-till and reduced-till were most negative in 2004, calculated at –9.47 and –3.87 bu/acre, respectively, representing the corresponding yield loss of each practice relative to conventional tillage (see Table 3). No-till's marginal effect also included a significant interaction with diversity, which found that no-till coupled with wheat monoculture reduced yields by an additional –7.85 bu/acre relative to conventional till and fully diversified farms (see Table 3). In Zone 1, no-till had a significant and negative effect of –11.6 bu/acre on wheat yield (see Table 3). Reduced tillage did not have a significant effect, though its coefficient was negative, –3.11 bu/acre (see Table 3). No-till had a significant and positive interaction with diversity that resulted in a marginal effect that was only slightly negative, –1.89 bu/acre for no-till farms in a wheat monoculture (see Table 3). Tillage had no significant effect on yields in Zone 3 (see Table 3).

Table 4 includes the results of the regression model (equation 2) for net economic return generated by all crops produced and marketed on the farm. Economic returns were much more responsive to management practices than crop yields, suggesting that costs incurred when employing management practices have significant effects even when productivity is unchanged. Regression results for the economic returns models had increased levels of explanatory power compared to the yield models, and each of the returns equations had a greater number of significant variables (see Table 4). Insecticide use, which had a positive effect on yields in Zones 1 and 2, was significant only in Zone 1, where it had an interaction with year. According to the results for Zone 1, the main effect of insecticide was not significant, but it had a significant interaction with year in 2002 resulting in a positive marginal effect of $2.82 per year (see Table 3). Insecticides' modest effect and lack of significance in the other cases is likely explained by the high cost of insecticides relative to yield gains that insecticides provided. For example, in Zone 2 although insecticides increased yields by an average of 13 bu/acre in the years when it was used, the increased revenue generated was not able to offset the cost of purchasing and applying insecticides, resulting in no positive return on insecticide sprayings.

The effects of RWA- and GB-resistant varieties on economic return were significant, but their overall effects were modest in Zones 1 and 2 (see Table 4). The main effect of RWA in Zone 1 was a loss of $1.39 per acre, and in Zone 2 RWA-resistant varieties had only a significant interaction in 2004 with a corresponding overall gain of $4.49 per acre (see Table 4). This result is somewhat unexpected for Zone 1, since RWA-resistant varieties had substantial positive effects on wheat yield in that zone, increasing yields by 9.79 and 10.8 per acre in 2002 and 2004, respectively (see Table 3). A likely explanation is that fields planted with RWA-resistant wheat required insecticide sprays whose costs eroded the yield gains, suggesting that RWAs weren't the primary pest during those infestations. The planting of GB-resistant varieties had an effect only in Zone 1, where its main effect was estimated as a gain of $2.10 per acre (see Table 4). The significant interaction of GB with year in 2004 turned its overall effect negative in 2004, resulting in a loss of $7.20 per acre (see Table 4). The economic loss in 2004 further suggests that the yield losses and infestation in 2004 were not from RWAs or GBs (see Table 4).

Crop diversity had a significant effect on economic returns that was generally positive across all three zones (see Table 4). The main effects of diversity in Zone 1 were estimated as losses of $3.33 and $1.53 per acre for wheat monoculture and modestly diverse farms, but positive interactions with tillage and year turned their returns positive in some instances (see Table 4). The overall effect

Table 4. Effects of Management Practices on Net Returns across All Crops Grown on the Farm ($ per year)

		Western Great Plains	Sub region		
Variables	Levels of Variables	(All Zones)	Zone 1	Zone 2	Zone 3
Intercept		8.6202***	4.7861***	17.3034***	10.0701***
Year	2002	–1.2822	–3.5132**	–5.2961	–0.6709
	2003	0.1742	–1.1511	–4.344	1.036
	2004	–2.517	–4.3967***	–5.8404	1.2654
Location[b]	33 counties	***	***	***	***
Zone (Zone 3 = 0)	1	–2.122***	N/A	N/A	N/A
	2	–0.6945	N/A	N/A	N/A
Tillage (conventional = 0)	No–till	–2.56***	0.06426	–7.2798***	–1.5824**
	Minimum till	–3.2261***	–0.6056	–8.5087***	–2.3206**
Crop diversity (full = 0)	Wheat only	–6.4972***	–3.3311**	–3.4805	–5.5389***
	Some diversity	–5.0398***	–1.5308*	–7.6829***	–4.3331***
RWA resist. var. (>10% = 0)	<10% RWA planted	0.9612*	1.1838***	0.8237	0
GB resist. var. (>10% = 0)	<10% GB planted	–1.5355*	–1.4551**	–1.1438	0
Insecticide use (>10% = 0)	<10% used	–0.1773	0.2449	–1.2294	0.2961
Tillage x crop diversity	No–till x wheat only	3.5564***	–0.03638	5.5679***	0
	No–till x some diversity	3.4232***	0	0	6.6264***
	Min. till x wheat only	4.2986***	1.5842*	5.2146***	0
	Min. till x some diversity	3.5771***	0	0	1.9482
Year x tillage	2002 x no–till	–1.1223	–0.603	2.8191	–0.8167
	2002 x min. till	–1.2375	–0.1247	2.9346	–2.171
	2003 x no–till	–1.0634	0.7812	1.2478	–1.4111
	2003 x min. till	–1.0261	0.2692	3.068***	–0.1124
	2004 x no–till	–0.5965	–0.02513	2.6286	–0.9924
	2004 x min. till	–0.7838	–0.6174	2.5954	–0.8788
Year x diversity	2002 x wheat only	3.6527***	4.846***	3.5813***	2.5192
	2002 x some diversity	2.2123***	3.9842***	2.3525	1.2964
	2003 x wheat only	2.5451***	2.0677**	2.5423	2.9464**
	2003 x some diversity	0.7344	0.6541	2.2256	0.5365
	2004 x wheat only	1.8913*	4.2573***	2.8047	0.2156
	2004 x some diversity	–0.00514	1.203	1.7636	–1.3601
Year x RWA resist. var	2002 x <10% RWA planted	–0.7394	0.02612	–1.1713	0
	2003 x <10% RWA planted	–0.7046	0.8963	–2.1214**	0
	2004 x <10% RWA planted	0.6582	–0.2236	0.03513	0
Year x GB resist. var.	2002 x <10% GB planted	–0.1462	–0.3833	–0.4974	0
	2003 x <10% GB planted	0.8054	–0.5935	0.3622	0
	2003 x <10% GB planted	1.3903	3.0448**	–0.3276	0
Year x insecticide use	2002 x <10% used	–0.02587	–0.3833	0.3437	–0.6404
	2003 x <10% used	–1.6611	–0.5935	0.8708	–2.5856
	2004 x <10% used	0.4365	3.0448**	0.9142	–0.3769

Note. The intercept term reflects the value for conventional tillage, full diversity, planted RWA– and GB–resistant varieties, and insecticide use.

[a] * is significant at the 10% level, ** is significant at the 5% level, and *** is significant at the 1% level.

[b] County location variable was highly significant, with F value 225.59.

of the wheat monoculture on reduced-till farms ranged from a low of $0.10 per acre in 2003 to as high as $9.61 per acre in 2002 (see Table 4). On no-till and conventionally tilled wheat monoculture farms returns were mixed, with negative returns of $0.03 and $3.06 per acre in 2002 and 2003, respectively, and a positive return of $9.61 per acre in 2004 (see Table 3). On modestly diverse farms, the overall effect of diversity was positive only in 2002, when returns were $6.00 per acre.

Diversity had in general a positive effect on economic returns in Zone 2 (see Table 4). The main effect of the wheat monoculture was estimated as a loss of $12.11 per acre except for 2002, when its interaction with year resulted in an overall effect of $0.01 per acre (see Table 4). On modestly diverse farms, the main effect was estimated as a loss of $58.98 that improved slightly from its interactions with tillage. On no-till farms, the overall effect on modestly diverse farms would be a loss of $27.96 per acre, and on reduced-tilled farms the overall effect would be $31.84 per acre (see Table 4). In Zone 3 the main effects of diversity were both positive, with main effects estimated as losses of $30.69 and $19.63 per acre for wheat monoculture and moderately diverse farms, respectively (see Table 4). The wheat monoculture's positive interaction with reduced tillage resulted in an overall positive effect of $13.27 per acre that increased further in 2003 to $21.97 per acre (see Table 3).

No-till had its greatest effect on yields in Zone 2, where it had mixed effects with yield losses and gains varying between –9.87 and 18.4 bu/acre (see Table 3). According to the economic returns model, the cost savings from eliminating (or reducing) tillage was not large enough to offset the lost revenue from reduced yields. In Zone 2, the main effects of no-till and reduced tillage were estimated at –$7.28 and –$8.51 per acre, respectively, corresponding to actual losses of $53.00 and $72.42 per acre (see Table 4). When combined with a medium level of diversity, no-till performed somewhat better economically. No-till's interaction with a medium level of diversity was estimated at $5.57 per acre, resulting in an overall marginal effect of $31.02 per acre (see Table 4). In Zone 1, however, results suggest that the cost savings of eliminating tillage compensated for any yield loss. In the economic returns model the main effect of tillage was not significant, but no-till had a significant interaction, with a medium level of diversity estimated at $1.59 per acre. That estimate corresponds to an overall marginal effect of $2.53 per acre. In Zone 3 tillage had no effect of yields, but according to the economic returns model both no-till and reduced tillage had a significant effect (see Table 4). No-till had a negative effect on economic returns, suggesting that no-till equipment costs coupled with greater chemical costs (insecticides and/or herbicides) were higher for no-till compared to the other tillage practices. The overall effect of reduced tillage in Zone 3, including its main effect of –$2.32 and its positive interaction with diversity, was calculated at $18.49 per acre (see Table 4). Model results suggest that for reduced tillage, production costs would also be higher due to additional costs incurred from equipment and chemical purchases required for the medium diverse farms.

Discussion

Crop diversity has been promoted widely in the western Great Plains following the 1996 change in federal policy that gave producers greater flexibility by eliminating base acre requirements. Crop diversity had a significant and positive effect on net returns in and across all three zones according to model results, which on average more than doubled returns from $29 to $69 per acre compared to a wheat monoculture (Figure 2). Diversity's higher economic returns could be the result of improved pest management. A companion study to our economic survey was conducted by entomologists and weed scientists who recorded pest and weed population data on demonstration farms located within the vicinity of our sampled farms (Giles et al., 2008). Aphid populations, including both RWA and GB, were lower on the demonstration farms that had diversified cropping systems compared to monoculture in the northern and southern zones (Giles et al., 2008). Likewise, Andow (1991) and Gardiner et al. (2009) found more beneficial insect populations in fields where producers had diversified their portfolio. Weed populations (*Bromus* and *Chenopodium*) were also significantly lower on the demonstration farms that had diversified rather than maintained the traditional monoculture in the northern and southern zones (Giles et al., 2008). Producers voiced particular concerns that monocrop wheat was increasingly susceptible to weed pressure and that switching to systems with more broadleaf crops was a more viable long-term strategy. Our results hence suggest that diversifying crops in the western Great Plains region can increase returns by depressing aphid and weed populations, leading to potentially higher yields and reduced chemical costs.

Reduced tillage practices have been promoted in the western Great Plains to improve pest and weed management and conserve resources such as soil, water, and beneficial invertebrates. According to model results, across all three zones net returns were highest on conventionally tilled farms and fell off significantly as tillage was reduced (see Figure 2). Pittelkow et al. (2015) used a meta-analysis with 610 literature citations and found that in the aggregate, no-till lowered crop yield compared to conventional till. In general, however, the production literature reports tillage as having mixed effects on productivity. Higher returns from reduced and no-till field practices were reported in several studies (DeVuyst & Halvorson, 2004; Ribera, Richardson, & Hons, 2004; Archer, Hayorson, & Reule, 2007; So, Desborough, & Grabski, 2009). Other studies, however, have found negative returns under similar types of cropping systems and agroecological conditions (Schillinger & Young, 2004; Kumudimi, Omielan, Van Sanford, & Grabau, 2008; Halde, Keith, & Martin, 2015; Pittelkow et al., 2015). Schillinger and Young (2004) studied no-till in south-central Washington state and argue that no-till has clear soil conservation and other environmental advantages that can still warrant its use.

Although no-till currently provides some benefits to producers, it is expected that with continued research and as producers gain more experience in no-till farming, additional benefits will be

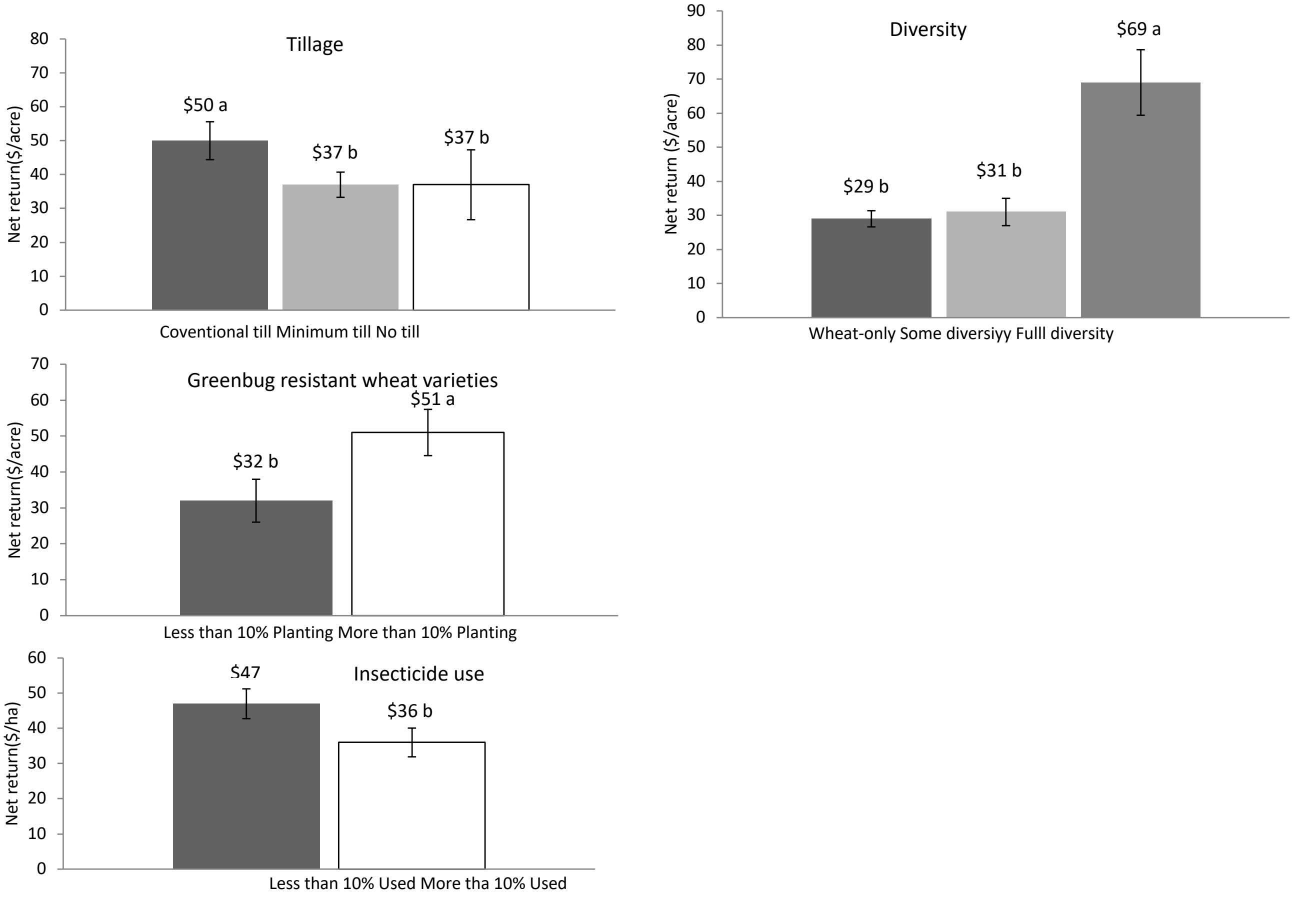

Figure 2. Marginal Effect of Each Management Practice Net Returns across All Crops Grown on the Farms

generated. For example, one of the production issues associated with no-till is the buildup of weed pressure. No-till farms in the survey spent more than twice the amount on herbicides compared to conventionally tilled farms, \$12.96 versus \$5.14 per acre. With improved weed management on no-till and reduced-till fields, herbicide costs could be reduced along with potentially higher yields.

Insecticide use increased net returns through higher wheat yields but was not always able to offset the cost of purchasing and applying insecticides. Insecticides appear to play an important role in IPM as a complementary input to wheat-resistant varieties, particularly since the net return of using insecticides was not significantly higher than planting wheat varieties resistant to GB. Many farms used wheat-resistant varieties and insecticides, suggesting that they did not have complete confidence in wheat-resistant varieties as the sole protectorate from RWA and/or GB infestations. Net returns of planting wheat varieties resistant to RWA and/or GB were not in general significantly greater than not planting conventional nonresistant wheat varieties, nor did planting resistant varieties significantly reduce insecticide costs.

CONCLUSION

The objective of the research was to determine the combined effects of farm management and various IPM strategies on wheat grain yield and net returns for farms in the traditional wheat region of the western Great Plains. Data were collected on crop diversity, tillage system, insecticide use, and the planting of wheat-resistant varieties from four production seasons across a sample of 141 winter wheat–based farms. Based on fitted regression models, wheat grain yields were significantly higher on farms that applied insecticides in two of the four years. The positive association between insecticide use and significant wheat yields was not surprising. Prudent use of insecticides could be expected to protect against yield loss, and insecticides are more likely to be used on crops with greater yield potential. Modeling results also suggest that crop diversification had a positive effect on wheat grain yields and that conventional tillage produced the highest yields.

Production practices had a much more profound effect on economic returns than crop yield. Net returns were significantly affected by tillage system, level of crop diversity, planting resistant varieties, and insecticide use. The combination and bundling of different management practices typically generated higher economic returns. For example, the combinations of tillage with crop diversity and insecticide use with wheat-resistant varieties generated significantly higher economic returns. This suggests that extension services and policy makers should encourage producers to be more flexible in their IPM strategies. In the short run, farms with the fewest resource constraints and the greatest flexibility in reallocating land, labor, and machinery will be the early adopters and the ones most likely to benefit. The bundling of IPM practices will require specialized tillage equipment and the managerial skills to develop and implement economic thresholds on when to apply insecticides. Likewise, farms that have the flexibility to diversify and grow a variety of crops in response to agronomic and market conditions will also have an advantage in being able to bundle IPM strategies.

Wheat varieties resistant to insects (RWAs and GBs) had no substantial effect on either wheat yield or economic returns. This is consistent with the performance of RWA- and GB-resistant varieties that have been introduced in the recent past. While the performance of resistant varieties has been only modestly successful, stakeholders should continue to encourage the development of wheat-resistant varieties even as they continue to be challenged by viral strains evolving into new biotypes that can often outpace their research and development efforts. Advances in technology to identify and map genetic coding and information in both wheat and pest populations present optimistic prospects for the development of more productive resistant varieties. Moreover, planting wheat-resistant varieties is one of the more environmentally friendly and economically productive practices available as part of IPM strategies.

Further research will be required to identify which farm types will be best suited to fully implement optimal IPM strategies. Since it is likely that the smaller farms will be the most resource constrained, limiting their opportunities to invest in new technology and being least prepared to implement IPM practices, extension efforts should focus on forging pathways for smaller producers to overcome constraints. This could include identifying and implementing economically viable cropping alternatives in addition to wheat. Smaller producers could also be provided guidance on how to optimize their machinery complement. Farms that are constrained by available machines to a single tillage system may benefit by investing in a complement of machines that can be used in both no-till and conventional tillage environments, which could also prove useful when diversifying into new crops.

ACKNOWLEDGMENTS

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NOTES

1. In this essay, western Great Plains refers to the drier semiarid areas of the Great Plains parts of Kansas, Nebraska, Colorado, New Mexico, Texas, and Oklahoma. Precipitation occurs mainly in spring and early summer, which combined with high summer temperatures (above 95°F) results in frequent drought (Malone, Decker, & Wiechmann (2016).

2. Equation 1 includes only a single interaction term, but additional interaction terms were also considered. The model that best fit the data included the interaction terms “tillage—crop diversity,” “year—insecticide use,” “year—tillage,” and “year—crop diversity.”

3. Fallow received its revenue from the government as a direct payment.

Because of interaction terms, marginal effects were calculated to include both main and secondary effects.

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APPENDIX:
DATA SUMMARY STATISTICS

Table A1. Number of Producers and Total Land Cropped by Tillage System, 2002–2005

	No-Till		Minimum Till		Conventional Till		Total
Study Area	Number of Observations[a] (%)	Total Acres Cropped (% of Wheat and Fallow Area)	Number of Observations (%)	Total Acres Cropped (% of Wheat and Fallow Area)	Number of Observations (%)	Total Acres Cropped (% of Wheat and Fallow Area)	Number of Observations (%)
Zone							
Zone 1	48	11,221a (69)	104	4,114b (83)	28	3,291c (91)	180
Zone 2	16	6,955a (94)	136	4,558b (84)	16	3,363b (76)	168
Zone 3	24	2,583 (51)	40	2,879 (68)	152	2,257 (85)	216
State							
Colorado	32 (23)	11,839a (76)	104 (74)	5,642b (85)	4 (3)	3,800c (87)	140 (100)
Kansas	8 (17)	2,295 (43)	16 (33)	2,373 (52)	24 (50)	1,786 (71)	48 (100)
Nebraska	12 (21)	2,232 (70)	32 (48)	2,756 (68)	12 (22)	3,215 (80)	56 (100)
Oklahoma	16 (10)	2,315 (53)	24 (14)	3,087 (74)	128 (76)	2,315 (87)	168 (100)
Texas	12 (13)	894 (86)	72 (74)	3,108 (81)	12 (13)	3,138 (71)	96 (100)
Wyoming	8 (14)	1,698 (60)	32 (57)	3,187 (93)	16 (29)	3,327 (95)	56 (100)
Total	88 (16)	—	280 (50)	—	196 (34)	—	564 (100)

Note 1. Farms were maintained throughout each of four years of producer surveys. No-till farms directly seeded into crop residue for each of the four growing seasons. Three farms did not plant wheat for some years; hence, three observations were missing when weighted wheat-plant acres were included in the least-square means analysis.

Note 2. Lowercase letters inside the table indicate that a column is significantly different (95% confidence interval) compared to other columns. For example, letter "a" in Zone 1 indicates no-till acres significantly larger than minimum-tills acres, indicated with "b." Similarly, "b" in Zone 1 indicates that minimum-till acres are significantly larger than conventional-till acres, indicated with "c." Numbers without a lowercase letter indicate no statistical significance across tillage type.

[a] The length of observation is four years for each producer.

Table A2. Number of Producers by Crop Diversity

	Number of Producers			Wheat and Fallow Acres (%)[a]		
Study Area	Wheat Only	Some Diversity	Full Diversity	Wheat Only	Some Diversity	Full Diversity
Zone						
Zone 1	32	104	44	97a	76b	52c
Zone 2	44	96	28	95a	80b	50c
Zone 3	64	84	68	96a	79b	48c
State						
Colorado	28	92	20	94a	79b	53c
Kansas	8	4	36	94a	81a	43b
Nebraska	4	28	24	97a	77a	51b
Oklahoma	56	80	32	96a	79b	53c
Texas	20	56	20	96a	75b	49c
Wyoming	24	24	8	99a	83b	54c
Total	140	284	140	—	—	—

Note. Lowercase letters inside the table indicate that a column is significantly different (95% confidence interval) compared to other columns. For example, letter "a" in Zone 1 indicates that wheat-only acreage is significantly larger than some-diversity acreage, indicated with "b." Similarly, "b" in Zone 1 indicates that some-diversity acreage is significantly larger than full-diversity, indicated with "c." Numbers without a lowercase letter indicate no statistical significance across diversity.

[a] Wheat and fallow acres listed in the table as the percentage of total acres cropped.

Table A3. Number of Observations by Wheat Varieties Resistant to RWA and GB and Planted Wheat Area

	RWA			GB		
	#Observations[a]			#Observations[a]		
Study Area	Planted	Not Planted	Wheat Area[b]	Planted	Not Planted	Wheat Area[b]
Zone						
Zone 1	36	144	49	37	143	18
Zone 2	46	122	68	48	120	73
Zone 3	0	216	0	0	216	0
State						
Colorado	79	61	59	33	107	22
Kansas	0	48	0	0	48	0
Nebraska	2	54	25	4	52	25
Oklahoma	0	168	0	0	168	0
Texas	0	96	0	40	56	77
Wyoming	1	55	8	8	48	13
Total	82	483	—	85	479	—

[a] Four observations were obtained from each farm, one for each of the four years.

[b] The percentage of acres planted to resistant varieties relative to the total acres planted to wheat on those farms that planted resistant varieties.

Table A4. Number of Producers Who Used Insecticide for Wheat Field and Wheat Acres Treated with Insecticide, 2002–2005

	Insecticide: Used		Insecticide: Not Used
Study Zone	Number of Observations	Wheat Acres Treated (%)	Number of Observations
Zone			
Zone1	10 (10)	22 (22)	170 (170)
Zone2	32 (32)	57 (57)	136 (136)
Zone3	55 (28)	57 (58)	160 (188)
State			
Colorado	18 (18)	44 (44)	122 (122)
Kansas	18 (0)	46 (0)	30 (48)
Nebraska	0 (0)	0 (0)	56 (0)
Oklahoma	37 (28)	61 (58)	131 (140)
Texas	18 (18)	84 (84)	78 (78)
Wyoming	6 (6)	22 (22)	50 (50)
Total or Average	97 (70)	64.0 (46.9)	467 (494)

Note: Numbers in parentheses indicate the number of farms that used insecticides specifically for managing RWAs and/or GBs.

Table A5. Insecticide Cost by Planting Wheat Varieties Resistant to RWA and/or GB Compared to Costs of Nonresistant Varieties, 2002–2005

	Resistant Wheat Varieties		Non-Resistant Wheat Varieties	
Study Area	Number of Observations[a]	Insecticide Cost ($/acre/year)	Number of Observations	Insecticide Cost ($/acre/year)
Zone				
Zone 1	55	0 (0)	125	0.07 (0.07)
Zone 2	90	0.34 (0.34)	78	0.26 (0.26)
Zone 3	0	0 (0)	216	1.15 (0.70)
State				
Colorado	90	0.14 (0.14)	50	0.26 (0.26)
Kansas	0	0.00 (0.00)	48	0.70 (0.00)
Nebraska	6	0.00 (0.00)	50	0.00 (0.00)
Oklahoma	0	0.00 (0.00)	168	1.23 (0.83)
Texas	40	0.48 (0.48)	56	0.18 (0.18)
Wyoming	9	0.00 (0.00)	47	0.10 (0.10)
Total or Average	145	0.35 (0.35)	419	0.67 (0.40)

Note. Numbers in parentheses indicate insecticide costs for farms that used insecticides specifically for managing RWA and GB.

[a] The number of observation included wheat varieties resistant to RWA and/or GB. There were farms planted that used both RWA- and GB-resistant varieties.

Table A6. Wheat Yield (bu/acre), Wheat Return ($/acre), Wheat Area (acres), Total Cropped Area (acres), and Net Return per Farm across All Crops Produced ($/acre)

Study Area	Wheat Yield	Wheat Return	Wheat Area	Net Return	Total Cropped Area[a]
Zone					
Zone 1	26 (0.81)	55 (2.7)	1,221 (86)	80 (12)	6,755 (310)
Zone 2	18 (0.76)	55 (2.8)	1,494 (89)	105 (12)	4,656 (290)
Zone 3	38 (0.72)	49 (2.4)	1,303 (79)	235 (11)	2,397 (274)
State					
Colorado	22 (0.76)	55 (2.4)	1,869 (93)	83 (11)	7,731 (258)
Kansas	45 (0.85)	78 (5.9)	913 (159)	373 (27)	2,056 (631)
Nebraska	27 (1.94)	56 (6.2)	709 (147)	81 (28)	2,785 (663)
Oklahoma	36 (0.79)	38 (2.5)	1,414 (85)	210 (12)	2,460 (271)
Texas	19 (1.17)	51 (3.7)	1,141 (113)	142 (17)	3,033 (399)
Wyoming	20 (1.58)	54 (5.0)	1,069 (147)	60 (23)	3,136 (540)
Average	28 (14)	53 (36)	1,341 (1,159)	158 (185)	2,619 (2,442)

Note. Numbers in parentheses are standard deviation of the mean. Crops with fewer than 10 observations were dropped from the statistical analysis.

[a] Acres include fallow areas due to crop rotation.

Table A7. Net Return by crops and Fallow

Crop	Number of observation	Net return ($/acre)	yield (bu./acre)
Alfalfa	94	248.67	3.60
Barley	10	13.93	15.62
Corn	103	20.37	43.79
Cotton	57	96.89	372.58
Fallow	316	-10.97	—
Millet (Hay)	53	28.08	1.50
Millet (Proso)	107	20.35	19.40
Oats	21	7.21	28.25
Oats (Hay)	20	21.24	1.06
Sorghum (Forage)	25	66.76	3.57
Sorghum (Grain)	238	52.15	39.99
Sorghum Sudan	89	58.85	2.07
Soybeans	57	68.43	25.28
Sunflowers	23	60.63	543.35
Sunflowers (Oil)	85	29.01	677.00
Winter Wheat	561	52.80	28.05
Average	1895	47.45	87.47

Note: the crops that were less than 10 observations were dropped.