Harvest Index and Straw Yield of Five Classes of Wheat

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Abstract

Wheat straw is a potential cellulosic feedstock for bioethanol. This study was conducted to evaluate straw yield potential and its relationship with grain yield for wheat (*Triticum spp.*) grown in the United States. The specific objective was to determine if differences in straw yield and harvest index (HI) exist between and within regions and/or wheat classes. Using on-going variety performance trials in eight states, a total of 255 varietal trial entries from five classes of wheat were surveyed for above-ground biomass. Averaged over all wheat classes and regions the HI was 0.45. Soft red winter wheat in Kentucky had, on average, the highest HI and lowest straw yield among regions and wheat classes. Soft white winter wheat under irrigation in the Pacific Northwest produced the highest straw yield. Hard red winter wheat in the southern plain states of Texas and Oklahoma had, on average, the lowest HI. Differences in the amount of precipitation and cultivars were the major contributors to the variation detected within wheat classes. The amount of wheat straw available as cellulosic feedstock in a state or wheat class can be estimated using the grain yield estimates provided by the National Agricultural Statistics Service and the class specific HI.

Keywords

Wheat, harvest index, straw yield, biomass

Abbreviations

DW, durum wheat; HI, harvest index; HRSW, hard red spring wheat; HRWW, hard red winter wheat; SRWW, soft red winter wheat; SWSW, soft white spring wheat; SWW, soft white wheat; SWWW, soft white winter wheat; SGI, Sun Grant Initiative.

1. Introduction

As fossil fuel resources are expected to diminish, the development of a large bioenergy economy has been proposed as an alternative to the current fossil fuel dependent energy system. Bioethanol, a renewable fuel, can reduce dependence on fossil fuels and decrease the net emissions of carbon dioxide [1] and [2]. Large-scale production of bioethanol is often criticized for using food sources including corn and other grains as raw material [3]. Crop residues such as wheat straw and corn stover will need to become an increasingly important source of cellulosic feedstock for bioethanol [4].

An estimated 90.5 million ha of wheat (*Triticum spp.*) was planted in the United States in the four year period of 2012 to 2015 [5]. The material suitability, compatibility with handling infrastructures, and processing technology of wheat straw has been well studied [6], [7], and [8]. However, the productivity of wheat straw has not been characterized across regions, climates, and wheat classes. Straw is produced from three species, six classes, and hundreds of cultivars of wheat grown under a wide range of environmental conditions in the United States [9]. In order to successfully manage wheat straw as a commodity and to help position it in the biofuel industry, it is crucial to establish a geospatial database of straw yield and to understand the relations among biomass, grain yield, and straw yield.

Harvest index (HI), defined as the grain yield of a wheat crop expressed as the decimal fraction of aboveground biomass production, indicates directly the allocation of biomass to grain and indirectly the partitioning between grain and straw production [10] and [11]. HI values allow

for convenient prediction of straw yields as grain yield data are readily available for most if not all wheat producing regions of the USA at the county level. Representative HI values for modern varieties of wheat generally fall within the range of 0.3 to 0.6 [12]. The observed progressive increase in wheat HI over the past decades is mainly a result of the introduction of dwarfing genes which reduced straw length and increased grain yield potential and response to nitrogen fertilizer due to reduced lodging [12] and [13]. A number of studies have demonstrated that HI is affected by genetic variations within certain cereal class and environmental variations within certain climate region. Larsen et al. found that the highest yielding winter wheat cultivars yielded more than 50% more straw and over 30% more glucose and xylose than the lowest yielding ones [1]. Engel et al. reported significant effects of cultivars, water regimes, and N levels on HI in hard red spring wheat [14]. HI was also known to be affected by abiotic stresses and sowing dates [15] and [16].

A collaborative effort, funded by Sun Grant Initiative [17], was undertaken to better understand the potential of wheat straw yield as a feedstock for cellulosic ethanol across the United States. Given the limited funding for this work, data were gathered from existing and ongoing variety evaluation trials in each of the participating states. Consequently only regionally adapted varieties were represented in the respective trials and few if any varieties were shared among trial locations. The specific objective of this survey was to investigate if differences in straw yield and HI exist among and within wheat classes. The purpose of the study was not to compare wheat cultivars per se, but rather to obtain an initial idea of the amount of variability among wheat classes and production regions.

2. Materials and methods

The aboveground biomass, grain yield, and straw yield of 12 varietal trial entries of durum wheat (DW; *Triticum durum*), 40 entries of hard red spring wheat (HRSW; *T. aestivum*), 14 entries of hard red winter wheat (HRWW; *T. aestivum*), 174 entries of soft red winter wheat (SRWW; *T. aestivum*), three entries of soft white spring wheat (SWSW; *T. aestivum*), and 12 entries of soft white winter wheat (SWWW; *T. aestivum*) were surveyed in eight states (AZ, ID, KY, MN, ND, OK, OR, and TX) of the United States from 2008 to 2010 (Table 1 and 2). Five out of the six US wheat classes were included in the survey: DW, HRSW, HRWW, SRWW, and soft white wheat (SWW). The soft white class was divided in two subclasses (SWSW and SWWW) based on growth habit. These varietal trial entries were represented in multiple location-years. All location-years were replicated three or four times with the exception of Oklee MN which was replicated three times in 2009 and 2010 but only two times in 2008 (Table 1). A total of 1858 observations were collected for 255 varietal trial entries across all location-years.

Table 1 here.

Table 2 here.

Agricultural experiment stations, as part of the Land-Grant University system across the US, conduct field crop trials annually using replicated small-plot trials. These trials are conducted under authority granted by the Hatch Act of 1877 to conduct performance trials on farm crops and interpret the data to the public. Individual plots or experimental units in the trials used to collect the data presented in this study varied from 4.1 to 7.4 m² among cooperators. Each experimental unit contained one entry and was managed using locally appropriate production practices to maximize grain yield. Grain yield and above ground biomass data used

in this study was collected by one of two methods (Table 2). In the first method, above ground biomass was estimated by hand harvesting a randomly selected quadrat within each experimental unit as the crop reached the harvest ripe stage and weighed. The area harvested varied from 0.14 to 0.16 m² among cooperators. Plants were cut off just above the soil surface and the cutting height ranged between 2 to 7 cm. Harvested bundles were threshed with a stationary thresher and the harvested grain was weighed. Straw yield was calculated by subtracting the weight of the grain from the total biomass weight. In the second method, the whole experimental unit was harvested with a small plot combine and the straw was collected behind the combine and weighed immediately following the mechanical harvest. . Total biomass was calculated as the sum of the straw and grain weights. The HI value was obtained by dividing the grain yield by the aboveground biomass of the sample in either sampling method.

The potential bias between and within the two sampling methods is less than 4% of the total length of the plant which could result in 1% variation in HI (data now shown). Therefore the grain yield and above ground biomass data collected for this study is robust and can be combined despite having two different sampling methods and having the variation in the reported height of the header of the combines used to harvest whole experimental units.

Although moisture content of either grain or straw was not recorded at the time of harvest, samples at all locations were taken at the time the wheat crop were harvest ripe or Zadoks growth stage 93 [18]. The moisture content of grain at harvest ripe is between 11% and 16% by weight as the standard moisture content for wheat is 13.5% moisture. The corresponding moisture content of the straw at harvest ripe is similar to that for harvested grain [19, 20]. Both wheat grain and straw can be stored indefinitely at ambient temperatures at the standard moisture content and are not subject to spoilage as long as the samples are kept dry.

Temperature and precipitation data for each of the location years were compiled ad-hoc using the nearest weather station for which complete records could be found in U.S. Global Historical Climatology Network's daily summaries database [21]. Average maximum and average minimum air temperatures were calculated by averaging the respective daily average maximum and minimum temperature from the day of the trial at an individual location-year was seeded through the day the trial was harvested. The precipitation was reported as the cumulative amount of precipitation between seeding and harvesting for the trial at an individual location-year.

Data were subjected to the PROC MIXED procedure for ANOVA in SAS [22]. Data pooled across varietal trial entries, replications, and location-years were analyzed. The model contained wheat class and state in which state was treated as a nested effect within wheat class. Least square means were estimated for wheat classes after controlling for the nested effects of state. Means were separated using Fisher's LSD ($P=0.05$). It should be noted that the collected data are unbalanced both within and between classes due to the fact that not all classes are represented in each state or location-year where the survey was conducted.

3. Results and discussion

HI ranged from 0.33 to 0.61 for the five classes of wheat surveyed in eight states during 2008 to 2010 (Table 3). Soft white wheat generally had higher grain yields than other classes of wheat. The data on HI and grain yield were similar to values reported in the literature [5] and [12]. Regardless of growing environment, SRWW produced the highest HI (0.61) among all wheat classes (Table 3). SRWW also had the lowest straw yield (3.4 t ha^{-1}) and aboveground biomass (8.6 t ha^{-1}) but did not produce the highest grain yield. SWWW, DW, HRSW, and SWSW had intermediate HI values, ranging from 0.49 to 0.42. SWSW and SWWW were the

most productive in straw (9.6 and 9.4 t ha⁻¹ respectively) and aboveground biomass (16.6 and 17.0 t ha⁻¹ respectively). HRWW had the lowest HI (0.33) and the lowest grain yield (4.1 t ha⁻¹) largely due to their limited biomass production as a result of the limited amount of available moisture in the regions where they were grown. These observations emphasize the importance of combining HI with aboveground biomass as the assessment criterion for straw yield. HI alone indicates the partitioning of biomass not the quantitative productivity. Though strong relations may exist among HI and yield parameters, a high HI does not necessarily suggest high grain yield or low straw yield; and vice versa. Assessment of HI must be based on relatively constant biomass to be meaningful for yield comparisons [11].

Variations in HI and yield parameters were detected within wheat class. A large difference was found between SWWW grown in ID and OR (Table 4). SWWW grown in OR was 66% lower in straw yield, 18% lower in grain yield, and 48% lower in aboveground biomass, but was 62% higher in HI, when compared with those grown in ID. This can largely be explained by the low precipitation in the rain fed sites in OR versus the irrigated site near Parma, ID. HRWW grown in OK and TX was consistent in HI and grain yield but was substantially different in straw yield and aboveground biomass. HRWW grown in OK produced more than twice the straw and aboveground biomass than those grown in TX. Less variability was present among participating states within the HRSW class (Table 4). HRSW grown in AZ had high HI and low straw yield and HRSW grown in ND had low HI and low grain yield, compared to the other three states. Environmental factors including air temperatures and precipitation have been known to exert influence on HI and yields [11], [23], and [24]. Climatic differences among states, particularly available moisture, may thus be a significant contributor to the variability in HI and yield parameters within wheat class as demonstrated by SWWW grown in ID and OR

(Table 5). The low HI observed in ND in 2009 coincided with severe foliar fungal diseases caused by , *Septoria* spp. and leaf rust. Therefore it is possible that biotic stresses may also affect HI. Other contributing environmental factors include pest and disease activity. Variations in harvest method and straw yield determination method contributed to the within-class variability as illustrated by the differences within SWWW grown in ID and OR or HRWW grown in OK and TX (Table 2).

Table 3 here.

Table 4 here.

Table 5 here.

As part of the SGI effort, the present study has quantified straw yield and aboveground biomass for five classes of wheat grown in eight states of the United States between 2008 and 2010. Across wheat classes and regions, an average of 1.23 tonnes of straw was produced per ha for every tonnes of grains harvested, which corresponded to an overall HI value of 0.45. The potential for wheat straw to serve as a feedstock can be approximated by using the average wheat yield within class/ region and multiplying it with class/region specific HI.

The strength of the study lies in the large number of observations and the reasonably consistent practices among the collaborators, which allows for an initial assessment of the genetic and environmental variations among wheat classes.. The unbalanced nature of the data is inevitable because not all classes of wheat are grown in each of the regions/states. Regions/states

had thus to be analyzed as a nested effect within wheat class. This precludes the examination of the possible interactions between wheat class and growing environment.. Furthermore, the survey was conducted on existing varietal trials rather than trials that were specifically designed to measure the effect of weather on grain and biomass yield. Year-over-year variability in temperatures and precipitation is inherent to dryland cropping and sampling across years accounts for those effects. Average air temperatures were relatively stable across the years for most locations but precipitation fluctuated considerably for some locations, especially Maricopa AZ and Parma ID. However, irrigation supplemented the received precipitation in either year the data was collected in Parma ID to meet crop water needs. The results of this initial survey suggest that additional sampling of either varietal trials or dedicated biomass trials can further refine the estimates presented in this paper.

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4. Conclusion.

The present study has investigated the potential of wheat straw as a cellulosic ethanol feedstock across the major wheat growing regions in the US by quantifying straw yield and aboveground biomass for five US wheat classes. An overall HI of 0.45 suggests that over half the above ground biomass is potentially available as feedstock annually. However, differences in straw yield and HI were detected among wheat classes and regions. SRWW produced the highest HI and lowest straw yield among wheat classes. SWSW and SWWW produced the highest straw yield. HRWW had the lowest HI. Variations within wheat class are attributable to differences in growing conditions when these trials were conducted, the genetic differences between entries in the individual trials, and differences in cultural practices. Differences in precipitation are likely

the largest contributor to these observed differences. The major limitation of the study is the limited number of years sampled. Initiation of dedicated biomass trials across classes and regions should allow for more precise estimates and improve the predictive power of the estimated HI and shed more light on the question whether annual differences in precipitation are more important than the overall climatic differences between states within classes. Nonetheless the class specific HI estimated in this study allow for the amount of wheat straw available as cellulosic feedstock in a state or wheat class to be estimated using the grain yields provided by the National Agricultural Statistics Service and the class specific HI with the formula below.

$$\text{Straw yield} = \left(\frac{1 - HI}{HI} \right) \times \text{Grain yield}$$

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Table 1. Location-year, #replications, latitude, longitude, planting and harvest dates of the participating states (total n=1858 for 255 cultivars across all locations-years).

State	Harvest Year	Location (#replications)	Latitude	Longitude	Planting Date	Harvest Date
			----decimal degree----		-----mm/dd/yy-----	
AZ	2008	Maricopa(4)	33.069	-111.972	01/04/08	06/13/08
AZ	2009	Maricopa(3)	33.069	-111.972	12/12/08	06/04/09
ID	2008	Parma(4)	43.800	-116.938	10/11/07	08/07/08
	2008	Parma	43.800	-116.938	03/19/08	08/07/08
ID	2009	Parma(4)	43.800	-116.938	10/07/08	
	2009	Parma	43.800	-116.938	03/25/09	
KY	2008	Lexington(4)	38.200	-84.300	10/30/07	06/25/08
KY	2009	Lexington(4)	38.200	-84.300	10/22/08	06/25/09
KY	2010	Lexington(4)	38.200	-84.300	10/26/09	06/22/10
MN	2008	Fergus Falls(3)	46.123	-96.180	04/23/08	08/13/08
MN	2008	Oklee(2)	47.778	-95.859	05/07/08	08/25/08
MN	2009	Oklee(3)	47.778	-95.859	05/19/09	08/27/09
MN	2009	Perley(3)	47.151	-96.798	05/19/09	08/27/09
MN	2010	Oklee(3)	47.778	-95.859	04/10/10	07/26/10
ND	2008	Lisbon(3)	46.330	-97.658	04/18/08	08/14/08
ND	2009	Lisbon(3)	46.330	-97.658	05/04/09	08/27/09
OK	2008	Apache(4)	34.894	-98.361	10/11/07	06/04/08
OK	2008	Lahoma(4)	36.388	-98.088	10/25/07	06/16/08
OR	2008	Sherman(3)	45.485	-120.712	10/03/07	07/23/08
OR	2008	Benton(4)	44.632	-123.198	10/25/07	08/12/08
OR	2009	Umatilla(3)	45.733	-118.519	10/21/08	07/28/09
TX	2008	Abilene(3)	35.494	-100.024	10/15/07	06/13/08
TX	2008	Dallam(3)	36.037	-102.411	10/09/07	06/13/08

Table 2. Wheat class, harvest method, and straw determination method of participating states.

State	Harvest Year	Location	Wheat Class	Harvest Method	Cutting Height	Straw Yield Determination
					—cm—	
AZ	2008, 2009	Maricopa	DW, HRSW	hand harvest	3	biomass minus grain
ID	2008, 2009	Parma	HRSW, SWSW, SWWW	hand harvest	2	weighed straw
KY	2008, 2009, 2010	Lexington	SRWW	small combine	7	weighed straw
MN	2008	Fergus Falls, Oklee	HRSW	hand harvest	2	biomass minus grain
	2009	Oklee, Perley	HRSW	hand harvest	2	biomass minus grain
	2010	Oklee	HRSW	hand harvest	2	biomass minus grain
ND	2008, 2009	Lisbon	HRSW	hand harvest	5	biomass minus grain
OK	2008	Apache, Lahoma	HRWW	hand harvest	2	biomass minus grain
OR	2008	Sherman, Benton	SWWW	small combine	5	weighed straw
	2009	Umatilla	SWWW	small combine	5	weighed straw
TX	2008	Abilene, Dallam	HRWW	small combine	3	weighed straw

Table 3. Least square means of harvest index among five of the six US wheat classes: Durum wheat (DW), hard red spring wheat (HRSW), hard red winter wheat (HRWW), soft red winter wheat (SRWW), and soft white wheat (SWW). The soft white class was divided in two subclasses based on growth habit: soft white spring wheat (SWSW), and soft white winter wheat (SWWW). Different letters denote significant difference at P=0.05. Data pooled across participating states, varietal trial entries, and location-years are presented (total n=1858 for 255 cultivars across all locations-years).

Wheat Class	Harvest Index	Straw Yield	Grain Yield	Aboveground Biomass
		t ha ⁻¹		
DW	0.46c	7.3b	6.0c	13.3b
HRSW	0.42d	8.1b	5.7d	13.8b
HRWW	0.33e	6.1c	4.1f	10.2c
SRWW	0.61a	3.4d	5.2e	8.6d
SWSW	0.42d	9.6a	7.0b	16.6a
SWWW	0.49b	9.4a	7.6a	17.0a

Table 4. Least square means of harvest index among five of the six US wheat classes: Durum wheat (DW), hard red spring wheat (HRSW), hard red winter wheat (HRWW), soft red winter wheat (SRWW), and soft white wheat (SWW) grown in eight states. The soft white class was divided in two subclasses based on growth habit: soft white spring wheat (SWSW), and soft white winter wheat (SWWW). Different letters denote significant difference at P=0.05. Data pooled across varietal trial entries and location-years are presented (total n=1858 for 255 cultivars across all locations-years).

Wheat Class	State	Harvest Index	Straw Yield	Grain Yield	Aboveground Biomass
—————t ha ⁻¹ —————					
DW	AZ	0.46c	7.3de	6.0d	13.3c
HRSW	AZ	0.50b	5.7ef	5.7de	11.4de
HRSW	ID	0.42cd	9.1bc	6.7bc	15.8b
HRSW	MN	0.41d	9.5b	6.2cd	15.7b
HRSW	ND	0.35ef	8.0cd	4.3f	12.3de
HRWW	OK	0.33f	8.4c	4.2f	12.6cd
HRWW	TX	0.33f	3.8g	4.1f	7.9f
SRWW	KY	0.61a	3.4g	5.2e	8.6f
SWSW	ID	0.42d	9.6b	7.0b	16.6b
SWWW	ID	0.37e	14.1a	8.3a	22.4a
SWWW	OR	0.60a	4.8f	6.8b	11.6e

Table 5. Climatic features for trial location-years in participating states.

Location	Approx. Growing Season	Average Maximum Air Temperature			Average Minimum Air Temperature			Precipitation		
		°C			°C			mm		
		2008	2009	2010	2008	2009	2010	2008	2009	2010
Maricopa AZ	January-June	27.6	29.3	—	8.1	9.4	—	86	29	—
Parma ID [†]	March-August	24.4	25.1	—	7.6	8.4	—	43	108	—
Parma ID [†]	October-August	15.9	16.5	—	2.1	2.6	—	130	169	—
Lexington KY	October-August	14.2	14.0	14.1	5.0	4.5	5.1	1170	882	781
Fergus Falls MN	May-August	22.9	—	—	11.1	—	—	398	—	—
Oklee MN	May-August	22.6	21.7	23.4	10.1	9.9	12.5	284	411	457
Perley MN	May-August	—	22.8	—	—	9.3	—	—	230	—
Lisbon ND	May-August	25.1	23.6	—	11.3	10.4	—	276	269	—
Apache OK	October-June	22.0	—	—	6.3	—	—	366	—	—
Lahoma OK	October-June	19.2	—	—	3.2	—	—	810	—	—
Benton OR	October-July	14.4	—	—	2.8	—	—	1604	—	—
Sherman OR	October-July	13.3	—	—	1.5	—	—	196	—	—
Umatilla OR	October-July	—	15.7	—	—	2.4	—	—	170	—
Abilene TX	October-July	22.6	—	—	8.0	—	—	357	—	—
Dallam TX	October-June	18.4	—	—	-0.4	—	—	71	—	—

[†] Location with irrigated trial.