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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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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_{*v}/u'_{*o}, RFV) can be modeled by:

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

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_{*v}/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'_{*o}/u_{ref}	
	m	m^{-2}	m^2 m^{-2}	m		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 ($\dot{u}_*/u_{ref}$) 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

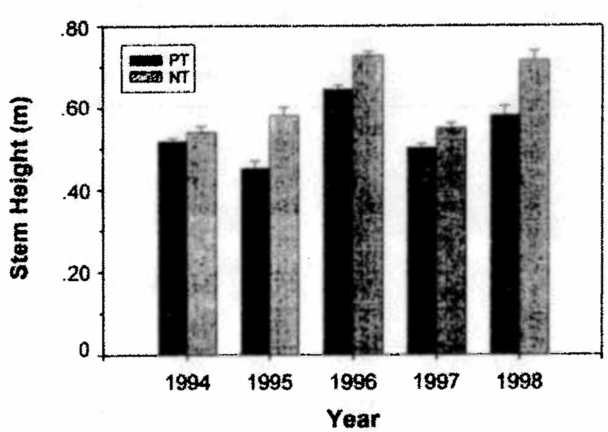

Fig. 1. Stem height for years and preplant tillage treatments. Stem height is measured from the soil surface to the bottom of the spike. PT refers to preplanting moldboard-plow tillage and NT is no-tillage. Standard error of the mean bars are included.

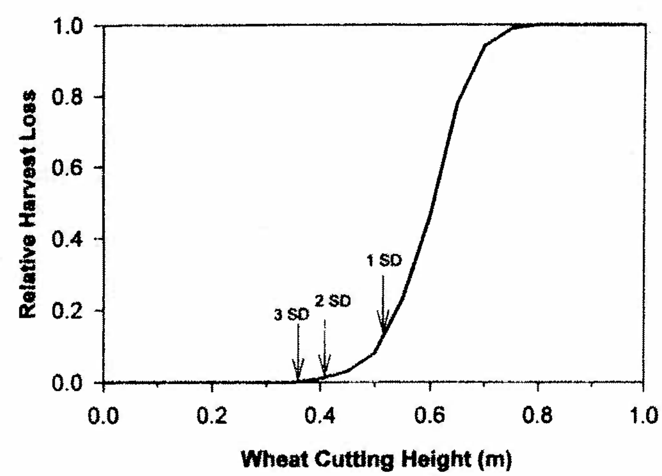

Fig. 2. Grain-yield losses expected for different combine cutting heights assuming a normal distribution with mean = 0.6 m and 3 standard deviations (SD) of about 0.2 m. The relative harvest losses (one-tailed) for 1, 2, and 3 SD from the mean are noted by arrows on the figure.

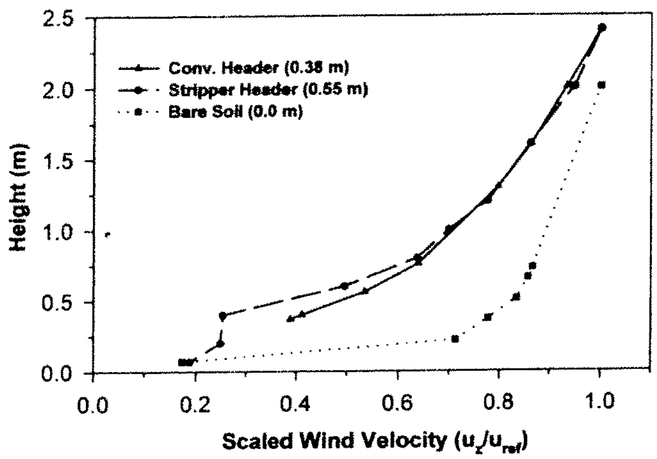

Fig. 3. Wind profiles over standing wheat residues.

(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

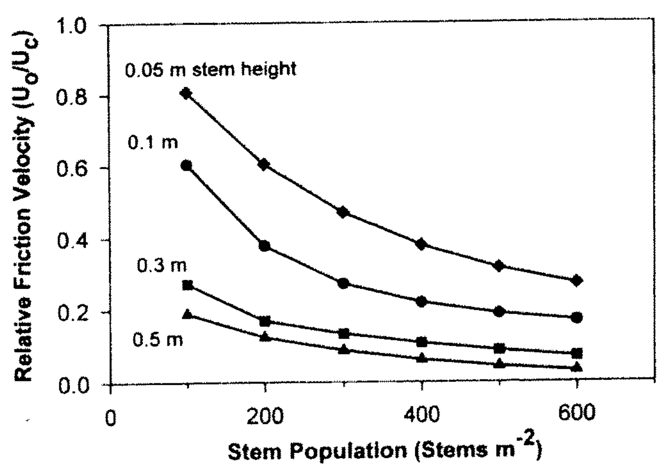

Fig. 4. Relative friction velocity (RFV) for different stem heights and populations. Data are derived from the work of Hagen and Armbrust (1994).

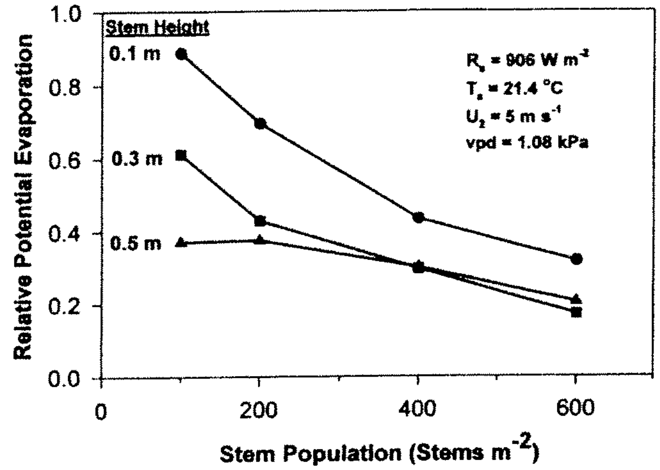

Fig. 5. Relative potential evaporation (RPE) for different stem heights and densities. R_s is solar irradiance, T_a is air temperature, U_2 is wind speed, and vpd is vapor pressure deficit, referenced at a 2-m height at solar noon.

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.

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-

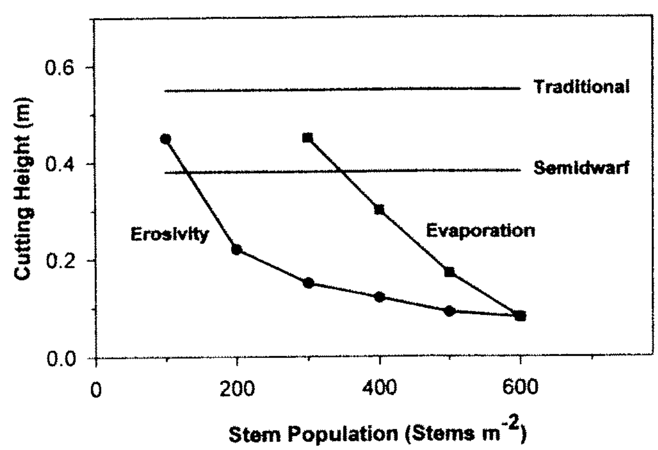

Fig. 6. Relationships to estimate harvest, erosion, and evaporation losses. The horizontal lines represent the maximum cutting height expected to result in tolerable harvest losses (<0.5%) for tall and semidwarf cultivars based on data from standard Colorado State University variety trials. The curves 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}).

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