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Effect of Harvesting Time on Forage Yield and Quality of Whole-Crop Oat in Autumn-Sown Regions of China

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Abstract

Harvesting time is a key factor that affects both the yield and quality of forage crops. To determine the optimal harvesting time for forage oats cultivated in autumn-sown oat regions in China, the yield and quality of 28 oat lines were evaluated at different growth stages, including booting, heading, flowering, and filling stage. The results showed the Fresh Yield (FY), Dry Yield (DY) and Plant Height (PH) of all tested oats consistently increased as the harvesting time was delayed, while the Crude Protein (CP) and Water-Soluble Carbohydrate (WSC) decreased. Furthermore, the contents of Neutral Detergent Fiber (NDF) and Acid Detergent Fiber (ADF) increased initially, peaked at the flowering stage, and then decreased when harvested at the filling stage. In contrast, the Relative Feed Value (RFV) and Grading Index (GI) changed with a converse trend to NDF and ADF. According to the comprehensive evaluation of forage yield and nutrient quality, cutting forage oats at the filling stage can achieve a relatively high yield and quality. These findings provide valuable information for farmers and researchers in the region to improve oat cultivation practices and maximize yield and quality.

Introduction

Oat (*Avena sativa* L.) is one of the most widely cultivated cool-season cereal crops used for both human consumption and animal feed [1]. As a forage crop, oat can be used as grazing feed, silage, and hay, making it an important source of livestock feed worldwide. In recent years, the demand for oat as forage has increased, with over half of the oats planted in the United States harvested for forage. Similarly, large-scale production of oat forage also has been reported in Brazil, Australia, and China. Forage oat has many desirable ecological and physiological characteristics, such as high yield, high crude protein, rich water-soluble carbohydrate, and high digestible neutral dietary fiber, making it an excellent feed with good palatability [1]. In addition, many factors such as a relatively short growing season, high resistance to abiotic stress, and adaptability have contributed to the universal acceptance of oat as a forage crop.

High yield and quality are essential in crop cultivation. Both traits are influenced by multiple factors, including genotype, plant density, harvesting time, and fertilization [2,3]. Of them, harvesting time is the primary factor affecting both forage yield and quality. Many studies have indicated that postponing harvesting time, increased the fiber content of feed crops, while the crude protein content decreased, resulting in reduced forage digestibility and relative feed value [4,5]. However, harvesting forage with the highest quality might significantly reduce its yield [6,7]. Therefore, selecting the most suitable harvesting time requires better understanding of the changes in nutrient content during the crop maturity process and the feeding value at different development stages. Several studies have reported on the relationships between forage yield and quality in oats at different maturity stages. The optimum harvesting time for forage oat with high fodder quality has been suggested to be the booting stage [8]. However, harvesting forage oats at the late heading stage may be desirable to maximize forage dry matter content potential because increased forage dry matter can compensate for reduced forage nutritional content [9].

With the development of animal husbandry and adjustment of the agricultural structure in China, animal husbandry has become increasingly important in the national economy, and the demand for forage has increased significantly. As one of the main pastoral areas, autumn-sown oat regions in China is seriously short of high-quality forage. Based on the unique planting system in the region, there are many idle winter fields from autumn harvest to spring snowing that can be utilized for planting high-quality and high-yield forage, such as oat. However, there is limited information available in the literature regarding the changes in yield potential and nutritional quality during the growth cycle of autumn-sown oats cultivated as a whole-crop for ensiling in China. Here, the primary objectives were to understand changes in yield and nutritional values of forage oat during the growth cycle and to determine the optimal harvesting time for forage oat grown in autumn-sown regions in China. These results could provide a technical foundation for the high-yield cultivation of local forage oats.

Materials and Methods

Climate and environmental conditions

Field experiments were conducted during the 2017-2018 cropping season at the Chongzhou experimental station of Sichuan Agricultural University (103°38’E, 30°32’N), located in the Chengdu plain of the main autumn-sown oat regions in China. The region has a typical subtropical monsoon climate with an elevation of 507 m, annual precipitation ranging from 1000–1300 mm and annual mean temperature of 15.9^{o}C.

Plant materials

A total of 28 oat lines were used in this study (Table 1). Among these lines, 18 were cultivars released by Chinese breeders from Hebei, Jilin, Gansu, and Qinghai provinces of China over the last 20 years. Two forage oats from the United States and Canada were also included in this study. In addition, eight advanced lines (F7) from a cross between WAOAT2132 and Caracas [10] were selected due to their high lodging resistance.

Field trials

The experiment was laid out in a randomized complete block design with four replicates. To assess the effect of harvesting time on the yield and quality of forage oats for feeding purposes, four different harvesting times were applied corresponding to four developmental stages, including booting (Zadok’s 45), heading (Zadok’s 55), flowering (Zadok’s 65), and filling (Zadok’s 75). The plots were 1.8 m wide by 5 m long with a net plot size of 9 m^2 and an inter-row spacing of 30 cm. Planting date was October 13 in 2017. Oat seeds were hand drilled at a rate of 1,700,000 kernels ha^{-1}, and then hand-thinned to 1,600,000 plants ha^{-1}. One week prior to sowing, nitrogen and super phosphate fertilizers were applied at a ratio of 80 kg ha^{-1}. Other field management followed local standards [11].

Assessment of agronomic traits

The Plant Height (PH) and other forage yield-related traits including Fresh Yield (FY) and Dry Yield (DY) were assessed at each harvesting time. To measure the PH, ten representative plants in each plot were chosen, and the mean values were used for further analysis. Forage was hand-harvested from four 1-m rows in the center of each plot (1.2 m^2) at a 5-cm-stubble height, and weighed immediately for FY. After the measuring FY, a 500 g fresh sample was collected from each plot and separated into leaves and stems. All plant fractions were then dried in paper bags to a constant weight at 65^{o}C under forced air, and the percentage of dry matter content within each sample was calculated and subsequently used to calculate the DY from each plot. Dried samples were ground in a shredder to pass through a 1 mm screen and stored in sealed plastic paper bags for further nutritive composition analysis.

Nutritive value evaluation

Quality traits including Crude Protein (CP), Water-Soluble Carbohydrate (WSC), Acid Dietary Fiber (ADF) and Neutral Dietary Fiber (NDF) were assessed for each sample. The CP was determined using the Kjeldahl method [12], the ADF and NDF were estimated by the sequential method [13], while the WSC was determined using the anthrone reaction rate [14]. For all traits mentioned above, the values were expressed on a percentage of the dry-mater basis and the mean values were used for statistical analysis.

Relative feed value (RFV) was calculated from Digestible Dry Matter (DDM) and digestibility Dry Matter Intake (DMI) using ADF and NDF, respectively. The formula used for to calculate RFV [5] is below:

$$RFV = DDM \times DMI/1.29$$

$$DDM = 88.9 - 0.77 \times ADF$$

$$DMI = 120/NDF$$

Grading Index (GI) was used to evaluate the forage quality. It was calculated by using Voluntary Dry Matter Intake (VDMI) and Net Energy for $_{\text{lactation}}$ (NE_L) with the following formula:

$$GI = VDMI \times NE_L \times CP/NDF$$

$$VDMI = 1.2 \times BW/NDF$$

$$NE_L = (1.085 - 0.0124 \times ADF) \times 9.29$$

Where BW was body weight of cow, calculated as 600 kg. The RFV and GI grading standards are shown in Table 2.

Statistical analysis

The ANOVA was used to evaluate the effects of harvesting time and cultivar on yield- and quality-related traits of tested oat lines with both harvesting time and cultivar as fixed effects. When significant treatment effects occurred, means were separated using Fisher’s LSD at a 5% significance level. All these analyses were conducted by using the SPSS (v.26) software (SPSS Inc., Chicago). Pearson’s correlation coefficients (r) of pairwise traits were calculated based on the mean values using the R package “corrplot” (https://github.com/taiyun/corrplot).

Results

Weather data during the 2017-2018 cropping season

The monthly average temperature and precipitation are shown in Figure 1. From sowing to harvesting, the temperature and precipitation first decreased and then increased. Between the 60-80 days after sowing, the precipitation decreased with increased temperature, making this a relatively dry time period.

Impact of harvesting time on yield of oat forage

The FY, DY, and PH, for forage oat harvested at the booting, heading, flowering, and filling stages are shown in Table 3. The values of all these tested traits were continuously increased with delayed harvesting time. The FY of the 28 oat lines varied from 25,540.50 to 53,446.43 kg/ha across the different harvesting times. Delayed harvesting time to the filling stage increased the FY at the booting, heading, and flowering stages by 52.21%, 31.38%, and 16.05%, respectively. The highest DY was observed at the filling stage with an average value of 16,053.45 kg/ha, which is significantly higher than at other stages. At all harvesting times, the average PH of 28 oat lines were over 90 cm. The average PH showed a similar increase to FY and DY across various harvesting stages. Analysis of variance revealed significant effects of harvesting time, cultivar, and cultivar×harvesting time interactions on forage oat yield (Table 5).

The effect of harvesting time on nutritive value of oat forage

The nutrient values of forage oat harvested at different stages are shown in Table 4. During plant maturation from booting to filling stage, the CP content tended to continuously decrease, but CP contents were similar at the flowering and filling stages. The effect of harvesting time was significant for ADF and NDF contents, which showed a similar trend of increasing from booting to filling stage and then decreasing. The highest WSC content of 10.58% was obtained at the booting stage, with reduced oat WSC content at the heading, flowering, and filling stages by 11.5%, 30.1%, and 37.4%, respectively. Similarly, ANOVA also revealed significant effects of harvesting time, cultivar, and cultivar×harvesting time interactions on forage oat nutritive values (Table 5).

Further, the RFV and GI of forage oat harvested at various stages were estimated (Table 4). Forage oat harvested at the booting stage had the highest RFV and GI values, and the RFV and GI values of forage oat dramatically decreased when harvested at the heading, flowering, and filling stages. The lowest values of both RFV and GI were observed at the flowering stage.

Correlation between yields and quality components

A correlation analysis of comprehensive yields and nutritional values revealed that (FY and DY) were negatively correlated with CP and WSC. Conversely, a significantly positive correlation was observed between yields and NDF, as well as between yields and ADF (Figure 2). This result suggested that delaying harvesting time led to increased yields of forage oat with a gradual thickening of the plant's cell wall, an increase in fiber content, and a decrease in digestible nutrients, thus reducing the palatability of forage oats.

Table 1: List of oat varieties used in this study.

Code	Variety	Source
1	Bayou No. 3	Hebei
2	Bayou No. 18	Hebei
3	Bayan No. 4	Hebei
4	Baiyan No. 2	Jilin
5	Baiyan No. 7	Jilin
6	Baiyan No. 18	Jilin
7	Baiyan No. 19	Jilin
8	Yuanza No. 1	Hebei
9	Zhangyan No. 4	Hebei
10	GL381	Hebei
11	Longyan No. 3	Gansu
12	Dingyan No. 2	Gansu
13	Kuibeike oat	Canada
14	Qingyin No. 2	Qinghai
15	Tian oat	Qinghai
16	Caoyou No. 1	Inner Mongolia
17	Mengyan No. 1	Inner Mongolia
18	Tianyan No. 2	Canada
19	KNOA	America
20	Haywire	America
21	3-299	Sichuan Agricultural University
22	3-297	Sichuan Agricultural University
23	3-109	Sichuan Agricultural University
24	3-307	Sichuan Agricultural University
25	3-179	Sichuan Agricultural University
26	3-252	Sichuan Agricultural University
27	3-204	Sichuan Agricultural University
28	3-283	Sichuan Agricultural University

Table 2: The RFV and GI grading standards.

Grade	Special grade	Grade A	Grade B	Grade C	Grade D
Relative feed value (RFV)	>151	125~150	103~124	87~102	75~86
Grading index (GI)	>30	19~26	9~13	4~6	2~3

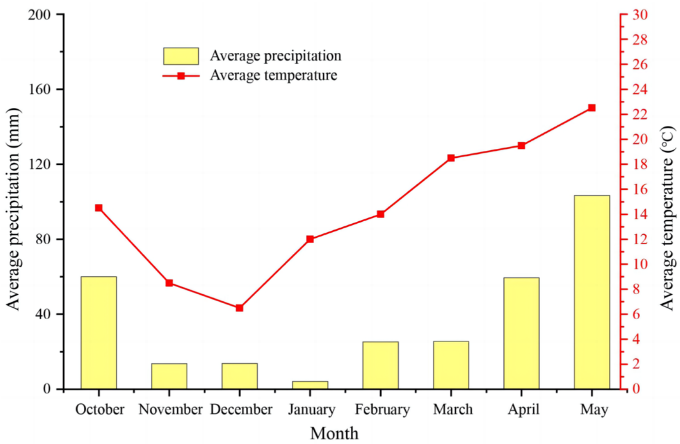

Figure 1: Monthly average precipitation and temperature in Chongzhou, Chengdu during the 2017-2018 cropping season.

Table 3: The mean value along with standard deviation of agronomic traits in different harvesting time.

Trait†	Treatment	Mean±SD	CV‡	95%CI§
FY (kg/ha)	Booting	25540.50±3900.78^{d}	0.15	24027.93-27053.06
	Heading	36676.19±3905.92^{c}	0.11	35161.63-38190.74
	Flowering	44867.85±2980.63^{b}	0.07	43712.09-46023.62
	Filling	53446.43±4931.63^{a}	0.09	51534.14-55358.71
DY (kg/ha)	Booting	4071.09±683.79^{d}	0.17	3805.95-4336.24
	Heading	7991.51±825.09^{c}	0.10	7671.58-8311.45
	Flowering	11335.70±1118.20^{b}	0.10	10902.11-11769.29
	Filling	16053.45±1380.42^{a}	0.09	15518.18-16588.72
FY (cm)	Booting	97.70±6.87^{d}	0.07	95.03-100.36
	Heading	117.01±6.28^{c}	0.05	114.58-119.45
	Flowering	129.30±3.92^{b}	0.03	127.78-130.82
	Filling	140.88±5.64^{a}	0.04	138.70-143.07

†FY, fresh yield; DY, dry yield; PH, plant height.
‡CV, coefficient of variation. §95%CI, 95% confidence interval.

Table 4: The mean value along with standard deviation of nutritive value in different harvesting time.

Trait†	Treatment	Mean±SD	CV‡	95%CI§
CP (%)	Booting	23.53±1.84^{d}	0.08	22.81-24.24
	Heading	13.85±0.77^{c}	0.06	13.55-14.14
	Flowering	11.74±0.99^{b}	0.08	11.36-12.13
	Filling	10.79±0.91^{a}	0.08	10.44-11.14
NDF (%)	Booting	42.76±3.16^{d}	0.07	41.54-43.99
	Heading	55.38±3.02^{c}	0.05	54.21-56.55
	Flowering	62.79±2.67^{b}	0.04	61.75-63.82
	Filling	57.24±2.48^{a}	0.04	56.28-58.20
ADF (%)	Booting	25.98±2.55^{d}	0.10	24.99-26.97
	Heading	33.42±1.92^{c}	0.06	32.67-34.16
	Flowering	37.42±1.76^{b}	0.05	36.74-38.09
	Filling	33.38±1.85^{a}	0.06	32.66-34.10
WSC (%)	Booting	10.58±0.76^{c}	0.07	10.29-10.88
	Heading	9.36±0.73^{b}	0.08	9.07-9.64
	Flowering	7.40±0.92^{b}	0.12	7.05-7.76
	Filling	6.62±0.90^{a}	0.14	6.27-6.97
RFV	Booting	150.39±14.74^{d}	0.10	144.68-156.11
	Heading	105.89±6.07^{c}	0.06	103.54-108.24
	Flowering	88.72±4.98^{b}	0.06	86.79-90.65
	Filling	102.39±4.89^{a}	0.05	100.49-104.29
GI	Booting	67.93±11.95^{d}	0.18	63.30-72.56
	Heading	20.43±2.58^{c}	0.13	19.43-21.43
	Flowering	12.47±1.80^{b}	0.14	11.77-13.17
	Filling	14.86±1.86^{a}	0.13	14.14-15.58

†CP, crude protein; NDF, neutral detergent fiber; ADF, acid detergent fiber; WSC, water-soluble carbohydrate; RFV, relative feed value; GI, grading index.
‡CV, coefficient of variation. §95%CI, 95% confidence interval.

Table 5: The effect of harvesting time and cultivar on oat yield and quality related traits.

Treatment	df	FY	DY	PH	CP	NDF	ADF	WSC
Harvesting time (HT)								
Booting		25625^{d}	4094^{d}	97.70^{d}	23.52^{a}	42.76^{c}	25.97^{c}	10.58^{a}
Heading		36742^{c}	7965^{c}	117.01^{c}	13.84^{b}	55.38^{b}	33.42^{b}	9.36^{a}
Flowering		44851^{b}	11328^{b}	129.30^{b}	11.74^{bc}	62.78^{a}	37.42^{a}	7.40^{b}
Filling		53528^{a}	16050^{a}	140.88^{a}	10.79^{c}	57.24^{b}	33.38^{b}	6.62^{b}
F-value†								
C	27	9.91**‡	10.12**	63.54**	2.06**	6.61**	3.66**	1.39*
HT	3	918.76**	413.15**	5736.10**	579.50**	1198.75**	379.36**	56.04**
Interactions								
C×HT	81	1.66**	2.45**	5.791**	1.56**	4.40**	2.28**	2.23**

†df: degrees of freedom; FY: Fresh Yield; DY: Dry Yield; PH: Plant Height; CP: Crude Protein; NDF: Neutral dietary fiber; ADF: Acid Dietary Fiber; WSC: water-soluble carbohydrate; C: cultivar; HT: Harvesting Time; C×HT: Cultivar and harvesting time interaction.
‡The symbols * and ** represent the significance levels of $p < 0.05$ and $p < 0.01$, respectively.

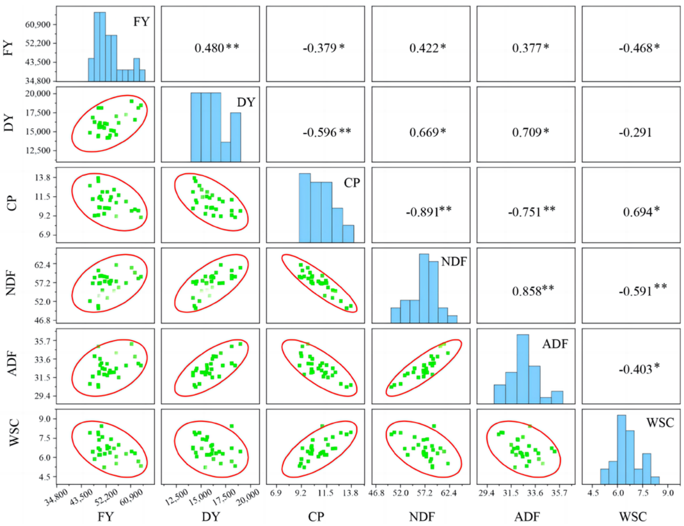

Figure 2: Correlation matrix of forage oat yield-related traits and nutritional characteristics. FY: Fresh Yield; DY: Dry Yield; CP: crude protein; NDF: Neutral Dietary Fiber; ADF: Acid Dietary Fiber; WSC: Water-Soluble Carbohydrate. The number on the upper panel represents Pearson correlation coefficient between the two parameters. The symbols * and ** represent the significance levels of $p < 0.05$ and $p < 0.01$, respectively.

Discussion

Farmers aim to produce high yield oat forage with good quality. However, the processes leading to high yield and good quality have opposite development directions in the growth and development of forage crops [15,16], and are closely correlated with the stage of maturity at harvest. Therefore, harvesting forage oat at an appropriate growth stage is key to maintaining the balance between yield and quality. Thoroughly understanding the changes in yield potential and nutritional quality during the growth cycle of oat is a prerequisite for determining the optimal harvesting time for forage oat.

In this study, the yield and quality of 28 oat lines harvested at four growth stages were evaluated in 2017-2018. The results showed that forage yield increased with prolonged maturity, while the quality conversely decreased. These results are in accordance with previous studies [4,17,7]. Increased yield with postponed harvesting time has been attributed to the increase of PH, the decrease of stem and leaf moisture content and the continuous accumulation of dry matter yields [18,15,19,20]. In this study, the average PH of the 28 oat lines at the filling stage is 140.9 cm, which is 44.2% higher than that at the booting stage. Correspondingly, delaying harvesting time from the booting stage to the filling stage increases the fresh and dry yields by 108.9% and 294.3%, respectively, thus supporting the increase of plant height as the main contributor of yield increase.

CP, WSC, ADF, and NDF are the major characteristics used to evaluate forage quality. The concentrations of CP and WSC are positively related to forage quality, while ADF and NDF content are negatively related [5,21]. In this study, the CP and WSC content continuously decreased with the delay in harvesting time, consistent with previous studies [22-26]. The decrease in CP might be associated with the decrease in the proportion of leaves, which are the main contributors of protein in sorghum [27,28]. The fiber content of forage crops increases while quality and digestibility decrease as harvesting time is prolonged. In this study, the delay in harvesting increased the content of ADF and NDF, which reached a peak at the flowering stage, but decreased at the filling stage. Previous studies revealed that the decrease in dietary fibers with plant maturity was related to increased lignin content [29], and the synthesis and accumulation of lignin usually occur during the formation and thickening of the secondary cell wall [17]. The RFV and GI are widely used to predict the intake and energy value of forage [30]. The trend of RFV was opposite those of ADF and DNF contents, but related because these contents were used to calculate RFV [31,32]. As the harvesting time is delayed, the RFV and GI values show a trend from high to low to high, possible due to the large accumulation of starch during the filling stage, which reduces the fiber content and therefore increases the RFV and GI values.

Due to the inconsistency between the peak of hay yields and the optimal period of nutrition of forage crops, the optimal harvesting time should balance hay yield and nutrition quality to achieve the best results. Some previous studies suggested that the optimal harvesting time for forage oats is after the filling stage, such as at the milk to early dough stage [8,9]. In this study, the highest quality forage oats occurred when oats were harvested at the booting stage; however, the yields at this stage were very low. In contrast, harvesting forage oats at the filling stage resulted in peak yields but significantly lower quality, reflected by the decrease of CP and the increase of NDF and ADF. Despite the lower crude protein content of forage oats at the filling stage, the protein yield per unit of land area might increase with the extension of harvesting time due to the high dry matter yield per hectare of land as reported by previous studies [33]. Additionally, harvesting oats at the filling stage resulted in a significant decrease in NDF and ADF contents compared to harvesting at the flowering stage, suggesting that higher quality can be obtained at the filling stage. These results suggest that the optimal harvesting time for forage oats grown in autumn-sown oat regions in China is at the filling stage, allowing farmers to obtain high yields with relatively higher quality forage oats.

Conclusions

This study evaluated the yield and quality of 28 lines of oats harvested from booting to filling stages. The results revealed that forage yield and plant height consistently increased with prolonged maturity, while the contents of crude protein and water-soluble carbohydrate gradually decreased. In contrast, the contents of acid detergent fiber and neutral detergent fiber increased initially, peaked at the flowering stage, and then decreased when harvested at the filling stage. Based on both yield and quality, the optimal cutting time for forage oats grown in autumn-sown oat regions in China is at the filling stage. This stage allows forage oats to achieve a relatively high yield and quality.

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Data availability statement: Upon reasonable request, the datasets of this study can be available from the corresponding author.

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