Evaluation of management practices for converting grassland back to cropland

A.D. Halvorson, C.A. Reule, and R.L. Anderson

ABSTRACT: Minimum-till (MT) and no-till (NT) systems were evaluated for converting seeded grassland back to cropland. Nitrogen fertilization needs to optimize grain yields following grass and to optimize hay yields from the grassland were also evaluated. Tillage treatments — conventional till (CT), MT, and NT — were established on a Weld silt loam soil that had been seeded to grass about 30 yr following more than 30 yr of crop-fallow. Nitrogen treatments were 0, 45, and 90 kg N/ha (0, 40, and 80 lb N/a) applied to each crop in a winter wheat (Triticum aestivum *L.)-corn (*Zea mays *L.)-fallow rotation or annually to grass plots. Residue cover at wheat planting averaged 18, 44, and 73% for CT, MT, and NT, respectively. Soil water recharge was minimal between grass kill and wheat planting; however, soil NO_3-N increased 115, 69, and 54 kg N/ha (103, 62, and 48 lb N/ac) for CT, MT, and NT, respectively. Wheat grain yields were greater with CT 2,685 kg/ha (40 bu/ac) and MT 2,558 kg/ha (38 bu/ac) than with NT 2,052 kg/ha (30.5 bu/ac). Lower wheat yields with NT resulted from lack of grass control. Wheat yield responses to N varied with year and were dependent on available water supplies. Corn grain yields were low [1,233, 2,063, and 1,564 kg/ha (19.7, 32.9, and 24.9 bu/ac) for CT, MT, and NT, respectively] due to limited growing season water. Average wheat 6,298 kg/ha (5,623 lb/ac) and corn 5,040 kg/ha (4,500 lb/ac) phytomass production exceeded that of the fertilized grass [1,529 kg/ha with 90 kg N/ha (1,365 lb/ac with 80 lb N/ac)]. Producers converting CRP grass to crop production can use MT and NT practices to maintain soil erosion control.*

Key words: CRP conversion, cropland, crop rotation, corn, dryland, grassland, hay, nitrogen, tillage system, wheat.

The 1985 Food Security Act (U.S. Congress 1985) established the Conservation Reserve Program (CRP), which resulted in extensive areas of highly-erodible cropland being seeded primarily to native and introduced grass species. The primary purpose of CRP was to reduce soil loss by wind and water erosion. Other CRP objectives included reduced production of major crops, farm income enhancement, improved water quality, improved fish and wildlife habitat, and enhanced ecological diversity (CAST 1990).

In March 1986, farmers began to submit bids for CRP enrollment, and about 13.7 million ha (33.9 million ac) were enrolled by January 1990. The CRP program was funded for a 10-yr period, after which producers had the option of keeping their CRP fields in grass or converting their fields into cropland. Schertz (1995) reported that a 1993 Soil and Water Conservation Society survey of post-CRP land use indicated that 63% of the CRP acres would be converted back to cropland. If CRP fields are converted back to cropland, then conservation management systems should be used to retain the soil conservation benefits gained during the 10-yr CRP period (Aase et al. 1997; CAST 1990; Schertz 1995). Schertz (1995) indicated that research data are needed on the best methods for bringing CRP land back into crop production. In the central Great Plains after the ninth sign-up period, Colorado had 0.79 million ha (1.95 million ac) of CRP contracted, Kansas had 1.16 million ha (2.86 million ac), and Nebraska had 0.55 million ha (1.35 million ac) contracted for CRP (USDA 1990).

Land enrolled in CRP is now eligible to be removed from the program and put back into crop production. Because CRP fields were highly erodible when placed in the conservation program, the 1985 Food Security Act required producers to maintain erosion control on these lands following CRP to be eligible to participate in other government farm programs. Many questions arose as to how to best convert CRP to cropland while maintaining soil erosion control. Information is needed on: 1) how to effectively convert CRP grassland back to cropland while maintaining soil erosion protection; 2) fertility needs following CRP (Fixen 1996); 3) tillage and herbicide needs to effectively convert grassland back to cropland; 4) use of more intensive cropping systems than crop fallow; and 5) improving productivity of CRP grassland to encourage farmers to keep the land in grass. Based on these needs, research was initiated in 1990 with the following objectives: 1) determine whether CRP-type grassland can be converted to cropland using MT or NT systems; 2) determine N fertility needs to optimize crop yields; and 3) determine if forage production on CRP-type grassland can be increased by N fertilization.

Methods and materials

To simulate CRP conditions at the end of 10 or more years of continuous grass, a research site representative of surrounding CRP land was located at the U.S. Department of Agriculture's Agricultural Research Service (USDA-ARS) Central Great Plains Research Station at Akron, Colo. The site was predominantly Weld silt loam soil (fine montmorillonitic, mesic Aridic Paleustoll), and had been in crop fallow more than 30 yr before being planted back to grass in about 1960.

The grass was occasionally hayed (possibly 30 to 40% of the time), but not fertilized to anyone's knowledge during the period prior to conversion back to cropland in 1990. This is similar to the occasional haying of CRP grassland during periods of drought to provide needed forage for livestock producers. Average grass composition in 1990 before application of treatments was 80% crested wheatgrass (*Agropyron cristatum* L.), 13% blue grama (*Bouteloua gracilis*), 2% sand dropseed (*Sporobolus cryptandrus*), and 5% alfalfa (*Medicago sativa* L.).

New sets of tillage and N plots were established each of three consecutive years. A split-plot, randomized, complete block design was used with three replications. CT, MT, and NT tillage treatments were compared on main plots (each 9.1 x 12.2 m, or 30 x 40 ft), with N rates as subplots (3.0 x 12.2 m, or 10 x 40 ft). Existing old grass litter was not mowed or removed before applying tillage treatments. Nitrogen treatments included 0,

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Reprinted from the Journal of Soil and Water Conservation
(First Quarter 2000) Volume 55 Number 1

45, and 90 kg N/ha (0, 40, and 80 lb N/a) applied broadcast at or just prior to planting with ammonium nitrate as the N source.

The first set of CT treatments received initial sweep plow tillage to kill the grass/legume mixture on May 7, 1990, and the second set on April 4, 1991, and the third set on October 21, 1991. Tillage was repeated as needed until wheat planting the following September.

The first set of MT plots were initially sprayed with glyphosate (N-phosphonomethyl glycine) on May 7, 1990, at a rate of 2.2 kg ai/ha (2 lb ai/a) to kill the grass/legume mixture, followed by a sweep plow tillage operation about 4 wk later. The second and third sets of MT plots first received an initial sweep plow tillage on April 4, 1991, and October 21, 1991, respectively. The tillage operations were followed with an application of glyphosate (1.1 kg ai/ha, or 1 lb ai/a) on May 22, 1991, and glyphosate (1.1 kg ai/ha, or 1 lb ai/a) plus 2,4-D (2,4-dichlorophenoxyacetic acid, 0.56 kg ai/ha, or 0.5 lb ai/a) May 4, 1992, for the second and third sets of MT plots, respectively.

The first set of NT plots were initially treated with glyphosate (2.2 kg ai/ha, or 2 lb ai/a) on May 7, 1990; the second set was treated with glyphosate (1.1 kg ai/ha, or 1 lb ai/a) on May 6, 1991, and the third set were treated with glyphosate (1.1 kg ai/ha, or 1 lb ai/a) plus 2,4-D (0.56 kg ai/ha, or 0.5 lb ai/a) on May 4, 1992, after the grass greened up in the spring and was actively growing. Unlike the third set of CT and MT plots, grass kill in the third set of NT plots was delayed until the spring of 1992 because grass was under water stress in October 1991, and not actively growing. (This would have resulted in poor herbicide performance and grass kill).

After initial operations, CT plots were tilled (undercutter), and the MT and NT plots were chemically fallowed [glyphosate (1.1 kg ai/ha, or 1 lb ai/a) plus 2,4-D (0.56 kg ai/ha, or 0.5 lb ai/a)], generally 3 to 4 times, until winter wheat planting.

A winter wheat-corn-fallow (W-C-F) rotation was followed with the first crop being wheat. Winter wheat (TAM 107) was planted (approximately 2.2 million seeds/ha, or 900,000 seeds/ac) with a Haybuster 1000 series disk drill about Sept. 20 each year with 22 kg P/ha (20 lb P/a) placed with the seed. The wheat plots were harvested in early July each year by making a 1.5-m (5-ft) wide pass through the length (12.2 m, or 40 ft) of each plot with a plot combine. The grain samples were cleaned before determining grain yield (12% moisture content).

Corn (Pioneer 3732) was planted in early May 1992 with a Buffalo planter equipped with a disc opener. The seeding rate was about 37,000 seeds/ha (15,000 seeds/ac) and row spacing of 0.76 m (30 in). Corn was planted on the second (1993) and third (1994) sets of plots with a JD Maximerge planter. The corn was generally harvested in late September to mid-October. Weed control for the corn crop was provided with a preplant application of glyphosate (1.1 kg ai/ha, or 1 lb ai/a) and atrazine (1.1 kg ai/ha, or 1 lb ai/a). Corn grain yields (15.5% moisture) were determined by harvesting two corn rows the length (12.2 m, or 40 ft) of the plot area with a plot combine. Grain samples were cleaned before determination of grain yields.

Phytomass production (oven dry basis) was determined at wheat harvest by cutting whole-plant samples from a minimum area of 1 m^2 from an unharvested area of each wheat plot with a bundle cutter. Wheat residue (straw) production was estimated by subtracting grain weight from total phytomass production. Corn stover produced was estimated by subtracting grain yields from measured total phytomass production. Phytomass production was determined from hand sampling whole corn plants from 2.4 m (8 ft) of corn row in early September that would not be used for grain harvest. Phytomass production was used to estimate corn silage yields at 70% moisture content.

The first set of plots established in 1990 was fallowed after corn harvest in October 1992 until wheat planting in September 1993. Wheat (second cycle of the W-C-F rotation) was planted on the first set of plots in September 1993. Wheat was harvested a second time from the first set of plots in July 1994.

Percent residue cover was estimated on each tillage plot using a line transect method just prior to wheat and corn planting. In addition, surface crop residue was collected from a 1 m^2 area of the soil surface, washed and dry weight determined. Soil samples were collected from each tillage treatment at grass kill, just prior to wheat planting, and from all treatments just prior to corn planting to a depth of 180 cm (6 ft) for determination of gravimetric soil water and soil NO_3-N content. Samples were collected before N fertilization. Soil sampling depths were 0 to 15 cm (0 to 6 in), 15 to 30 cm (6 to 12 in), and in 30-cm (12-in) increments to 180 cm (6 ft) depth. Soil water content measured after the fallow period (October 1992 to September 1993) in the first set of plots was used as an estimate of field capacity for the 180-cm (6-ft) profile.

Nitrogen treatments (0, 45, and 90 kg N/ha or 0, 40, and 80 lb N/ac) were established on grass plots [9.1 x 12.2 m (30 x 40 ft) with 3.0 x 12.2 m (10 x 40 ft) N subplots] in September 1990. The grass plots were randomly located within each block of the cropped plots with three replications. These N treatments were included to determine if the grass forage production could be increased sufficiently to compete economically with crop production. The N source was ammonium nitrate applied broadcast on Sept. 18, 1990, on April 8, 1992, and on Sept. 21, 1992. The grass plots were harvested the first time on June 14, 1991, by hand cutting 7.4 m^2 (8.9 yd^2) from the center of each plot. Because of drought conditions during April and May, 1992, the grass plots were harvested on May 20, 1992, by hand cutting 2 m^2 (2.4 yd^2) from the center of each plot. The grass plots were harvested on June 9, 1993, with a plot forage harvester that cut 11 m^2 (13.2 yd^2) from the center of each plot and again on June 8, 1994. Forage yields are expressed on an oven dry weight basis. Soil samples were collected (same procedure as for cropped area) from the grass plots for water and soil NO_3-N measurements in the spring of 1992, 1993, and 1994.

Statistical analyses of the data were performed using SAS (SAS Institute 1991). All significant differences discussed are at the 0.05 probability level unless otherwise stated. The Least Significant Difference (LSD) method was used to separate treatment differences.

Results

Surface residue cover at planting. Average residue cover at winter wheat planting for the 3 yr, as measured by the line transect method, increased significantly ($P < 0.001$; $LSD_{.05} = 6.6\%$) as tillage intensity decreased with 18, 44, and 73% residue cover for the CT, MT, and NT systems, respectively. Percent residue cover varied with year and tillage treatment ($P = 0.001$; $LSD_{.05} = 8\%$). Residue cover at wheat planting was 26, 45, and 75% in 1990; 17, 25, and 64% in 1991; and 12, 64, and 81% in 1992 for the CT, MT, and NT treatments, re-

Table 1. Changes in soil water at initial grass kill and at wheat planting each year (significant interaction) and soil N levels at grass kill and wheat planting as a function of tillage treatment (significant interaction) in the 0- to 180-cm (0- to 6-ft) soil depth.

	Soil water, cm/180-cm depth			
	Grass	Wheat		
Year	Kill	Planting	$LSD_{.05}$	$LSD_{.10}$
1990	22.2	29.0	2.0	1.7
1991	27.9	26.2	2.0	1.7
1992	32.5	34.2	2.0	1.7

	Soil NO_3-N, kg N/ha/180-cm depth			
Tillage	Grass	Wheat		
Treatment	Kill	Planting	$LSD_{.05}$	$LSD_{.10}$
CT	26	141	21	18
MT	43	112	21	18
NT	34	88	21	18

spectively. Quantity (weight) of residue on the soil surface increased with decreasing tillage intensity with a significant year by tillage treatment interaction ($P = 0.007$; $LSD_{.05} = 304$ kg/ha). Quantity of residue on the soil surface at wheat planting was 358, 809, and 1,780 kg/ha (320, 722, and 1,589 lb/ac) in 1990; 376, 405, and 989 kg/ha (336, 362, and 883 lb/ac) in 1991; and 43, 1,231, and 1,391 kg/ha (38, 1,099, and 1,241 lb/ac) in 1992 for the CT, MT, and NT treatments, respectively. Averaged across three years, quantity of surface residue at wheat planting was significantly ($P < 0.001$; $LSD_{.05} = 248$ kg/ha) increased with a reduction in tillage with residue levels of 259, 815, and 1,388 kg/ha (231, 728, and 1,239 lb/ac) for the CT, MT, and NT treatments, respectively. The residue cover for CT may not meet residue requirements at planting for effective soil erosion control. The MT and NT treatments provided more potential protection from wind and water erosion than CT treatment.

Surface crop residue levels at corn planting in 1992 were 1,480, 1,926, and 3,183 kg/ha (1,321, 1,720, and 2,842 lb/ac) for CT, MT, and NT plots, respectively, with NT having significantly greater ($P = 0.001$; $LSD_{.05} = 393$ kg/ha) residue levels than the CT and MT systems. Estimated residue cover by line transect was also significantly greater ($LSD_{.05} = 14\%$) with NT (88%) compared to CT (51%) and MT (58%). Surface crop residue levels remaining after corn planting in 1993 were 272, 965, and 1,098 kg/ha (243, 862, and 980 lb/ac) for CT, MT, and NT plots, respectively, but were not significantly different ($P = 0.22$). Residue levels estimated by the line transect method showed that NT (45%) and MT (39%) treatments had significantly ($P = 0.02$; $LSD_{.05} = 17\%$) greater residue levels than the CT (17%) treatment.

Table 2. Precipitation (mm) received during study and 87-yr average at Akron, Colo.

Month	Year					87-yr average
	1990	1991	1992	1993	1994	
Jan	19	2	25	6	10	8
Feb	4	4	5	14	5	9
March	43	28	50	12	2	21
April	38	21	5	49	61	43
May	104	104	28	26	22	76
June	24	53	107	44	6	63
July	120	80	51	122	69	69
Aug	112	26	98	23	30	52
Sept	18	3	5	21	11	31
Oct	27	10	20	94	70	23
Nov	20	37	20	26	26	14
Dec	2	11	6	12	13	11
Total	530	378	420	450	325	419

Soil water. Changes in soil water between initial grass kill and wheat planting showed a gain in water for the 1991 crop, a slight loss of soil water for the 1992 crop, and only a small increase for the 1993 wheat crop (Table 1). Tillage treatment had no significant effect ($P = 0.41$) on soil water content at wheat planting, with water contents of 31 (12.2), 30 (11.8), and 28 cm (11.0 in)/180 cm (6 ft) soil depth for the CT, MT, and NT treatments, respectively. Soil water in the 0-to-180 cm (0-to 6-ft) profile at wheat planting was considerably below field capacity in 1991 and 1992. Field capacity was estimated to be about 39 cm (15.4 in) water/180 cm (6 ft) depth based on soil water samples taken in September 1993, following a fallow period.

The 1993 wheat crop started the season with the most soil water, which reflects the fact that the grass was initially tilled in October 1991 in the CT and MT plots, resulting in a longer fallow period before wheat was planted September 1992. The 1992 June-to-August precipitation (Table 2) also was above normal, which influenced the soil water content at wheat planting in September 1992. Soil water at wheat planting was greatest in September 1993, following a 12-mo fallow period in this W-C-F rotation on the first set of plots. Soil water in September 1993 was 39.2, 38.4, and 37.8 cm/180-cm depth (15.4, 15.1, and 14.9 in/6-ft depth) for the NT, MT, and CT treatments, respectively. Soil water in September 1993 was not significantly different among tillage or N treatments.

Soil nitrate-N. Soil NO_3-N levels were generally low at initial grass kill with no significant differences among tillage treatments, but had significant differences across years with 14, 43, and 45 kg N/ha/180-cm soil depth (13, 38, and 40 lb N/ac/6-ft depth) for 1990, 1991, and 1992, respectively. At wheat planting, soil NO_3-N had increased similarly across years (data not shown), but varied significantly with tillage treatment. Differences in soil NO_3-N among tillage treatments are shown in Table 1. Increase in soil NO_3-N during the short fallow period before wheat planting was greatest for CT and lowest with NT. The effects of mechanical tillage on mineralizing N from soil organic matter was very evident in this study. The difference among tillage treatments in soil NO_3-N at initial grass kill and soil NO_3-N at wheat planting indicates that about 115, 69, and 54 kg N/ha (103, 62, and 48 lb N/ac) was mineralized in the 0-to-180

Table 3. Precipitation (mm) received during selected crop and non-crop periods.

Crop year	Grass dormancy (Jan-April)	Grass kill to wheat planting (May-Sept)	Wheat cropping season (Oct-June)	Wheat harvest to corn planting (July-April)	Corn growing season (May-Sept)
1990	105	377	——	——	——
1991	55	265	260	——	——
1992	84	422 (Oct-Sept)	278	251	290
1993	——	——	197	276	236
1994	——	363*	238	376	138
86 yr Avg	81	292	268	280	292

*From 1992 winterwheat harvest (July) to 1993 winter wheat planting (Sept.).

cm (0-to-6 ft) soil depth during the initial fallow period for CT, MT, and NT, respectively.

Soil NO_3-N at corn planting varied by year and N rate (P = 0.004) with soil NO_3-N levels of 66, 91, and 84 kg N/ha/180 cm (59, 81, and 75 lb N/ac/6 ft) in 1992; 66, 98, and 163 kg N/ha/180 cm (59, 88, and 146 lb N/ac/6 ft) in 1993; and 97, 106, and 137 kg N/ha/180 cm (87, 95, and 122 lb N/ac/6 ft) in 1994 for the 0, 45, and 90 kg N/ha (0, 40, and 80 lb N/ac) rates, respectively. Except for 1992, residual soil NO_3-N increased with increasing N rate.

Wheat yields. Wheat grain yields for CT (2,685 kg/ha, or 40 bu/ac) and MT (2,558 kg/ha, or 38 bu/ac) were significantly greater (P = 0.03, $LSD_{.05}$ = 469 kg/ha) than those yields obtained with NT (2,052 kg/ha, or 30.5 bu/ac) when averaged across 3 yr. The lower yield with NT resulted from lack of control of the grass/legume mixture. Averaged across years, visual estimates of ground area still occupied by grass at wheat planting was 0, 1, and 23% for CT, MT, and NT, respectively, with an $LSD_{.05}$ = 5%. The continued water and nutrient use by the grass in the NT plots resulted in less water and nutrients being available to the wheat crop. Ultimately, this reduced the yield of the NT plots. Precipitation for the study period is reported in Table 2 and cumulative precipitation received during selected crop and non-crop periods is shown in Table 3.

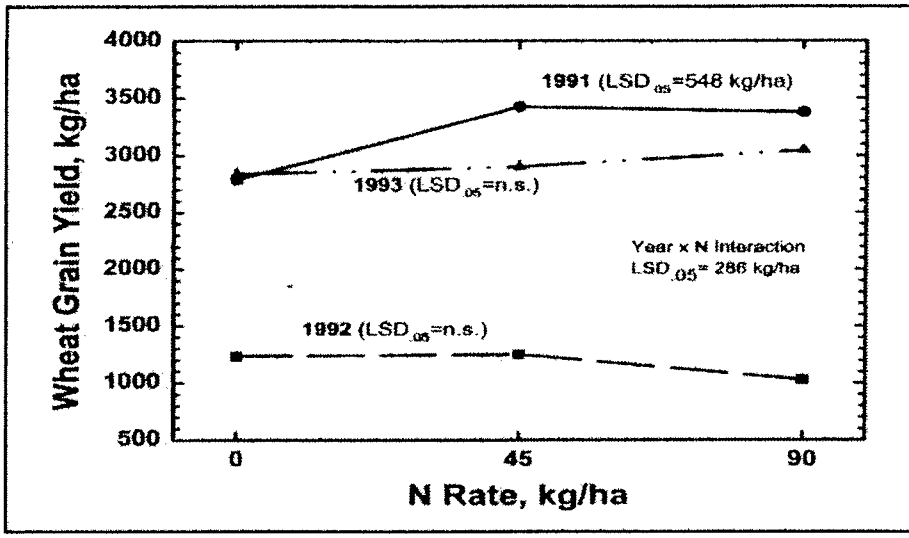

Figure 1. Winter wheat grain yields (12% moisture basis) as a function of N rate and year (significant year x N rate interaction) following grass removal.

When averaged across years, N fertilization did not significantly (P = 0.10) affect wheat grain yields in this study; however, the year x N interaction was significant (P = 0.05). In 1991, wheat yields increased with the application of 45 kg N/ha (40 lb N/ac) and then leveled off at the highest N rate (Figure 1). In 1992, the wheat crop was water-stressed, resulting in low yields and no response to N fertilization. The 1993 wheat yields were greater than in 1992, but there was no significant response to N fertilization. Lack of response to N fertilization might be expected due to the large amount of soil N available to the wheat crop at planting (Table 1) and the low yield potential due to limited water supplies (Tables 1, 2, and 3). Wheat grain yields in 1991 (3,196 kg/ha, or 2,854 lb/ac) and 1993 (2,927 kg/ha, or 1,779 lb/ac) were significantly greater (P = 0.001; $LSD_{.05}$ = 574 kg/ha) than in 1992 (1,171 kg/ha, or 1,046 lb/ac). The lower grain yield in 1992 reflects the lack of soil water recharge during the initial fallow period and below normal April and May precipitation (Tables 1 and 2).

Winter wheat grain yields in 1994 for the second cycle of the W-C-F rotation on the first set of treatments showed no significant response to tillage or N treatment. Wheat yields averaged 2,129 kg/ha, or 31.7 bu/ac. This is an acceptable yield considering the below average precipitation in May and June 1994 (Table 2). Precipitation from April 1 to June 30, 1994, was only 8.9 cm (3.5 in). Due to the drought, the 1994 wheat crop did not respond to N fertilization.

Wheat residue (straw) returned to the soil surface at harvest averaged 3,875 kg/ha (3,460 lb/ac) over the 3 yr, with the only significant response due to year. Straw yields were not affected by tillage and N treatment. Straw yields did vary significantly (P = 0.01; $LSD_{.05}$ = 1,397 kg/ha) by year with yields of 4,306 kg/ha (3,845 lb/ac) in 1991, 2,006 kg/ha (1,791 lb/ac) in 1992, and 5,313 kg/ha (4,744 lb/ac) in 1993. Total phytomass production (grain + straw) varied only by year with 1991 (7,454 kg/ha, or 6,655 lb/ac) and 1993 (8,237 kg/ha, or 7,354 lb/ac) producing significantly (P = 0.003; $LSD_{.05}$ = 1,840 kg/ha) higher phytomass yields than 1992 (3,201 kg/ha, or 2,858 lb/ac). Tillage and N treatments had no affect on phytomass production in this study.

Corn yields. Corn grain yields (15.5% moisture) were significantly (P = 0.03; $LSD_{.05}$ = 570 kg/ha) affected by tillage treatment when averaged across the 3 yr with MT (2,063 kg/ha, or 32.9 bu/ac) having a significantly greater yield than CT (1,233 kg/ha, or 19.7 bu/ac). The NT grain yield was 1,564 kg/ha (24.9 bu/ac). Corn yields were not significantly influence by N fertilization. Corn grain yields were significantly different (P = 0.01; $LSD_{.05}$ = 728 kg/ha) across years with 1992 (2,350 kg/ha, or 37.4 bu/ac) and 1994 (1,796 kg/ha, or 28.6

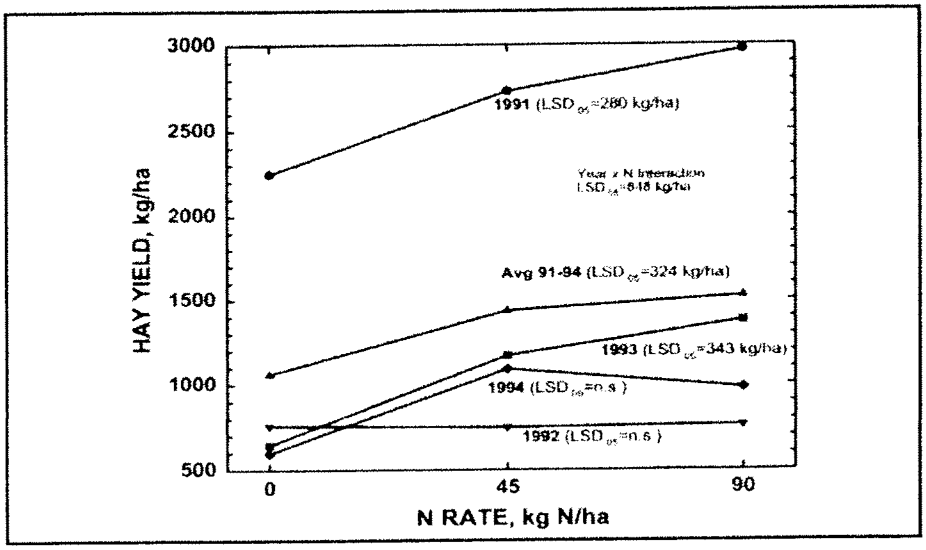

Figure 2. Grass hay yields (oven dry basis) as a function of N fertilizer rate for 1991, 1992, 1993, 1994, and 4-yr average (significant year x N rate interaction).

bu/ac) having a greater yield than 1993 (714 kg/ha, or 11.4 bu/ac). Growing season precipitation was below average in 1993 and 1994 (Table 2), which resulted in low corn yields due to water stress.

Corn silage yields (70% moisture) were only influenced by years with no significant affect of tillage treatment or N fertilization, with an average yield of 16.8 Mg/ha (7.5 t/ac) or a dry matter yield of 5 Mg/ha (2.2 t/ac). Silage yields for 1992 (25.4 Mg/ha, or 11.3 t/ac) were significantly ($P = 0.01$; $LSD_{.05} = 7.3$ Mg/ha) greater than those for 1993 (12.4 Mg/ha, or 5.5 t/ac) and 1994 (12.8 Mg/ha, or 5.7 t/ac). Dryland corn produced acceptable silage yields, but there was not enough soil water or rainfall to produce acceptable grain yields. Salvaging the corn crop as a forage crop rather than as a grain crop in drought years may be an option for some producers. A crop requiring less water to produce an economical yield, such as proso millet (*Panicum miliaceum* L.), may have been a better choice following winter wheat planted on grassland that had not had a lengthy fallow period to recharge the soil profile with water.

Grass hay yields. Grass response to N fertilization varied by year (Figure 2) with a significant ($P = 0.03$) year x N interaction. Hay yields increased with increasing N fertility levels in 1991 and 1993, but not in 1992 and 1994. The largest response to N came with the first 45 kg N/ha (40 lb N/ac) added, with yields tending to level off above this N rate. Hay yields averaged across N treatments were significantly ($P = 0.01$; $LSD_{.05} = 907$ kg/ha) greater in 1991 (2,649 kg/ha, or 2,365 lb/ac) than in 1992 (755 kg/ha, or 674 lb/ac), 1993 (1,063 kg/ha, or 949 lb/ac), and 1994 (887 kg/ha, or 792 lb/ac). The greater hay yield in 1991 most likely resulted from the 104 mm (4.1 in) rain received during May that stimulated growth of the grass. Average hay yield across N rates and 4 yr was only 1,339 kg/ha (1,196 lb/ac), a very low yield that would not compete well with crop production. Spring soil NO_3-N averaged 31, 34, and 53 kg N/ha/180 cm depth (28, 30, and 47 lb N/ac/6 ft) for the 0, 45, and 90 kg N/ha (0, 40, and 80 lb N/ac) treatments, respectively, when averaged across 1992, 1993, and 1994 with no significant differences among years. Spring soil NO_3-N levels were not significantly different ($LSD_{.05} = 13$ kg N/ha) between the 0 and 45 kg N/ha (40 lb N/ac) rates, but increased significantly with the 90 kg N/ha rate (80 lb N/ac), indicating that the grass was not utilizing all of the N applied. Spring soil water averaged 30 cm (11.8 in) in the 0-to 180-cm (6-ft) profile, which was about 9 cm (3.5 in) less water than a full soil profile and did not vary over years or N treatment. Limited plant-available water (soil water plus growing season precipitation) contributed to the low hay yields in this study.

Discussion

Crop yields following grass will depend on the amount of soil water storage that occurs during the initial non-crop fallow period before planting the first crop, and rainfall during the crop production period. Winter wheat grain yields were 24 and 20% greater with CT and MT, respectively, than with NT because of poor grass control in the NT plots. In this study, herbicide alone in the NT system did not completely control the perennial grasses, which competed with the wheat and corn crops for water and nutrients. Combining one tillage operation with herbicides controlled the grasses in the MT system. Schlegel and Thompson (1997) also reported problems with controlling grass when using NT systems in Kansas to convert CRP grassland back to cropland. Our observations suggest that at least one tillage operation may be needed to kill the grass. The herbicides burned the grass down to the point that it looked dead, but new shoots would reestablish from the crowns in the NT plots following precipitation events.

Environmental concerns and a desire to preserve the positive effects of soil carbon storage during CRP (Aase et al. 1997; Follett 1998; Reeder et al. 1998; Schertz 1995) by governmental agencies and producers has resulted in efforts to convert CRP grassland to cropland using NT. However, NT may not be the most effective nor the most economical method for producers in semiarid regions, such as eastern Colorado, western Nebraska, and western Kansas. Herbicides effectively controlled perennial grasses for short periods in this study, but long-term control was not consistent. Schlegel and Halvorson (1996) and Lyon and Holman (1997) also reported varying results on the effectiveness of using NT practices to convert CRP grassland to cropland in the central Great Plains. This contrasts with the work of Aase et al. (1997) in northeast Montana, who reported no problems with killing crested wheatgrass with glyphosate in a NT system when precipitation was above average. Their NT spring wheat yields were equal to those with moldboard plow and sweep tillage.

Reasons for lack of long-term grass control in NT may be two-fold. First, translocation of glyphosate to older roots and dormant root buds can be ineffective in old plant stands (Claus and Behrens 1976). Therefore, buds in the root system not affected by glyphosate reestablished the grass community. Secondly, glyphosate is generally most effective when applied to grasses in early stem elongation. Our grass stand was composed of both cool- and warm-season species, which reached the appropriate growth stage for effective control approximately 4 to 6 wk apart. In this study, we experienced drought conditions that may have impacted the effectiveness of glyphosate in killing the grass (Kelvorn and Wyse 1984). Grass control possibly could be improved with fall application of glyphosate when sufficient fall moisture is present to stimulate fall growth (Ivany 1981).

Producers are encouraged to view take-out of CRP from a long-term perspective involving crop rotations for the central Great Plains. NT corn after winter wheat has been shown to increase gross income (Dhuyvetter et al. 1996) and produce more residue over the length of the rotation compared to a NT winter wheat-fallow rotation. When converting from grass to cropland in the central Great Plains, best results may be obtained by using an MT system with one or two non-inverting shallow tillage operations along with herbicides to initially take out the grass before planting the first crop. Then convert to an NT production system for the second crop, such as corn or proso millet. This sequence may offer producers an economic and environmental benefit. Sufficient residue was maintained with the MT and NT systems, even following a poor 1992 wheat crop with low straw production, to provide substantial protection from soil erosion. Until the rootzone has been recharged with water following grass kill, selection of a crop with lower water requirements than corn following wheat in the rotation may be advised to obtain economical grain yields of the second crop.

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Reprinted from *Agronomy Journal*
Vol. 92, No. 6

Optimizing Wheat Harvest Cutting Height for Harvest Efficiency and Soil and Water Conservation

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ABSTRACT

Winter wheat (*Triticum aestivum* L.) productivity is frequently limited by water availability and degraded by wind erosion. Managers of harvest operations must balance soil and water-conservation benefits of maintaining sufficient stubble height with the risk of losing grain yield due to unharvested spikes below the combine cutting height. This study calculated the relationship between expected harvest losses and conservation of soil and water at various combine cutting heights. Mature wheat spike height frequency distributions for 5 yr were collected for different tillage and residue-cover levels. Wind-velocity profiles were measured for different stem frequencies and heights at three sites with harvested wheat stubble. Potential evaporation of water was calculated by PENFLUX, a Penman-type energy balance model. Potential soil loss was computed from the relative friction velocity (RFV). Stem heights were generally normally distributed, regardless of year or treatment. Quantifying RFVs at the soil surface and relative evaporation rates showed that combine cutting heights <0.1 m offered little protection from erosive winds for sparse stands with <280 stems m^{-2}. Higher cutting heights of 0.3 or 0.5 m increased protection, especially for sparse stands, but the relative benefits of increasing stem frequencies declined with higher cutting heights. Under normal sowing rates and conditions, harvesting wheat with a cutting-type header at two-thirds of its height will give 80% of the maximum soil and water conservation protection. Harvesting with a stripper-header combine attachment might be a potential new technology to further maximize soil and water conservation while minimizing harvest losses.

PRODUCTIVITY OF WINTER WHEAT CROPPING SYSTEMS in the semiarid Central Great Plains is frequently limited by water stress and degraded by wind erosion. Soil loss from wind erosion can exceed tolerable levels (NRCS, 1992). Reducing soil erosion is important for many reasons, including protecting air and water quality, and maintaining soil productivity. Soil erosion-control measures are also currently required to be in compliance with federal programs (McMaster and Wilhelm, 1997). Soil and water conservation is necessary to sustain productivity, profitability, and environmental quality in semiarid cropping systems.

When harvesting wheat, the cutter bar is typically set as low as feasible to harvest as many of the spikes as possible. Few data are available on the mature spike height distribution of wheat, and these data pool all culms (the main stem and all tillers). Culms differ both in their height and grain yield, but in general, main stems are taller and produce more grain than primary tillers, which in turn are taller and higher yielding than secondary tillers (McMaster et al., 1994; Power and Alessi, 1978).

Adjustment of the cutter bar height is also an important residue-management decision that determines both the height of standing residues and the amount of soil covered by loose, cut residues. Residue, particularly under conservation tillage practices, will impact both soil-water evaporation and soil loss from wind erosion.

Residue architecture (number, diameter, and height of standing residue) and the amount of soil covered by loose residue alter the surface microclimate, and thereby impact the degree of water conservation. Surface residues reduce potential soil-water evaporation by shading the soil surface and reducing convective exchange of water vapor at the soil–atmosphere interface (Aiken et al., 1997; Van Doren and Allmaras, 1978). Strips of partial mulch cover increase preplant soil warming (Bristow and Abrecht, 1989) while standing stems increase crop water use by increasing the transpiration fraction of total water evaporation (Lascano et al., 1994). Vertical residue orientation is more important than horizontal orientation in snow catch (Nielsen, 1998).

Standing crop residues reduce wind erosion by absorbing the wind's energy, raising the zero velocity point above the soil surface (Bilbro and Fryrear, 1994; Siddoway et al., 1965), reducing the boundary-layer wind velocity, and by preventing the downwind avalanching of soil particles (van de Ven et al., 1989; Woodruff et al., 1972). The height, diameter, and number of stems per unit area determine the effectiveness of standing residues because these characteristics determine the silhouette area through which the wind must pass. Friction velocity at the soil surface, which drives the erosion process (Hagen, 1996), declines exponentially with increasing silhouette-area index (residue height × stem diameter × population). Reductions in the wind/erosion ratio calculated from field-measured wind speeds are similar to values calculated from wind-tunnel studies (Nielsen and Aiken, 1998). Short standing stubble will reduce protection from soil erosion by wind (Hagen, 1996) and snow catch and increase soil-water evaporation compared with taller stubble. Black and Siddoway (1977) showed that the stubble height of the previous crop is a critical factor influencing wheat grain yield because taller stubble captured more snow and reduced soil-water evaporation, resulting in greater early spring vigor, increased tillering, and nodal root growth.

Producers must therefore balance competing objectives. To optimize grain harvest, the combine is set as

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Published in Agron. J. 92:1104–1108 (2000).

Abbreviations: RFV, relative friction velocity; RPE, relative potential evaporation; SAI, stem area index; SD, standard deviations.

low as possible to harvest spikes close to the ground. However, leaving as much residue standing as tall as possible will help maintain future productivity because it reduces soil-water evaporation and loss of soil to wind erosion. The objectives of this work were to determine the mature wheat spike height frequency distribution and use this distribution to calculate the relationships among combine cutting heights, expected harvest losses, soil-water evaporation, and wind erosion.

MATERIALS AND METHODS

Five years of field data were collected at the Colorado State University Horticultural Farm in Fort Collins, CO (40°36′46″ N, 10°59′42″ W) to determine mature spike height frequency distributions for a short stature, semidwarf winter wheat (cv. TAM 107) commonly used in the Central Great Plains. Two preplant tillage systems were used: Preplant tillage by moldboard plowing and no-tillage. Each tillage treatment had three residue levels before plowing: Surface residue removed, existing residue levels from the previous crop, and twice-existing residue levels from the previous crop. The experimental design was a complete randomized block design with four blocks. Within each block, a split-plot design was imposed with tillage being the main effect and residue cover being the split effect. Plot dimensions were 10 by 15 m. The heights of 96, 80, 160, 160, and 160 shoots with mature spikes were measured from the soil surface to the collar (bottom) and apex of the terminal spikelet (top) of the spike from 1994 through 1998, respectively. To examine the heights of different cultivars, nine winter wheat cultivars varying in height class were measured (160 mature spikes per cultivar) in 1999 at the Colorado State University Wheat Variety Trials in Fort Collins. These cultivars received occasional irrigation (about 2–3 times in the spring and early summer). All height measurements were made just before harvest when internode elongation had ceased. The SAS (SAS Inst., 1991) ANOVA–General Linear Model (PROC GLM) and Wilk–Shapiro test for normality (PROC UNIVARIATE) were used to analyze the stem height data.

Wind-velocity profiles were measured at two sites on the Central Great Plains Research Station (6.4 km E of Akron, CO; 40°9′N, 104°9′W) from 14 Dec. 1995 to 3 Jan. 1996, 13 Aug. 1996 to 23 Sept. 1996, and at a third site on a cooperating farmer's field 3 km northeast of the station from 6 May 1996 to 20 May 1996. Fetch was approximately 300 m at the two research-station sites and approximately 1500 m at the farmers field site. Stem population and harvest height differed in each of the wheat fields (Table 1). Cutting heights varied with harvest method because of slightly different settings for sickle height, and the stripper header leaves most of the stem standing. We deployed cup anemometers (Qualimetrics, Sacramento, CA, and RM Young, Traverse City, MI) at 0.40-, 0.60-, 0.80-, 1.00-, 1.20-, 1.60-, 2.00-, and 2.40-m heights and a wind-direction sensor (RM Young) at a 2.40-m height. An on-site data logger (Campbell Scientific 21X, Logan, UT) sampled wind speeds and direction each minute and recorded 15-min average values. We computed scaled wind speeds [the ratio of wind speed at a given height above the soil surface (u_z) to wind speed (u_{ref}) at a reference height (2.4 m)]. This was done for periods when reference wind speeds >3 m s^{-1} and air temperature gradients were minimal such that neutral stability conditions were likely. We analyzed wind-speed data from three wind directions relative to row direction (parallel, perpendicular, and 45° to row direction). We reported data for parallel wind and row orientations because they produced the highest water evaporation/erosion conditions and would be the worst-case scenario for both evaporation and erosion. We used a least-squares procedure (Rosenberg et al., 1983, p. 136–137) to compute displacement height (d, m), roughness length (z_o, m), and friction velocity (u_*, m/s) parameters for the wind profile equation:

$$u_z/u_{ref} = (u_*/k)\ln(z - d/z_o) \quad [1]$$

where k is von Karmon's constant (0.4, unitless) and z is height (m) above the soil surface. We measured row spacing, stem height, and stem population at three to eight locations within 80 m upwind of the anemometer mast at the time of anemometer installation. We computed the stem area index (SAI) from:

$$\mathrm{SAI} = d_s h_s N \quad [2]$$

where d_s is stem diameter (m), h_s is stem height (m), and N is the number of stems m^{-2}. Previous unpublished data collected at this location show wheat stem diameters for all culms are typically 3 mm for the peduncle and penultimate internodes.

The erosive force of wind can be quantified by friction velocity. Hagen and Armbrust (1994) showed that the ratio of below canopy to bare-soil friction velocity (u_{*s}/u'_{*o}, RFV) can be modeled by:

$$\mathrm{RFV} = u_{*s}/u'_{*o} = 0.86\exp(-\mathrm{SAI}/0.0298) + 0.25\exp(-\mathrm{SAI}/0.356) \quad [3]$$

where SAI represents the effects of stem diameter, height, and population calculated with Eq. [2]. The RFV represents the degree of soil exposure to wind in the presence of standing stems, with a value of 1 equivalent to bare soil and values approaching zero indicating minimal exposure. We computed the RFV from Eq. [3] only for wind parallel to row direction for a range of stem densities and cutting heights, again, because this would be the worst-case scenario for evaporation and erosion. For illustrative purposes, we also computed u_{*s}/u_{ref} using the scaled friction velocity for bare soil (u'_{*o}/u_{ref}) derived from Eq. [1] and the RFV from Eq. [3].

The effect of stem height and population on water evaporation was computed using PENFLUX, solving for temperatures of soil and horizontal residue surfaces (Aiken et al., 1997). Shading and insulating effects of soil cover from horizontal and standing residues are explicitly quantified in this model.

Table 1. Residue attributes, aerodynamic properties, and wind erosivity.

Residue condition	Residue attributes			Aerodynamic properties				Relative friction Velocity†
	Height	Stems	SAI	d	z_o	u_*/u_{ref}	u'_{*s}/u_{ref}	
	m	m^{-2}	m^2 m^{-2}	m	m	ms^{-1}/ms^{-1}	ms^{-1}/ms^{-1}	
Stripper header	0.55	152	0.251	0.29	0.045	0.104	0.0065	0.123
Conventional‡	0.32	588	0.564	0.19	0.026	0.093	0.0031	0.059
Conventional‡	0.38	453	0.516	0.23	0.036	0.096	0.0027	0.051
Bare soil	NA	NA	NA	0.0	0.001	0.053	0.053	1

† Calculated from Eq. [3].
‡ The distinction between the two *conventional* residue conditions is the height of the cutter bar.

The relative potential evaporation (RPE) was quantified as the ratio of potential evaporation with residue cover relative to potential evaporation for bare, wet soil on a clear day with moderate wind conditions (5 m s^{-1}). An RPE value of 1 indicates an evaporation potential equivalent to evaporation from an exposed, wet soil surface while values approaching zero indicate minimal evaporation.

We evaluated trade-offs in harvest losses and conservation benefits by identifying conditions where these management objectives may conflict due to differences in cutting height. For each criterion (harvest losses, conservation of soil and water) we assigned a tolerance level. We computed the RFV and RPE for a range of stem densities and cutting heights. Assuming that harvest losses of 0.5% are tolerable, we identified cutting heights which would result in 80% of the maximum soil and water conservation benefits associated with cutting heights.

RESULTS AND DISCUSSION

Mature stem height is expected to vary with weather and management, and we found that mean stem height at maturity (measured from the soil surface to the base of the spike) significantly differed over years and with preplant tillage treatments (Fig. 1). Preplant tillage always resulted in shorter mature plants than in no-tillage. When the distributions of mature stem heights within each tillage treatment for a given year were analyzed, the distributions were not significantly different from a normal distribution (data not shown).

The nine winter wheat cultivars measured in 1999 varied in their height class from 0.69 to 0.98 m. Mature stem height for five of the nine cultivars (Arlin, Halt, TAM 107, Yuma, and Alliance) were normally distributed (data not shown). Three of the four cultivars (2137, Akron, and Prowers) that were not normally distributed were among the tallest cultivars. 'Jagger' was also not normally distributed. When not normally distributed, the distributions were slightly skewed toward more shorter culms. It is possible that irrigation allowed more of the shorter culms to survive and produce a spike.

Assuming that mature stem heights are normally distributed permits assessment of how cutting height will affect harvest losses by considering the number of standard deviations (SD) from the mean. For one-tailed situations, 1, 2, and 3 SD from the mean will contain 16, 2, and <0.5% of the population (Steele and Torrie, 1980, p. 578). Therefore, if a mean of 0.6 m and 3 SD (≈0.2 m) is assumed, then setting the combine cutting height to 0.4 m will result in harvest losses of <0.5% (Fig. 2). Interestingly, in conversations with farmers and extension personnel, a general rule often suggested for conservation practices is to cut wheat at two-thirds of the mean height, which would still result in >99.5% of the grain being harvested. If mature stem heights are not normally distributed with a slight skewness toward more shorter culms, little difference is found in harvest losses when cutting at 2 or 3 SD from the mean. The percentage of spikes >2 or 3 SD, respectively, from the mean were 4.4 and 1.6% (Prowers), 4.4 and 0% (2137), 3.7 and 0% (Jagger), and 2.5 and 1.3% (Akron).

The preceding analysis assumes equal grain yield for all spikes—an unlikely condition. McMaster et al. (1994) and Power and Alessi (1978) showed the grain yield of various culms of winter wheat for different conditions. Generally, the lowest grain-yielding spikes are on the shortest and youngest culms (McMaster, 1997); therefore our estimates are conservative, tending to overestimate harvest losses.

The conservation benefits of standing stems partly results from altered wind-speed profiles. Standing stems shift the zone of low wind speeds (e.g., *d*, Table 1) to ≈0.25 m above the soil surface, relative to a bare soil (Fig. 3). Standing stems also reduce the erosive force of wind or the scaled below-canopy friction velocity (u_{*v}/u_{ref}) by a factor ranging from 16 to 35, relative to the scaled above-canopy friction velocity (u_*/u_{ref}, Table 1). Taller stems result from a stripper-header attachment, which is a combine attachment that leaves virtually all standing residue intact. The taller (0.55 m) stems provide compensation for sparse stands (<280 stems m^{-2}), resulting in a wind profile similar to that of more dense stands harvested with a conventional header attachment

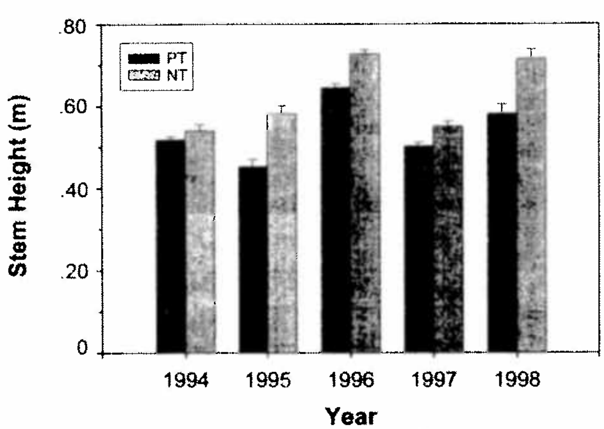

Fig. 1. Stem height for years and preplant tillage treatments. Stem height is measured from the soil surface to the bottom of the spike. PT refers to preplanting moldboard-plow tillage and NT is no-tillage. Standard error of the mean bars are included.

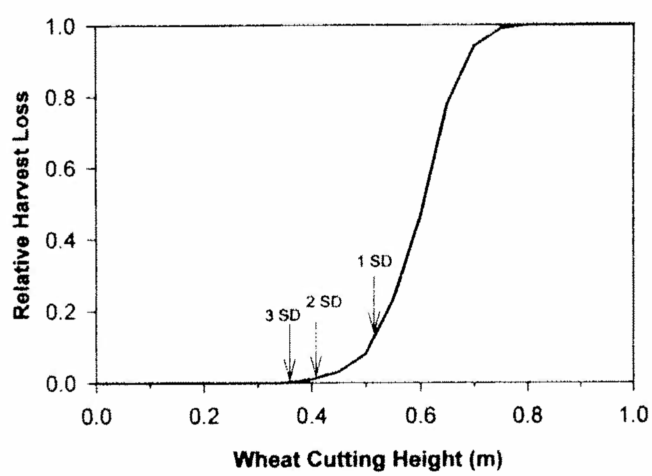

Fig. 2. Grain-yield losses expected for different combine cutting heights assuming a normal distribution with mean = 0.6 m and 3 standard deviations (SD) of about 0.2 m. The relative harvest losses (one-tailed) for 1, 2, and 3 SD from the mean are noted by arrows on the figure.

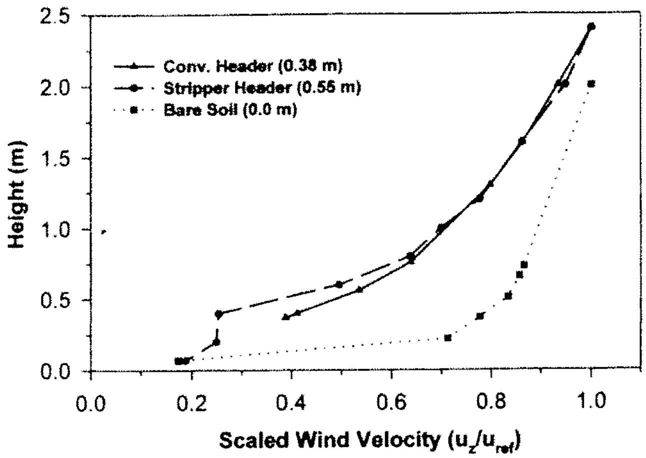

Fig. 3. Wind profiles over standing wheat residues.

(0.38 m stem height). This is in marked contrast to profiles for bare soil. These wind profiles illustrate the sheltering effects of standing stems.

The friction velocity at the soil surface quantifies the energy available for momentum transfer (e.g., the erosive force of wind). Effects of stem heights and population on the RFV are depicted in Fig. 4. An RFV of 1 indicates that the expected energy available for momentum transfer is identical for protected and exposed conditions; an RFV value approaching 0 indicates increasing protection against erosion. Increasing either stem height or population will decrease the RFV. A low cutting height of 0.1 m offers little protection for sparse stands (<280 stems m^{-2}), but protection increases with greater stem densities. Higher cutting heights of 0.3 m or 0.5 m increase protection for sparse stands, but the relative benefits of increased stem number decline for these higher cutting heights.

Increasing stem height, population, or both, not only reduces the expected erosive force at the soil surface, but also the evaporation potential (Fig. 5) by slowing convective vapor exchange and absorbing radiant energy, which drives the evaporation process. Water conservation increases with a lower RPE. A low cutting height (0.1 m) offers little protection from evaporative demand for sparse stands <300 stems m^{-2}. Protection increases with cutting height and stand population. Dense stands >400 stems m^{-2} provided little gain in protection with cutting heights >0.3 m.

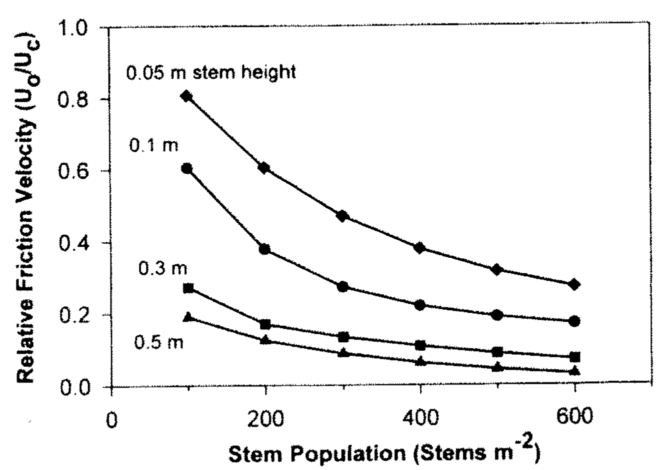

Fig. 4. Relative friction velocity (RFV) for different stem heights and populations. Data are derived from the work of Hagen and Armbrust (1994).

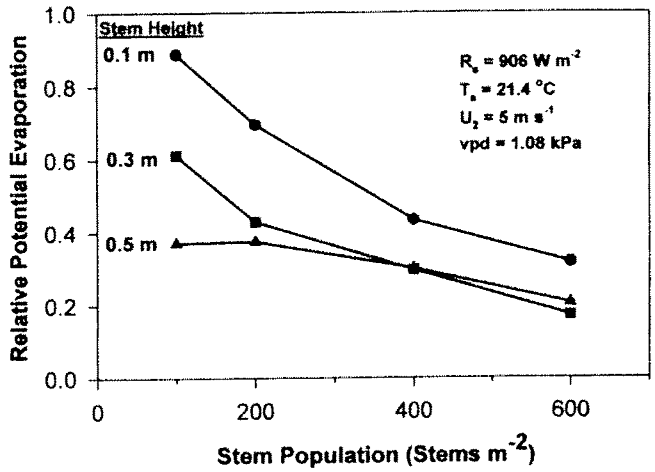

Fig. 5. Relative potential evaporation (RPE) for different stem heights and densities. R_s is solar irradiance, T_a is air temperature, U_2 is wind speed, and vpd is vapor pressure deficit, referenced at a 2-m height at solar noon.

Synthesizing these results, we sought the minimum cutting height required to achieve an arbitrary 80% of the potential protection for soil and water conservation, without sacrificing harvestable grain yield in excess of 0.5%. We derived these values from data presented in Fig. 4 and 5, taking the degree of protection afforded by a 0.5-m stem height as 100%. The results (Fig. 6) indicate, for example, a stand of 400 stems m^{-2} achieving 80% of the maximum protection from evaporative losses of water requires a cutting height of 0.31 m. However, the same degree of protection from the erosive force of wind only requires a cutting height of 0.13 m. Thus, setting the cutter bar height for water conserva-

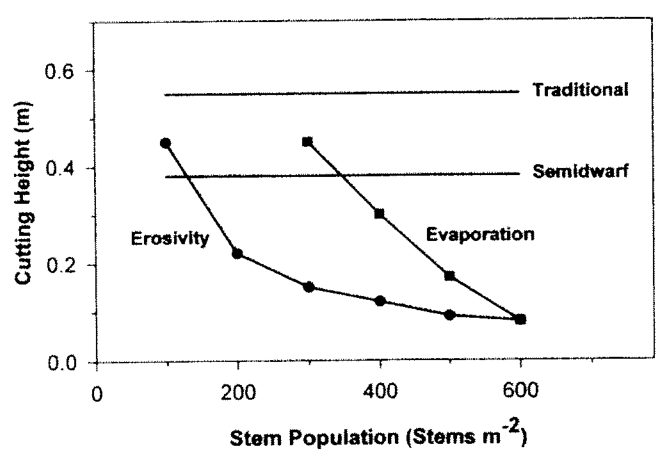

Fig. 6. Relationships to estimate harvest, erosion, and evaporation losses. The horizontal lines represent the maximum cutting height expected to result in tolerable harvest losses (<0.5%) for tall and semidwarf cultivars based on data from standard Colorado State University variety trials. The curves for erosivity and evaporation represent the minimum cutting height required to realize 80% of the maximum conservation benefits expected for a given stem population.

tion should assure an equal or greater relative degree of erosion protection as well. Further, no conflict results from harvest and conservation goals because both minima are lower than the cutting-height maxima permitted within the tolerable grain-yield loss threshold of 0.5%.

Conflicts between conservation and harvest goals become apparent for stand densities <350 stems m^{-2}. A cutting height of 0.45 m is required to achieve 80% of the maximum water conservation benefits for stand densities of 300 stems m^{-2}—a cutting height expected to cause harvest losses for semidwarf wheat varieties. A similar cutting height is required to achieve soil-conservation benefits for sparse stands of 100 stems m^{-2}, which is also expected to cause a similar increase in harvest losses. Farm managers can achieve conservation and harvest-efficiency goals (<0.5% grain-yield loss) for stands >350 stems m^{-2}. Sparse to moderate stands (<350 stems m^{-2}) require alternative harvest strategies to avoid these conflicts.

Farmers have multiple options to achieve both conservation and harvest-efficiency goals. Maintaining high stem populations provides benefits both in productivity and conservation. Farmers can impact stem populations by increasing sowing rates. Once plant density is established, then stem populations are determined by tillering and subsequent abortion rates. Water conservation minimizing water stress during early spring development phases will benefit tiller survival (McMaster et al., 1994). Stem height is limited by the genetic potential, particularly the presence or absence of dwarfing genes. The genetic potential is reduced by most abiotic and biotic stresses, particularly as they contribute to nutrition and water stress. Planting tall varieties in poorer, droughty soils can improve residue cover for conservation goals. Finally, investing in a stripper-header combine attachment assures maximal conservation benefits with minimal harvest losses because virtually all standing stems remain erect. This harvest strategy could be economically viable for fields with persistently sparse stands (<350 stems m^{-2}) when tall varieties are replaced by higher grain yielding semidwarf varieties.

CONCLUSION

Winter wheat plant height varied with year and crop management, but height was approximately normally distributed. Therefore, harvest losses exceeding 0.5% occurred when cutting above two-thirds of the average stand height. Increasing stem population, height, or both reduced the expected erosive force of wind and evaporation potential although the relative degree of protection was asymptotic at high residue levels. Farm managers can achieve both conservation and harvest-efficiency goals for moderate to dense stands (>350 stems m^{-2}) by cutting at two-thirds of stand height. These goals can conflict at lower stem populations. Soil conservation is assured when operators manage for water conservation. Crop culture to maintain high plant and stem populations maximizes harvestable grain yield, protects the soil from wind erosion, and reduces evaporation. Stripper-header type combine attachments may provide an economical harvest strategy to realize 100% of the conservation benefits of standing stems when tall straw varieties are replaced with higher grain yielding semidwarf varieties for land with chronic sparse stands (<350 stems m^{-2}).

ACKNOWLEDGMENTS

D. Palic, M. Harms, A. Figueroa, K. Couch, and T. Leonard provided assistance in collecting the field data and statistical analysis.

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