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Nitrogen Fertility and Weed Management Critical for Continuous No-Till Wheat in the Pacific Northwest[1]

FRANK L. YOUNG, MARK E. THORNE, and DOUGLAS L. YOUNG[2]

Abstract: No-till cropping is an option for growers needing to reduce soil erosion in the Palouse annual-cropped region of the Pacific Northwest, which is well suited for wheat production. A 6-yr field study was conducted to determine optimum levels of fertilizer and herbicide inputs in a no-till continuous wheat crop production system. Three levels of nitrogen (N) and two weed management levels (WML) were compared in a spring wheat (SW)–winter wheat (WW)–WW rotation through two rotation cycles. The high WML reduced weed densities about 50% compared with the low WML. In general, herbicide treatments were more effective on broadleaf weeds and may have facilitated a shift toward grass weeds. The high WML reduced grass weed biomass only at the reduced N levels, whereas the high WML reduced broadleaf weed density at all N levels. Variable environmental conditions affected wheat yield; however, yield tended to be highest where winter wheat immediately followed spring wheat. Nitrogen had little effect on weed density but increased crop yield about 13% with each increased N level. Crop yield was greater at the high versus low WML at each N level, even though weed density and biomass were reduced least between WMLs at the highest N level. The highest crop yield and net returns were obtained with the highest N and WML; however, none of the N and WML combinations were profitable.
Nomenclature: Winter wheat, *Triticum aestivum* L., 'Waverly', 'Daws', 'Edwall', 'Hill 81'.
Additional index words: Crop rotation, nitrogen fertilizer, weed/crop interaction.

INTRODUCTION

Producing crops without tillage is an effective method for reducing soil erosion on highly erodible land otherwise farmed by conventional tillage (Meyer et al. 1999). However, grower adoption of no-till has been dependent on both logistic and economic feasibility and the degree to which individual growers are willing to take risks (Krause and Black 1995; Williams et al. 1990). Therefore, success of growing no-till crops will depend on consistent and adequate crop yields and weed control obtained through knowledge of how pests and crops respond and interact within the production system.

In the Palouse region of the Pacific Northwest, winter wheat is the major crop grown because of the relatively wet, mild winters and dry summers (Appleby and Morrow 1990; Cochran et al. 1990). Because winter wheat is the most profitable crop, it is produced as often and on as much hectarage as possible, including steep hillsides that are prone to severe erosion. The Food Security Act of 1985 mandated growers to comply with soil conservation plans in order to receive farm program benefits. In the Pacific Northwest, yield loss caused by soil erosion has been offset by heavy N fertilization (130 kg/ha) in the fall and additional N (35 kg/ha) applied in the spring (Appleby and Morrow 1990).

Public concerns over health issues related to the use of agricultural chemicals have generated interest for production systems that avoid excessive chemical inputs. In addition, because of low per hectare profit margins, growers are interested in reducing variable production costs to increase profit. However, increases in crop yields since 1963 have been directly related to use of herbicides, fertilizers, and improved crop cultivars (Freyman et al. 1982). Fertilizer and herbicides are relatively easy to apply, cost effective, and have become an integral component of crop production. An integrated approach to sustainable no-till crop production must rely on management of inputs to produce an economically viable crop while reducing or eliminating pesticide and fertilizer contamination of groundwater and controlling soil erosion. In addition, producers may be required to reduce

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[2] Research Agronomist, USDA-ARS, Department of Crop and Soil Sciences, Washington State University, P.O. Box 646420, Pullman, WA 99164-6420; Former Associate in Research, Department of Crop and Soil Sciences, Washington State University, Pullman, WA 99164; Professor, Department of Agricultural Economics, Washington State University, Pullman, WA 99164. Current address of second author: Environmental Sciences, Ohio State University, Columbus, OH 43210. Corresponding author's E-mail: youngfl@wsu.edu.

agrichemical inputs through government mandates or by bankers loaning money.

Adoption of no-till farming represents a major shift in management and can increase risk for crop failure if production methods are not well developed. The dependence of conservation tillage on chemical inputs is well documented (Moyer et al. 1994); therefore, reducing chemical inputs may increase risks if predictable outcomes are unknown. Information is extremely limited, especially in the Pacific Northwest, on the long-term effect of reducing important inputs in continuous no-till wheat production. However, high no-till wheat yields are typically obtained with the highest applied amounts of N fertilizer (Halvorson et al. 1999; Kolberg et al. 1996; Rasmussen et al. 1997), which suggests reduced N input may be detrimental to no-till feasibility.

The competition between weeds and wheat for nutrients, especially N, has been reviewed but results are contradictory (Zimdahl 1990). A decrease in N can favor growth of some weed species (Carlson and Hill 1985; Jørnsgård et al. 1996; O'Donovan et al. 1997), which increases the reliance on herbicides. In contrast, density and seed production of downy brome, a major grass weed in Pacific Northwest winter wheat, increased with higher amounts of N (Rasmussen 1995). A decrease in N may favor weed species that gain a competitive advantage when crop competitiveness is reduced; conversely, increasing N will favor crop and weed species with similar resource acquisition patterns (Di Tomaso 1995).

Management of inputs can be a tool to shift competition to favor the crop. In no-till systems, fertilizer is typically placed below or to the side of crop seed, crop residue is left on the soil surface, and there is less soil disturbance than in a conventional tillage system (Young et al. 1999). As a result, weed flora and growth typically differs from that in conventional systems (McCloskey et al. 1998; Swanton et al. 1999; Wrucke and Arnold 1985). Grasses and other weeds that can germinate within or below the residue layer typically increase or replace broadleaf weeds that rely on soil disturbance for germination and establishment. However, certain weeds are less competitive if fertilizer is banded below or between crop rows compared with broadcasting on the surface (Kirkland and Beckie 1998; Mesbah and Miller 1999; Swanton et al. 1999). In addition, banded fertilizer can increase herbicide efficacy by promoting better crop acquisition of resources (O'Donovan et al. 1997) and may allow for reduced herbicide use in certain systems.

As weed flora respond to changes in production systems, management of N and herbicides in no-till systems are critical for successful and predictable crop production. This study is the first and only one in the Pacific Northwest to evaluate the combined effects of fertility and weed management on no-till wheat production and economics. The objectives of this research are to examine the feasibility of continuous no-till wheat production in the annual crop-based, Palouse region of the Pacific Northwest, and to determine how reducing N and herbicide use in a no-till continuous wheat system will affect crop production, weed density and biomass, and system profitability. This information may allow growers to choose which production variable, herbicides or N, to reduce if production costs must be trimmed.

Table 1. Three nitrogen (N) fertility levels applied to wheat in a 6-yr no-till cropping system study (1986–1991).[a]

Crop year	Rotation cycle	Years post-SW[b] crop	Crop[b]	N level 1.0×	0.75×	0.5×
				kg N/ha		
1986	1	—	SW	70	45	20
1987	1	1	WW	155	115	75
1988	1	2	WW	100	75	50
1989	2	—	SW	70	55	35
1990	2	1	WW	135	100	65
1991	2	2	WW	135	100	65
Total				665	490	310

[a] N was applied as urea–ammonium nitrate, ammonium phosphate, and ammonium thiosulfate during planting of each crop. The 1.0× level represents required N to produce a 5,700-kg/ha WW or a 4,000-kg/ha SW crop based on a 10-yr average; the 0.75× and 0.5× levels targeted 75% and 50% of the 1.0× level.

[b] Abbreviations: SW, spring wheat; WW, winter wheat.

MATERIALS AND METHODS

A 6-yr continuous-wheat, no-till cropping study was conducted from 1986 to 1991 on a cooperator's farm near Pullman, WA. Soil type was Palouse silt loam (fine-silty, mixed, mesic Pachic Ultic Haploxerolls) with 3.1% organic matter and 5.5 pH. The study included three N levels (Table 1) and two WMLs (Table 2) imposed over two no-till crop rotation cycles of SW-WW-WW. A single crop was grown each year, which represented a different phase and cycle of the rotation (Table 1). The maximum N level (1×) was based on N requirements for a 10-yr average crop yield of either 5,700 kg/ha WW or 4,000 kg/ha SW. The moderate (0.75×) and minimum (0.5×) N rates targeted 75% and 50% of the maximum rate, respectively. Herbicides and doses for each WML were determined from early-spring weed counts in all plots. The high WML was based on high-end registered rates and included various herbicides, depending on the

Table 2. One-year example of herbicides and rates (ae or ai) applied in low and high weed management levels (WML).[a]

		Low WML		High WML	
Crop sequence[b]	Weed group	Herbicide	Rate (kg/ha)	Herbicide	Rate (kg/ha)
WW following WW—first rotation cycle					
1988 in-crop[a]	Grass	Diclofop-methyl	0.56	Diclofop-methyl	1.12
	Broadleaf	Dicamba +	0.07	Bromoxynil +	0.28
		diuron	0.90	thifensulfuron	0.03
SW following WW—second rotation cycle					
1989 preplant	All	Glyphosate	0.16	Glyphosate	0.32
1989 in-crop	Grass	Diclofop-methyl	0.56	Diclofop-methyl	1.12
	Broadleaf	Bromoxynil	0.28	Bromoxynil +	0.28
				thifensulfuron	0.02
WW following SW—second rotation cycle					
1989 preplant	All	Glyphosate	0.21	Glyphosate	0.42
1990 in-crop	Grass	Diclofop-Methyl	0.84	Diclofop-methyl	1.12
	Grass +	Metribuzin +	0.28	Metribuzin +	0.33
	Broadleaf	bromoxynil	0.14	bromoxynil	0.21

[a] Dicamba plus diuron was a less-expensive herbicide choice compared with bromoxynil plus thifensulfuron.

[b] Abbreviations: SW, spring wheat; WW, winter wheat.

weed spectrum. The low WML used either herbicide rates up to 50% lower than the high WML if the same herbicides were used, or used fewer (bromoxynil and bromoxynil + thifensulfuron) or different (less expensive) herbicides than the high WML (Table 2).

The experimental design was a randomized complete block, split plot with N levels as the main-plot treatment and WML as the subplot treatment. Each block was replicated four times and contained three adjacent 6 by 18-m N-level plots split into two 3 by 18-m WML plots. Nitrogen and WML treatments were randomized the first year and remained the same for each plot throughout the experiment. Crop year was considered a repeated variable, because the same plots were used each year for each treatment, but each crop year represented a unique phase and rotation cycle combination.

Weed population densities were counted twice each year. The first census was in the spring, prior to in-crop herbicide applications, and the second census was preharvest at physiological maturity of the crop. Weed and crop aboveground biomass were destructively sampled during the preharvest census and oven-dried at 60 C for 48 h. Weed population data and crop and weed biomass were collected from two 1.0-m^2 subsample quadrats placed in each plot following crop emergence and were used for both spring and preharvest data collection. Subsamples for each plot were averaged for statistical analysis. Crop grain yield was determined by harvesting a 1.5 by 18-m area in each plot with a plot combine.

Crop Management. Each year, crops were seeded with a 2.5-m-wide no-till drill with the use of a paired-row configuration (Young et al. 1994). Double-disk openers were paired 13 cm apart for seed placement and each pair of openers was spaced 38 cm apart. Spaced between each pair of seed openers was another set of double-disk openers to deep-band fertilizer between and below the paired-seed rows. Spring wheat was seeded in April, and WW was seeded in September or October. During the first rotation cycle, cv. Waverly soft-white SW and cv. Daws soft-white WW were seeded at 90 kg/ha. During the second rotation cycle, cv. Edwall soft-white SW and cv. Hill 81 soft-white WW were seeded at 90 kg/ha.

Fertilizer as urea-ammonium nitrate, ammonium phosphate, and ammonium thiosulfate was applied with the no-till drill at seeding time. For consistency, all plots were fertilized with 15 kg/ha of phosphorus and 22 kg/ha of sulfur at each crop seeding. Nitrogen requirement for the 1× rate was determined from 1.8-m-deep soil cores extracted and analyzed prior to seeding each year's crop.

Herbicides were applied with a compressed CO_2 backpack sprayer with a 3-m hand-held spray boom. In-crop herbicide applications were typically made in April or May, based on crop and weed stage; however, in 1986 applications were made in June for broadleaf weeds, and in September for fall-germinating grass weeds prior to winter wheat seeding. In 1987, a herbicide application was made in October to the high WML plots, for broadleaf weeds that had germinated with the crop. In 1986 and 1989, glyphosate was applied prior to SW seeding for total weed control. An example of low and high WML herbicide treatments for one SW and two WW crops is shown in Table 2.

Crops were harvested in July or August, and in all

Table 3. P values associated with ANOVA fixed effects for spring and harvest weed counts, harvest weed biomass, and crop yield in a 6-yr continuous-wheat no-till research trial in eastern Washington State.

	Spring weed density		
Model effects[a]	Total	Grass	Broadleaf
N	0.3008	0.6920	0.3586
WML	0.0017	0.4259	0.0004
N*WML	0.2608	0.0045	0.5424
YEAR	<0.0001	<0.0001	0.0258
N*YEAR	0.6710	0.6034	0.5708
WML*YEAR	0.2584	0.5485	0.0384
N*WML*YEAR	0.5626	0.2814	0.8905
	Harvest weed density		
	Total	Grass	Broadleaf
N	0.4748	0.7457	0.1068
WML	0.0007	0.0016	0.0004
N*WML	0.1196	0.1946	0.0709
YEAR	<0.0001	<0.0001	0.0005
N*YEAR	0.5594	0.7364	0.4680
WML*YEAR	0.0507	0.1720	0.1855
N*WML*YEAR	0.8831	0.9881	0.2836
	Harvest weed biomass		
	Total	Grass	Broadleaf
N	0.9945	0.7248	0.0994
WML	<0.0001	0.0363	<0.0001
N*WML	0.0003	0.0125	0.0226
YEAR	<0.0001	<0.0001	<0.0001
N*YEAR	0.5920	0.5669	0.7584
WML*YEAR	0.0309	0.2391	0.0003
N*WML*YEAR	0.1693	0.1032	0.7920
	Crop Yield		
N	0.0016		
WML	<0.0001		
N*WML	0.3092		
YEAR	<0.0001		
N*YEAR	0.0100		
WML*YEAR	0.0021		
N*WML*YEAR	0.6121		

[a] Data were analyzed as a mixed model with nitrogen (N), weed management level (WML), and crop year (YEAR) as fixed effects. Replication was a random effect and not shown here.

years, except 1988, standing stubble was mowed with a rotary mower to reduce stubble height to 12–15 cm. In 1988, all plots were harrowed with a 3.7-m coil-tine harrow to uniformly distribute stubble and crop residue. Crop yield is presented at 0% moisture and 0% contamination.

Statistical and Economic Analysis. Crop yield, weed density, and weed biomass were analyzed with the use of the SAS mixed-model procedure (Littell et al. 1996). All combinations of N, WML, and crop year were used to model each dependent variable (Table 3). Random effects were rep, rep by N, and rep by N by WML. Crop year was considered a repeated effect. Differences for main effects and interactions were determined statistically significant at the $P \leq 0.05$ level and analyzed with the use of a protected LSD mean separation of least-squares means.

For the economic analysis, two adjustments were made to crop yields to realistically portray average market returns from harvested crops over the 6-yr experiment. First, the clean 0% moisture wheat yields were adjusted to reflect 10% combined moisture and chaff content, which is typical of marketed wheat in the study region (Young et al. 1994). This reflects the fact that producers are typically paid for wheat that has some minimal level of moisture and chaff. Secondly, all yields were normalized to average 6-yr levels by using relative yield data from a larger, concurrent experiment on the same field, which included each phase of the SW-WW-WW rotation every year from 1986 to 1991 (Young et al. 1996). For example, SW yields in the larger experiment were evaluated for the 2 yr in which SW was grown in this experiment. If SW yields in the larger experiment during 1986 and 1989 were only 90% of the 6-yr average SW yields of the larger experiment, then all SW yields for this experiment were normalized by multiplying them by (1/0.90). Similar adjustments were made for first and second year WW. This approach addresses part of the confounding from weather that might occur when each rotational crop is grown only once over the 3-yr rotation. For example, if SW, first-year WW, and second-year WW all happened to be grown in years that weather adversely affected these particular crops, the result would be a downwardly biased estimate of the long-run average economic return from the rotation if no adjustments were made.

The profitability analysis is based on returns over total costs. Total costs include land and other fixed costs as well as variable costs like operator labor and management, machine operations, fertilizer, seed, and herbicides. Fertilization and weed management costs were based on the exact treatments in the 1986–1991 experiment and 1991 input prices. This ensures that the prices are matched to the qualities and formulations of inputs used in the experiment. As is typical in modern agriculture, the ratio of production costs to crop prices in U.S. agriculture has fallen since 1991, but producers have adjusted by increasing farm size, crop yields, and input use efficiency. Costs of machine operations and overhead costs were based on a 1991 enterprise budget for wheat crops in the study region (Painter et al. 1991). A fixed cost for land was based on the prevailing share rent, where landlords receive one-third of the wheat crop and pay the same proportion of fertilizer and crop insurance expenses.

In comparing profitability of proposed treatments, projected 1991 to 1995 average crop prices and farm program provisions were used for all results (Painter and Young 1991). The resulting price for spring and winter soft white wheat was \$0.123/kg. Use of an average price avoids confounding production performance of the examined treatments with annual price variation. The market price of \$0.123/kg was used to value wheat production in the experiment because growers in the study region generally had insufficient historical wheat base hectarage to enroll a monoculture wheat rotation in the contemporary farm programs. The average Palouse farm had only 44% of its hectarage in wheat base at the time of the experiment (Halvorson 1991). However, the 1996 and 2002 farm bills have provided for payments to wheat farmers which are decoupled from historic wheat base hectarages. These bills provide payments that are linked to historical wheat yields and hectarages, but are not generally affected by current wheat plantings. These lump sum payments are also difficult to predict because they depend upon farm-specific yield and hectarage history, and sometimes annually changing program provisions. Nonetheless, the influence of these estimates of recent government payments on the level of estimated profits over all treatments will be discussed.

Profitability estimates for N and WML combinations for the entire 3-yr rotation will be presented on a ''rotational ha'' basis. For example, net returns of a rotational ha of SW-WW-WW are comprised of the sum of net returns from 1/3 ha of each rotational phase.

RESULTS AND DISCUSSION

The crop rotation sequence of SW followed by 2 yr of WW was aimed at maximizing winter wheat production. Growing SW every third year was intended to reduce diseases and winter annual weeds. Because only one phase of the crop sequence was present each year, weather (Figure 1) impacted results. In general, the first crop rotation cycle was characterized by below-normal precipitation and the second cycle received normal to above-normal precipitation (Figure 1).

Weed Density. At the onset of the study, weed density prior to 1986 spring seeding averaged 1100 plants/m^2 and represented the base-line weed population for the study area. Forty-five weed species were identified in this study (data not shown), with the most prevalent species being wild oat (*Avena fatua* L. #[3] AVEFA), downy brome, henbit (*Lamium amplexicaule* L. # LAMAM), prickly lettuce (*Lactuca serriola* L. # LACSE), jointed goatgrass (*Aegilops cylindrica* Host # AEGCY), mayweed chamomile (*Anthemis cotula* L. # ANTCO), and volunteer cereal crops. The 1986 spring weed density data were not included because it had not been influenced by any experimental treatments. Following 1986, the crop year influenced the total weed density (both grass and broadleaf) at both dates (before in-crop herbicide application and preharvest). The highest weed density prior to herbicide application in a growing crop was 695 weeds/m^2 in 1988 (Table 4). Weed density at harvest was also highest in 1988. The grasses—volunteer wheat, downy brome, wild oat, and jointed goatgrass—accounted for the majority of weeds for both 1988 dates, and at harvest in 1991. Each of these years represented the second consecutive year of WW. These data are consistent with other research that indicates grass weed density in conservation or no-till systems increases with continuous winter wheat cropping (McCloskey et al. 1998; Moyer et al. 1994; Young et al. 1996). Broadleaf weeds at harvest were most prevalent in the two SW crops and the 1988 WW crop (Table 4). Broadleaf weed density was lowest in 1987 and 1990 (first WW crop following SW), probably because of a reduction in winter annual broadleaf weed seed production following weed management for the SW crop and the competitiveness of the WW crop.

Averaged over all crop years and fertility levels, the high WML reduced total weed density approximately 50% compared to the low WML at both spring and harvest dates (Table 4). Spring weed counts were recorded prior to in-crop herbicide applications, thus reflecting the previous year's management on the nondormant, viable portion of the weed seed bank. With no-till, weed seeds become more concentrated at or near the soil surface (Yenish et al. 1992); however, herbicides can reduce the surface seed bank by reducing annual seed rain (Hoffman et al. 1998). Although not analyzed, total weed density at harvest had declined about 63% from the spring counts within each WML (Table 4) because of herbicide activity and/or crop interference. The low WML controlled broadleaf weeds but not grass weeds at the same level of efficacy as the high WML. Hartzler and Roth (1993) found that 100% weed control in no-till corn (*Zea mays* L.) during the previous year substantially reduced the current year's weed population of summer annual grasses, but had little effect on the broadleaf weed, common lambsquarters (*Chenopodium album* L.). In our research, previous years' weed management had a sub-

[3] Letters following this symbol are a WSSA-approved computer code from *Composite List of Weeds*, Revised 1989. Available only on computer disk from WSSA, 810 East 10th Street, Lawrence, KS 66044-8897.

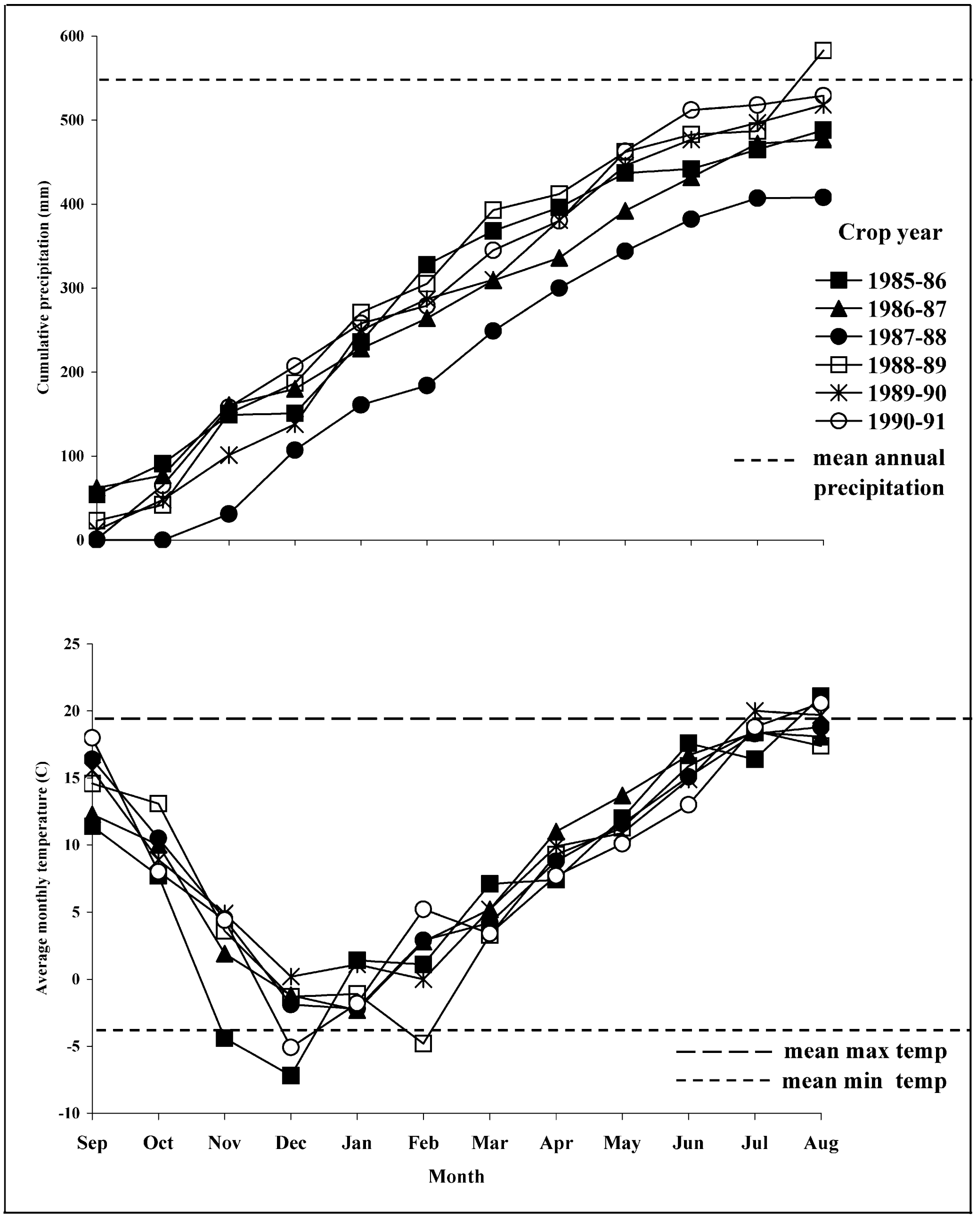

Figure 1. Cumulative precipitation (top) and average monthly temperature (bottom) in each crop year (October 1 to September 30) of the study. Weather data were recorded at Pullman, WA by a weather-recording station located 5 km from the research site with a maximum and minimum average monthly temperature (1954 to 2000) of 19.6 and −2.8 C, respectively, and an average precipitation (1949 to 2000) of 547 mm.

stantial effect on broadleaf weeds, but less effect on the winter annual grass weeds (downy brome and jointed goatgrass), further emphasizing the problem of winter annual grass weeds in Pacific Northwest wheat production. Our data also suggest that using a less intensive herbicide program in continuous wheat production may promote a faster shift toward hard-to-control grass weeds.

Complete weed control was neither expected nor obtained with either WML. In spring, grass weed density was similar for the high and low WML (Table 4); however, a significant interaction existed between N and WML (Table 3) where the grass weed population was reduced 40% at the high versus low WML at the 0.75× N level, but no differences were detected between WMLs at the other N levels (Figure 2). It was not clear why the difference was only at the 0.75× N level. At harvest, there was no interaction between N and WML, and grass weed density was 39% lower in high than low WML plots (Table 4). Decline in grass weed density between spring and harvest would have been due to control of spring-germinating grasses such as wild oat. In con-

Table 4. Weed density (plants/m^2) in spring (before in-crop herbicide application) and immediately before harvest as effected by nitrogen (N) level (proportion of recommended), weed management level (WML), and crop year.[a,b]

	Total weeds		Grass weeds		Broadleaf weeds	
Variable	Spring	Harvest	Spring	Harvest	Spring	Harvest
N level						
0.5×	360 a	130 a	170	105 a	190 a	30 a
0.75×	330 a	110 a	160	90 a	175 a	20 a
1.0×	270 a	110 a	140	95 a	130 a	15 a
WML						
Low	415 a	155 a	160	120 a	255	35 a
High	220 b	85 b	150	75 b	70	10 a
Crop year						
1986–SW		145 b	—	105 bc	—	40 a
1987–WW	205 c	80 c	85 b	70 cd	120	5 b
1988–WW	695 a	205 a	470 a	180 a	220	30 a
1989–SW	215 bc	75 c	75 b	50 d	135	30 a
1990–WW	290 b	45 c	95 b	35 d	195	9 b
1991–WW	200 c	150 b	55 b	140 ab	145	12 b

[a] Numbers followed by the same letter within a treatment group and column are not significantly different ($P \leq 0.05$). Groups of numbers without letters indicate statistical interaction with other treatment variables and are discussed elsewhere.

[b] Abbreviations: SW, spring wheat; WW, winter wheat.

trast, the differences observed in spring would have included seed-bank dynamics and fertility interactions that affected germination of winter annual grass weeds and ineffective selective control of jointed goatgrass, downy brome, and volunteer cereal wheat and barley (*Hordeum vulgare* L.) in the growing crop. Volunteer wheat was considered a weed because of the potential for increased intraspecific competition that could negatively impact grain yield. However, volunteer crop seedlings may suppress other weeds during critical periods of competition and contribute to grain yield.

In contrast to grass weeds, broadleaf weed density was influenced by herbicide inputs. There was a significant interaction between WML and crop year at the spring date (Table 3). High WML plots had fewer broadleaf weeds in each crop year (Figure 3), again reflecting changes in the weed seed bank. Broadleaf weed densities in low WML plots were greatest in 1988 and 1990 and reflected environmental conditions in both years. The 1987–88 crop year was the driest of the study and received 133 mm of precipitation less than the 51-yr average (Figure 1). No rain fell during September and October of 1987 when the WW crop was seeded, which delayed and caused simultaneous crop and weed emergence until late winter. The 1989–90 crop year was the warmest winter (Figure 1) and therefore, winter survival of fall-germinated broadleaf weeds was high. At harvest, broadleaf weed densities in both WMLs were similar and nearly 90% lower than at the spring date (Table 4). In general, broadleaf weeds were controlled more easily than grass weeds because of use of herbicides controlling a broad spectrum of broadleaf weeds.

Weed Biomass. Aboveground biomass is often used to determine plant competitive status as a measure of resource capture, particularly of N (Di Tomaso 1995). In our research, there was an interaction between N and WML (Table 3), which indicated several important re-

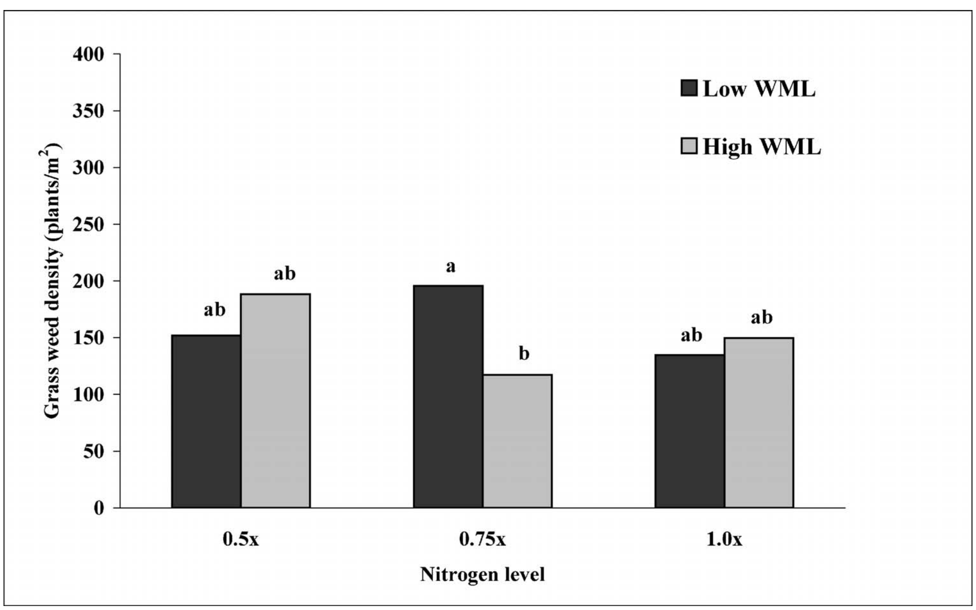

Figure 2. Effect of nitrogen (N) and weed management level (WML) on spring grass weed density averaged over 6 yr. Grass weed densities with the same letters are not significantly different ($P \leq 0.05$).

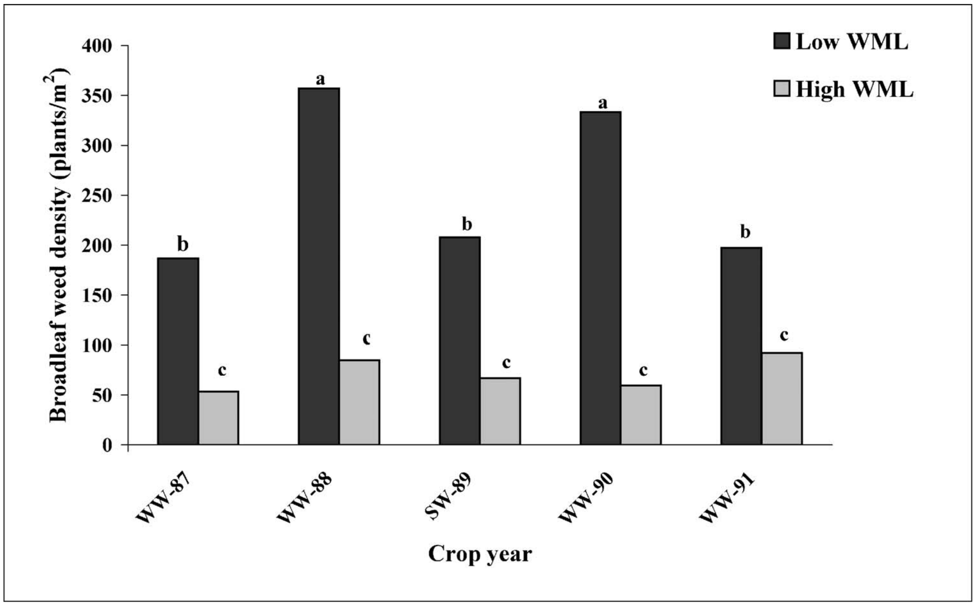

Figure 3. Effect of crop year (SW = spring wheat; WW = winter wheat) and weed management level (WML) on spring broadleaf weed density when averaged over nitrogen (N) levels. Broadleaf weed densities with the same letters are not significantly different ($P \leq 0.05$).

lationships. First, total weed biomass was greatest when both N and WML were lowest (Figure 4). However, the lowest weed biomass occurred at the two reduced N levels with the high WML. Reducing both inputs appeared to give the weeds a competitive advantage; however, the high WML was effective in reducing weed biomass when fertility was reduced. Second, grass and broadleaf weeds responded differently to input levels. At the high N level, grass weed biomass was similar for both WMLs (Figure 4). This relationship also existed for grass weed density (Figure 2). Broadleaf weed biomass was a minor component of the total weed biomass, especially at the high WML (Figure 4). Broadleaf weed biomass in the high WML was considerably less than in the low WML at each N level.

Weed biomass was also affected by an interaction between crop year and WML (data not shown). Biomass production was lower in the high WML compared to the low WML only when spring wheat was grown (1986 and 1989) and resulted from rate differences for herbicides targeting spring-germinating grass weeds such as wild oat. Total weed biomass was greatest in the 1991 crop year, primarily because of grass weeds (data not shown). In 1991, total weed biomass was similar for both WMLs and reflected a weed shift to grass weeds in the continuous wheat no-till system because of a lack of consistently effective control of winter annual grass weeds.

In our research, a relationship between weed biomass and weed density was not apparent (data not shown). In 1988, the second consecutive year of winter wheat during the first rotation cycle, total weed biomass was low primarily because of an extremely dry fall, which delayed winter annual weed growth and development (Figure 1). However, 1988 had the highest weed density during the study (Table 4). In contrast, weed density was low but biomass production was high in 1987 and 1991, which were characterized by relatively favorable environmental conditions through the fall and winter. During the 1986–87 crop year, moisture accumulation during the fall of 1986 was above the 51-yr average (Figure 1) and would have been sufficient to germinate winter annual weeds. Spring temperatures were favorable for crop and weed growth in 1987, which had the second warmest March and the warmest April and May of the study (Figure 1). The 1990–91 WW crop year had the second highest rain accumulation (Figure 1).

Crop Production. In general, the average grain yield increased about 13% with each increase in N level (Table 5). This result agrees with other research (Halvorson et al. 1999; Kolberg et al. 1996; Rasmussen et al. 1997) and indicates reducing N input may not be an option for successful no-till wheat production. When averaged over WMLs (significant N by crop year interaction, Table 3), grain yield was highest at the 1× N level compared to the 0.5 and 0.75× N levels every year except 1986 (Table 5). In 1986, wheat yields for the two highest N levels were similar.

There was also an interaction between WML and crop

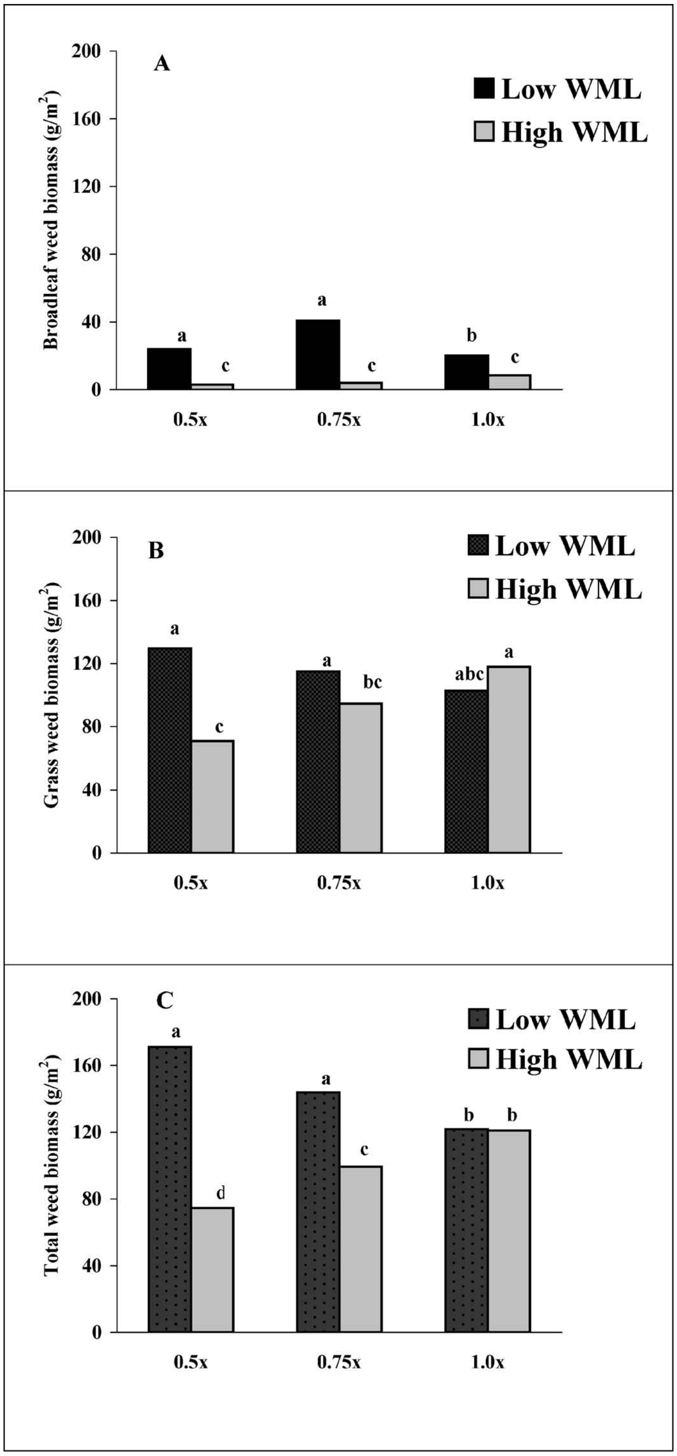

Figure 4. Effect of nitrogen (N) and weed management level (WML) on broadleaf (A), grass (B), and total (C) weed biomass at harvest when averaged over 6 yr. Within each weed category, weed biomass with the same letters are not significantly different ($P \leq 0.05$).

Table 5. Spring wheat (SW) and winter wheat (WW) yield (kg/ha) response to weed management level (WML) and nitrogen (N).

		N level[a]			WML[b]	
Year	Crop	0.5×	0.75×	1.0×	Low	High
1986	SW	820 j	1,100 ij	1,260 i	1,010 e	1,120 e
1987	WW	3,970 cd	4,720 b	5,250 a	4,460 b	4,840 a
1988	WW	2,900 h	3,080 gh	3,610 ef	3,120 d	3,260 d
1989	SW	3,280 fg	3,360 fg	3,720 de	3,100 d	3,800 c
1990	WW	3,840 cd	4,580 b	5,160 a	4,100 c	4,960 a
1991	WW	3,780 cd	4,160 c	4,600 b	3,900 c	4,460 b
	Average[c]	3,100	3,500	3,940	3,280	3,740

[a] Yields followed by the same letter in any column or row under any N level are not statistically different at $P \leq 0.05$ with the use of a protected LSD test. Simple effects are compared because of a significant interaction between N level and crop year.

[b] Yields followed by the same letter in any column or row under either WML are not statistically different at $P \leq 0.05$ with the use of a protected LSD test. Simple effects are compared because of a significant interaction between WML and crop year.

[c] Significant differences for main effects not indicated due to interactions.

year for grain yield (Table 3). In all years except 1986 and 1988, grain yield was highest with the high WML (Table 5). Positive crop yield response to the high WML ranged from 8% in 1987 to 21% in 1989 and 1990 (Table 5). Overall, wheat yield was 14% greater in high WML plots than in low WML plots. In 1986 or 1988, yields were similar regardless of WMLs. Wet planting conditions and cold spring temperatures during April 1986 (Figure 1) reduced crop establishment and subsequent production as the SW yielded about 70% less than the crop in 1989. Winter wheat planted in fall 1987 and harvested in 1988 did not germinate and emerge until February of 1988 due to the extremely dry fall (Figure 1), and was the lowest yield of any of the WW crops (Table 5).

Although the N by WML interaction was not statistically significant (Table 3), we intended to evaluate these input level comparisons at the outset of the research, as they are of direct interest to producers. During the 6-yr study, wheat yield was highest when N and WML were at a maximum, and lowest when both inputs were at a minimum (Figure 5). No statistical difference in yield was detected between the low WML at 0.75× N and the high WML at 0.5× N, or the low WML at 1.0× N and the high WML at 0.75× N. Therefore, an increase in grain yield could be obtained by increasing N to the next level, or by increasing WML from low to high.

In addition to environmental conditions affecting yield, WW yields were highest with the high WML in the year immediately following SW in both rotation cycles (Table 5). Wheat yield in the high WML decreased in the second consecutive year of WW following SW in

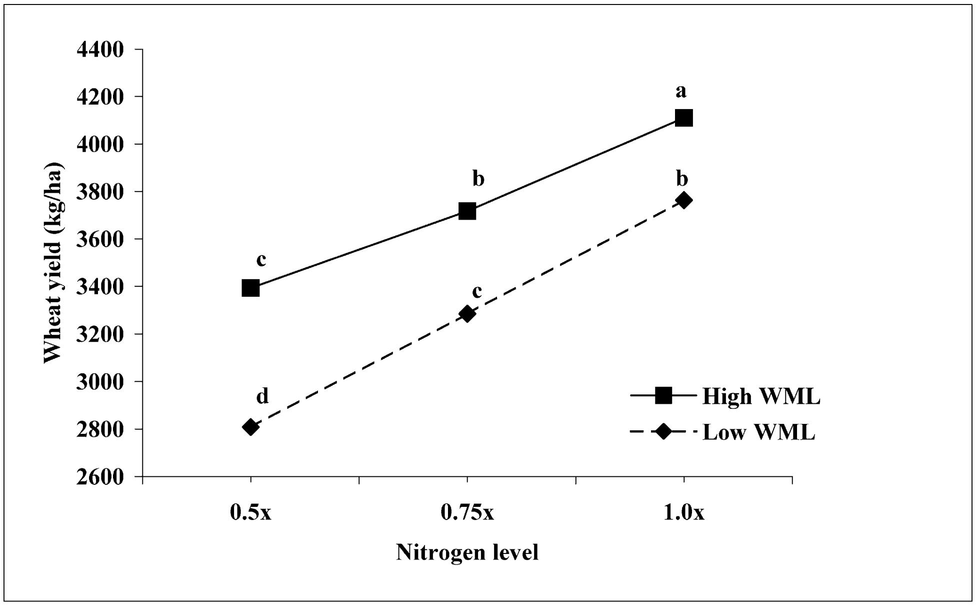

Figure 5. Yield of no-till wheat averaged over 6 yr as affected by nitrogen (N) and weed management level (WML). Yields followed by the same letter are not significantly different at $P \leq 0.05$.

both rotation cycles. With the low WML, the second year's yield decreased in the first rotation cycle only. Spring wheat in the high WML in 1989 produced more grain than WW in 1988, and produced similar yields to the low WML WW in 1990 and 1991 (Table 5). These results would suggest that success of a no-till continuous wheat rotation needs to include a periodic spring wheat crop and an intensive weed management program that includes adequate herbicides to target problem weeds.

Economics. Because only a part of the rotation was grown each year, tests of differences among rotational systems were not possible because there was no measure of temporal variability over the 6 yr. Therefore, net returns over total costs for the entire no-till SW-WW-WW rotation by N and WML are presented (Figure 6).

Not surprisingly, higher N produced higher net returns as well as higher yields. The maximum N and WML combination earned $114/ha more than the lowest N and

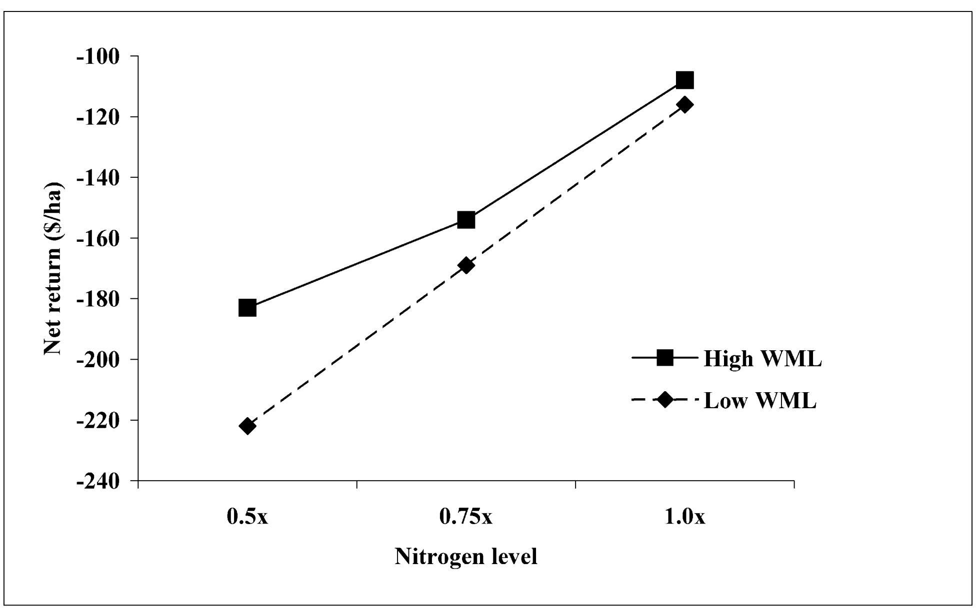

Figure 6. Net returns for no-till wheat averaged over 6 yr as affected by nitrogen (N) and weed management level (WML).

WML input level. In contrast to fertility, there was a relatively small profitability difference between low and high weed management; however, there is modest evidence that increased weed management paid off (Figure 6). The WML lines converge at the higher fertility levels for all crops implying slightly higher economic payoff to attentive weed management at lower N levels.

Under the production costs and market price used, none of the N and WML combinations earned a positive return over total costs. The highest WML and N combination lost $108.36/ha. However, total costs include a wage for the farmer's labor and a market return for his equity in land and other assets. Furthermore, decoupled government payments since 1996 could be expected to cover most of the market-price-based ''loss.'' Although the complex payments varied considerably over farms and also over time in response to congressional action, a conservative estimate of the average payment since 1996 in the study region would be $60 to $100/ha. These decoupled payments would apply uniformly to all treatments and leave the ranking unchanged, but they would push the absolute returns over total costs closer to zero. Zero represents a ''normal profit'' to all resources including the operator's labor, management, land, and machinery.

This research showed that no-till continuous wheat production was technically feasible in the annual-cropped region of the Palouse in the Pacific Northwest. However, the continuous wheat rotation was not profitable at any input level combination without government support. Given a different economic climate, this system may be an attractive option for growers needing to control soil erosion. Reducing N input does not appear to be a viable option, as any reduction caused a significant yield loss and a sharp drop in economic return. In addition, when N was reduced to the lowest level, controlling weeds became more dependent on herbicides due to an apparent less competitive crop. With adequate or optimum N input, reducing the WML may be an option, especially if the weed spectrum is dominated by annual broadleaf weeds. Simultaneously reducing N and WML is least attractive, as the lowest yield and economic return plus the highest weed production occurred when both inputs were at their lowest levels. This research also suggests that there may be a trade-off between reducing agricultural chemical inputs and reducing soil erosion in continuous wheat production. No-till has been shown to be effective in controlling soil erosion and can enable the use of a more intensive crop rotation system; however, chemical input appears to be a critical factor in the feasibility of no-till.

The SW-WW-WW rotation sequence, with only one SW crop was not sufficient to control grass weeds, particularly downy brome and jointed goatgrass. As weed seeds accumulated on the soil surface over time, successful establishment and competitiveness of the weeds became a function of favorable environmental conditions during the fall and winter. In a winter annual system, early fall-germinating weeds have the potential for greater resource capture and are a greater risk for reducing crop yield (Welsh et al. 1999). In our research, spring-germinating grass weeds such as wild oat were potentially controlled by spring herbicide applications, but fall-germinating grass weeds were not consistently controlled. In a related conservation-tillage study, a 3-yr rotation of WW–spring barley–spring pea (*Pisum sativum* L.) was more effective in controlling grass weeds and was profitable compared with continuous wheat (Young et al. 1996). Our research further illustrates the need for a diverse no-till cropping system for the annual-cropped region of the Pacific Northwest.

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