A Dual-Purpose Model for Spring-Sown Oats in Cold Regions of Northern China

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Abstract: Alpine regions in northern China are the traditional animal husbandry base. The lack of high-quality forage supply resulting from degradation of natural grasslands and low forage production due to short growing seasons greatly restricts development of animal husbandry in these areas. Spring oats have been widely planted in cold regions worldwide harvesting as either grains or forages because of their great adaptative ability to low temperatures and early maturation and high nutritional values. To maximize forage and grain production, we developed a dual-purpose model for spring-sown oats in the cold regions of northeastern China using two oat species, Avena nuda L. (cv. Bayou6) and Avena sativa L. (cv. Qinghai444). Growth, forage production and quality, grain yield, and re-growth ability of the two oats were investigated in field trials and field demonstration. Maximal dry weight was found to occur at 70 days of emergence for both oats with higher forage production and crude protein (CP) in Bayou6 than Qinghai444 oat species. Neutral detergent fiber (NDF) and acid detergent fiber (ADF) of the two oats increased with time during the early vegetative growing stage, while the relative feed value showed a decrease during vegetative growing stage. The re-growth ability following cutting for the two oats reduced with increasing growth times during vegetative stage. Plant height, tiller density, CP and NDF contents of re-growing seedlings harvested at 30–40 days of emergence did not significantly differ from those of un-cutting control. The overall cumulative dry weight of biomass following cutting at 30 days of emergence was significantly higher than that of control without cutting in both oat species. Seed yield from plots cut at 30 days of emergence for both oat species was insignificantly different from that of control plots. Harvesting of spring-sown oats at 30 days of emergence enhanced forage production, but it did not influence seed yield. Results from 2-year field demonstration confirmed these conclusions. These findings highlight that this dual-purpose oat management model can have great applications in the cold regions of China.

Keywords: oat species (Avena nuda L.; A. sativa L.); cutting stage; dual-purpose; re-growth; forage and seed production
1. Introduction

Diversification in crop production systems can decrease risks and improve profit opportunities [1]. Crops that provide forage production during vegetative growth and are subsequently harvested for grain are termed “dual-purpose” (DP) [1–3]. The DP cereal crops are valuable resources and attractive management options for several seasons [2]. Firstly, DP can provide higher production in forage, grain, or both [2,4]. For example, dual-purpose wheat (*Triticum aestivum* L.) and triticale (× *Triticosecale*) can provide more forage and grains by reducing disease incidence and lodging [1]. Secondly, DP forage can cover the seasonal shortage of animal feed with high digestibility and crude protein content, and is thus conducive to high livestock weight gain [5]. Thirdly, both experimental and modeling studies have demonstrated that the DP models are more profitable due to income from both forages and grains [4]. To date, DP crops are widely grown in those regions with relatively warmer winters [6]. Traditionally, DP cereal crops are typically sown in late autumn, and thus relatively warm temperatures can promote growth and accumulation of vegetative biomass during winter [2,7,8]. Moreover, the autumn-sown cereals can also efficiently use winter rains [8]. However, the DP cereal crops have not been reported in areas with cold winter and short frost-free periods. The spring-sown crops with either harvesting for forage or grains are the main planting model in the areas of long and cold winters [3], while few studies have focused on the DP cereal crops by sowing in spring in these areas.

The dual-purpose crop system is a complex process and may be regulated by many factors, including those of suitable crop species and/or cultivars, dynamic of growth patterns, agronomic traits, the ability to re-grow, and the management related to environmental and climatic changes [2,9]. It has been shown that cereal crops differ in their developmental patterns [3]. For example, accumulation of dry matter and nutritive traits differed among different oat cultivars [10], barley cultivars and between barley and triticale [3]. Thus, understanding the dynamics of growth for individual crops is important for their optimal utilization. Furthermore, the ability to re-grow after harvesting is an essential trait for dual-purpose crops [1,2]. The ability of re-growth differs among crops and cultivars with a given crop in different growing environments [2]. In addition, the field management can also influence the ability of re-growth. For example, it has been reported that the re-growth was enhanced and suppressed by irrigation and drought, respectively [2]. The mechanisms and management of DP crops may also differ between autumn-sown and spring-sown crops [10]. The growing period for autumn-sown crops is through the whole winter with a relatively lower temperature stage, while growth for spring-sown crops mainly occurs in relatively high temperatures [2]. Harvesting prior to winter may have limited effects on growing period for autumn-sown crops, and delays the growing period for spring-sown crops. Therefore, it is necessary to take into account the corresponding growing season for completing maturation of spring-sown crops [2]. However, few studies have evaluated the mechanisms and management related to DP crops in spring-sown cereal crops in general and oats in particular in the cold regions of northern China.

Oat is an important cereal crop worldwide, especially in the regions of high altitudes and latitudes because of its preference to cool climate, quick growth, and relatively short mature period [11,12]. Cold regions located in the high latitudes (≥45° N) and altitudes (≥1200 m) account for 1/3 areas of the territory in China [13], and are the traditional animal husbandry base [13]. The lack of high-quality forage supply due mainly to degradation of natural grasslands greatly restricts development of animal husbandry in these areas [13,14]. Oat is one of the traditional crops that are often used for grain harvesting as food in the cold regions of China [12,15]. The importance of oat forage in dairy industry is being recognized worldwide, and the demand for oat forage in China has increased markedly as evidenced by increasing import of oat hay from 1500 to 308,100 tons from 2008 to 2017 [16]. Therefore, how to enhance oat forage production and quality to meet the demand in local animal husbandry in the regions with long and cold winters is of practical importance. However, few studies have been reported on the dual-purpose harvesting model for spring-sown oats in China. The aim of this study is to determine the optimal patterns for spring-sown oats for harvesting forages and grains under irrigation in a cold region of northern China under field trials and field demonstration. Specifically,
we studied the dynamic changes in agronomic characteristics and forage quality during the growing season using two oat species that have commonly been planted in the regions. We further examined the re-growth ability of the two oat species by cutting at varying times after emergence during the growth season. Finally, we compared the overall forage production and seed yield under different cutting regimes and analyzed their driving factors. To verify the conclusions derived from the field trial studies, we further evaluated this harvesting model in a large field demonstration in the same area.

2. Materials and Methods

2.1. Study Site

The field trials and field demonstration were conducted at Xieertala experimental station and Xieertala Farm in Inner Mongolia Autonomous region, China (49°18′N, 120°3′E, elevation 850 m) during growing seasons in 2017 and 2018. Soil type is chestnut soil of the field trial. The chestnut soils occur widely in arid steppes and cover large areas in northern China. The parent material consists mainly of calcareous deposits with a predominance of loess like loams, calcareous sandy loams, loesses, calcareous sands, sandy loams, and alluvium. The basic conditions of meteorology are shown in Table 1. For the field trials, the previous crop was rapeseed (Brassica campestris L.) and harvested in autumn in 2017. The basic soils (0–20 cm layer) were sampled prior to sowing oats in spring (8 May 2018) and their chemical characteristics were measured: initial soil pH 6.70 ± 0.11, organic matter 33.1 ± 1.5 g kg⁻¹, total N 1.92 ± 0.2 g kg⁻¹, NH₄⁺-N 65.3 ± 2.2 mg kg⁻¹, NO₃⁻-N 34.2 ± 1.2 mg kg⁻¹, available P 10.2 ± 0.2 mg kg⁻¹, and available K 122.1 ± 10.1 mg kg⁻¹. For the field demonstration, the previous crop was also rapeseed, harvested in autumn in 2016 and 2017.

| Items                        | Xieertala      |
|------------------------------|----------------|
| Frost-free period (d)        | 110–125        |
| Growing season (Month-Month) | May–August     |
| Accumulated temperature ≥0 °C | 2279–2647      |
| Accumulated temperature ≥5 °C | 2159–2562      |
| Accumulated temperature ≥10 °C | 1856–2274     |
| Mean annual temperature (°C) | ~1.3           |
| Mean annual precipitation (mm)| 348.4        |
| Soil type                    | Chestnut soil  |

2.2. Oat Species

In this experiment, two oat species, Avena nuda (cv. Bayou6) and Avena sativa (cv. Qinghai444) were used in our studies. Both oat species have been planted in cold regions of Northern China [11,12,17]. The oat Bayou6 and Qinghai444 have mainly been used as cereal and forage, respectively. Both oat species can also be used as forages. The basic characteristics of seed lots are shown in Table 2.

| Oat Species              | 1000-Grain Weight g | Germination Rate % |
|--------------------------|---------------------|-------------------|
| Avena nuda L. cv. Bayou6 | 22.27 ± 0.10        | 98.5 ± 0.8        |
| Avena sativa L. cv. Qinghai444 | 33.15 ± 0.13   | 86.3 ± 2.0        |

2.3. Experimental Design

The studies contained both field trials and field demonstration. Field demonstration was conducted in Xieertala farm in 2017 and 2018. In 2016, we found that the growing season was longer than the whole growth period of oats. In addition, the oats can regenerate when cut in vegetative growing stage [10]. Thus, in 2017, we proposed and developed the dual-purpose harvesting model for spring-sown oats in field. In 2018, to study the mechanisms and optimize the dual-purpose model, the field trials and field demonstration were carried out in synchronization.
The field trials were established with a randomized block design with four replications for each oat species. Each plot was 5 × 3 m (15 m²). Five cutting regimes after seedling emergence were assigned, that is cutting at 30, 40, 50, 60, and 70 days after emergence of seedlings, respectively. The last cutting was done at 70 days after emergence of seedlings due to full ripping of oats and failure of re-growth following the cutting (see Figure 3). We thus defined cutting at 70 days after seedling emergence as the control in the present study. The cutting was done by hands using a sickle at 10 cm above ground. Plant height and tiller density were measured when harvested by cutting. Fresh and dry weight was also determined. The forage quality was assayed by measuring crude protein, neutral detergent fiber, acid detergent fiber for harvested shoots and relative feed values were calculated as described by Rohweder et al. (1978) [18]. Seed yields were harvested and weighed when oat plants grew to full maturation. The seeds were threshed by hand after the spike drying.

2.4. Oat Sowing and Management

The soil in this study was ploughed in autumn in the previous year with oil crop of rape (Brassica campestris L.). The oats in field trials were sown on 11 May 2018 with row space of 15 cm and depth of 5 cm in soil by a precision seed-planter (Hebei Nonghaha Machinery Group Co., Ltd., made in Hebei, China). The seed rate was 225 kg ha⁻¹. Base fertilizers were applied with mixture of 42 kg N, 24 kg P, 24 kg K per hectare during spring sowing. The experimental field was irrigated on 13 and 26 May with sprinklers to facilitate emergence and quick growth of oats.

2.5. Growth Stage

Vegetative growth was defined as from emergence to booting stage (GS10-GS39 based on Zadoks code), while reproductive growth was defined from booting stage to ripening (GS40-GS92 based on Zadoks code). Under different cutting stages, the vegetative and productive growth were determined.

2.6. Plant Height, Tiller Density, Aboveground Biomass, Seed Yield, and Grain Harvested Index

In each plot, half of the plot area (2.5 × 3 m) was cut at a 10-cm stubble height. Plant height was determined by measuring 10 randomly selected tillers in each plot. The tiller density (number m⁻²) was counted in a 1-m row of six randomly selected replicates and converted to per square meter in each plot. Fresh weight was measured immediately after cutting. Dry weight of aboveground biomass was determined by drying at 80 °C for 48 h in an oven. Seed yields were measured by harvested seeds in a plot of 4 m² (2 × 2 m) for each plot. The cumulative plant height was defined as plant height at cutting time plus plant height of re-growth by subtracting the stubble of 10 cm. The stubble height was 10 cm in the cutting time. The total dry weight of aboveground biomass was expressed as dry weight at cutting time plus dry weight of re-grown plants. The grain harvested index was expressed as seed yield/dry weight of aboveground biomass.

2.7. Forage Quality

Total nitrogen contents for aboveground biomass of the oat plants were measured by Kjeltec2200 (FossTM2200, Hillerød, Denmark), and crude protein (CP) concentrations were estimated by CP = total nitrogen × 6.25 as described by Silva et al. (2013) [19]. Neutral detergent fiber (NDF) and acid detergent fiber (ADF) of shoots were determined following the protocols of Nie et al. (2009) [20]. Relative feed value (RFV) is calculated as following protocols described by Rohweder et al. (1978) [18]:

\[
DDM = 88.9 - (0.77 \times ADF\%), \hspace{1cm} (1)
\]

\[
DMI = (120/\text{NDF}%), \hspace{1cm} (2)
\]

\[
RFV = DDM\% \times DMI\% \times 0.775, \hspace{1cm} (3)
\]

where DDM is digestible dry matter expressed by % of dry matter, and DMI is dry matter intake expressed by % of animal body weight.
2.8. Data Collected in Field Demonstration

The sowing areas for each oat species were about 100 ha in the field demonstration for each year, and previous crops for these studies was rapeseed harvested in the previous autumn. About one ha was not cut in the vegetative stage and taken as the control. Four quadrats of each 4 m² (2 × 2 m) were chosen to measure the plant height, tiller density, and dry weight of aboveground biomass in the field. The sowing dates were on 26 April 2017 and on 4 May 2018, respectively, in the farm by the no-tillage seeder (2BFM-17, Shandong Ingersoll Rand Machinery Industry Co., Ltd., made in Shandong, China). The protocols for sowing and management in the field demonstration were same as the field trials.

2.9. Data Analysis

For the field trials, one-way ANOVA (Duncan’s test) was used to evaluate plant height, tiller density, dry weight of aboveground biomass, crude protein, neutral detergent fiber, acidic detergent fiber, relative feed value, and grain harvest index after re-growth among different cutting times for each oat species (SPSS 21.0; SPSS, Chicago, IL, USA). From the whole growing-season perspective, the cumulative plant height, overall dry weight, and seed yield among different cutting treatments were also compared by one-way ANOVA for each oat species. The differences in vegetative and reproductive growth under different treatments were also compared by one-way ANOVA. The t test was used to compare the differences in each variable between the two oat species under the same treatments. Scatterplots with trendlines were used to show the effects of plant height and tiller density on dry weight of re-growth biomass for each oat species. Furthermore, structural equation modelling (SEM) was used to analyze coaction pathways of plant height and tiller density on dry weight of re-growth biomass. Amos version 17.0.2 (Amos Development Corporation, Chicago, IL, USA) was used to parameterize the SEM model. For the data in the field demonstration, one-way ANOVA (Duncan’s test) was used to compare the significance among treatments.

3. Results

3.1. Weather

The monthly precipitation in the growing season showed a pattern of an initial increase followed by a decrease in 2017, 2018, and the 30-year mean, and the maximum monthly precipitation occurred in July in 2018 and the 30-year mean (Table 3). The total precipitation in 2018 was comparable to the 30-year mean precipitation, suggesting that the year 2018 was a normal year in terms of precipitation. In contrast, the year 2017 was a dry year for less total precipitation (Table 3). The mean monthly temperature exhibited a single-peaked curve in growing seasons in both years, with the maximal value in July (Table 3). In addition, the patterns of precipitation and temperature were comparable during the growing seasons.

| Parameters          | Year | Apr. | May | Jun. | Jul. | Aug. | Sep. | Average/Sum |
|---------------------|------|------|-----|------|------|------|------|-------------|
| Monthly Precipitation (mm) | 2017 | 4.8  | 6.7 | 15.3 | 36.4 | 37.3 | 17.1 | 117.6       |
|                     | 2018 | 1.3  | 2.9 | 75.9 | 109.2| 59.5 | 47.4 | 326.2       |
| Mean monthly Temperature (°C) | 2017 | 2.4  | 9.6 | 19.3 | 23.4 | 19.4 | 9.5  | 13.9        |
|                     | 2018 | 3.3  | 12.4| 16.6 | 21.5 | 17.9 | 11.2 | 13.8        |
| 30-year mean        |      | 1.9  | 10.9| 18.1 | 20   | 17.7 | 10.3 | 13.2        |

3.2. Agronomic Characteristics and Forage Quality

The two oat species exhibited similar growth patterns after emergence in terms of plant height, fresh weight, and dry weight. Plant height of both oat species reached peak at 50 days of emergence with Bayou6 significantly higher than Qinghai444 after 50 days of emergence (Figure 1a). Fresh weight
of the two oat species peaked at 50 days of emergence, and there was no significant difference in fresh weight between the two oat species across the growth period (Figure 1b). The highest dry weight for the two oat species occurred at about 70 days of emergence, and Bayou6 exhibited significantly higher dry weight than its counterpart Qinghai444 after 50 days of emergence (Figure 1c).

We further monitored changes in parameters associated with nutritive quality of the two oat species, including crude protein (CP), NDF, ADF, and their relative feed values. Both oat species showed similar dynamic changes in CP, such that CP reached minimal values after 50–60 days of emergence, and thereafter peaked at approx. 90 days of emergence (Figure 2a). Similar to dry weight, CP values in Bayou6 were significantly higher than in Qinghai444 across most of the growing period (Figure 2a). The two oat species displayed comparable changes in NDP across the growing period, with NDP contents rapidly increased after 40 days of emergence, and maintained relatively constant value of about 56% until harvest (Figure 2b). The ADF values of both oat species increased gradually with growing extension after 30 days emergence (Figure 2c). The oat Qinghai444 exhibited significantly higher ADF values than oat Bayou6 at 60, 70, and 100 days of emergence (Figure 2c). The relative feed values for the two oat species showed rapid declines after 30 days of emergence, and maintained relative constant levels of 102–104 until 100 days of emergence (Figure 2d). These results suggest that oat Bayou6 has overall higher forage production and crude protein contents than oat Qinghai444.

Figure 1. Dynamic changes in plant height (a), fresh weight (b), and dry weight (c) of aboveground biomass for the two oat species during the growing season. * indicates significant difference ($p < 0.05$) between the two oat species (Bayou6 and Qinghai444) under the same growing stage. Data are means ± SE ($n = 4$).
Figure 2. The crude protein (a), neutral detergent fiber (b), acidic detergent fiber (c), and relative feed value (d) in aboveground biomass of oat in the growing process. Data are means ± SE (n = 4). * indicates a significant difference (p < 0.05) between the two oat species (Bayou6 and Qinghai444) under the same growing stage.

3.3. Effect of Cutting on Agronomic Characteristics

We found that the spring-sown oats can be harvested twice by cutting during vegetative growth stage. To maximize forage production and quality, we optimized the cutting stages after emergence by investigating effects of cutting stages on the agronomic characteristics of re-growing seedlings for the two oat genotypes. We set the control (CK) as those oat plants that were harvested at full maturity after 70 to 100 days of emergence. We then cut the oat plants after different days (30, 40, 50, 60 days) of emergence, and determined the parameters associated with re-growth in oat plants (plant height, tiller density, dry weight) and quality features (CP, NDF, and ADF) at the end of growing season. Generally, re-growth ability for the two oat species was reduced with growing extension, and the plants can no longer re-grow after 70 and 60 days of emergence for Bayou6 and Qinghai444, respectively (Figure 3). For example, compared to the control without cutting until full maturity (CK), height of re-grown plants after cutting at 30 and 40 days was comparable to that of CK plants for Qinghai444 (Figure 3a), while height of re-grown plants after cutting at 30–40 days was significantly reduced for Bayou6 (Figure 3a). Tiller density that is closely associated with re-growth was greater in Qinghai444 than in Bayou6 for control without any cutting (Figure 3b), and cutting at 30 days of emergence did not affect the tiller density for both oat species (Figure 3b). In contrast, cutting at 40, 50, and 60 days of
emergence led to significant reductions in tilling density for both oat species, with the magnitude of reduction in Qinghai444 being greater than in Bayou6 (Figure 3b). Cutting led to a significant decrease in dry weight of re-grown plants for both oat species, and the magnitude of reduction was greater for later than early cutting for the two oat species (Figure 3c). Forage quality of the re-grown plants was also significantly changed under different cutting regimes (Figure 3d–f). Cutting at 30 and 40 days after emergence had no significant impacts on contents of crude protein (CP) in re-grown oat plants for both oat species (Figure 3d). As the cutting time extended, the CP contents in re-grown plants were significantly decreased for both oat species (Figure 3d). Cutting at 30 and 40 days after emergence did not affect NDF contents in re-grown plants of Bayou6, and cutting at 50 and 60 days after emergence led to a significant reduction in NDF contents of Bayou6 plants (Figure 3e). In contrast, cutting had no impacts on NDF contents in Qinghai444 plants across the cutting times (Figure 3e). No significant differences in ADF contents for both oat species were detected among different cuttings (Figure 3f).

Figure 3. The agronomic characters (a–c) and forage qualities (d–f) of re-growth for the two oat species Bayou6 and Qinghai444 in the full-ripe stage. * indicates significant differences \((p < 0.05)\) between Bayou6 and Qinghai444 under the same treatment. The different lowercase letters indicate significant differences among treatments for each oat species. Data are means ± SE \((n = 4)\).
3.4. Effect of Cutting on Oat Growth and Production across the Whole Growing Season

Cutting significantly increased the cumulative plant height for both oat species, and the maximal increase occurred at cutting of 50 and 40 days after emergence for Bayou6 and Qinghai444, respectively (Figure 4a). The overall cutting effect on cumulative plant height was more obvious for Qinghai444 than for Bayou6 (Figure 4a). The cumulative dry weight for the overall forage was significantly increased by cutting except at cutting of 50 days after emergence for both oat species (Figure 4b). The seed yield was not significantly changed by cutting at 30 days after emergence, and was significantly decreased by cutting at 40, 50, and 60 days after emergence for both oat species (Figure 4c). Seed yield of Bayou6 was significantly higher than that of Qinghai444, regardless of cutting (Figure 4c).

![Figure 4](https://example.com/figure4.png)

**Figure 4.** Cumulative plant height (a), total dry biomass (b), and seed yield (c) under cutting stages across whole growing season. * indicates significant differences (*p* < 0.05) between Bayou6 and Qinghai444 under the same treatment. Significant differences are shown by different lowercase letters under varying cutting stages for each cultivar at *p* < 0.05. Data are means ± SE (*n* = 4).
3.5. Effect of Cutting on Growth Dynamics of Oat Species

To explain the increase in cumulative aboveground biomass of the two oat species following cutting, we further monitored the dynamic changes in cumulative dry weight of the two oat species under different cutting regimes. The cumulative dry weight for oat Bayou6 with cutting at 30, 40, and 50 days of emergence was higher than its control without cutting at the end of growth season (Figure 5a). For oat Qinghai444, cutting at 30 and 40 days of emergence led to a higher cumulative dry weight at the end of growing season compared to the control (Figure 5c). The cutting-induced increase in cumulative dry weight may be accounted for by extension of the vegetative growth phase for both oat species (Table 4). For example, vegetative growth period was extended up to 68 ± 1 and 77 ± 2 days for Bayou6 and Qinghai444 by cutting at 30 and 40 days of emergence compared to their un-cut control, respectively (Table 4). In contrast to vegetative growth, cutting did not significantly influence reproductive growth period for both oat species (Table 4).

Figure 5. The cumulative dry weight (a,c) for the different cutting stages and the growing stages by Zadoks code (b,d) for those oats without cutting during the growing season. Data are means ± SE (n = 4).

Table 4. Effects of cutting stage on growth days for oat species of Bayou6 and Qinghai444.

| Treatments      | Oat Bayou6 | Oat Qinghai444 |
|-----------------|------------|----------------|
|                 | Vegetative Growth (days) | Reproductive Growth (days) | Whole Growth Period (days) | Vegetative Growth (days) | Reproductive Growth (days) | Whole Growth Period (days) |
| No cutting (CK) | 40 ± 1d    | 30 ± 2a        | 70 ± 2d          | 40 ± 2d       | 30 ± 2a       | 70 ± 2d       |
| 30 days cutting | 68 ± 1c    | 32 ± 1a        | 100 ± 1c         | 67 ± 2c       | 33 ± 2a       | 100 ± 2c      |
| 40 days cutting | 77 ± 2b    | 33 ± 2a        | 110 ± 2b         | 76 ± 1b       | 33 ± 1a       | 109 ± 1b      |
| 50 days cutting | 83 ± 2a    | 31 ± 2a        | 114 ± 2a         | 84 ± 2a       | 33 ± 3a       | 117 ± 2a      |

Note: The different lowercase letters indicate significant differences among treatments for each oat species.
3.6. Dry Weight of Re-Growth and Its Driving Factors

The increase in overall dry weight of oat forages by cutting was significantly and positively linearly correlated to re-grown plant height and tiller density for both oat species (all \( p < 0.0001 \), Figure 6). When all factors were considered together, plant height and tiller density can account for nearly all variation in dry weight accumulation resulting from re-growth after cutting for both oat species (both \( R^2 > 0.99 \), Figure 7).

![Figure 6. Relationships between re-growth dry weight and plant height (a) and tiller density of the two oat species (b).](image)

![Figure 7. Structural equation models (SEMs) of re-grown dry weight via plant height, tiller density. Values associated with single-headed arrows are the direct path coefficients. Values associated with double-headed arrows indicate the correlation coefficients. \*\* indicates a significant difference at \( p < 0.01 \).](image)

3.7. Effects of Cutting on Grain Harvested Index

Cutting had significant effects on grain harvested index for both oat species (Figure 8). Compared to the control, cutting at 30 days after emergence significantly increased grain harvested index, but cutting at 40 days after emergence significantly decreased grain harvested index for both oat species (Figure 8)
Figure 8. Grain harvest indexes for the two oat species (Bayou6 and Qinghai444) among varying cutting times after emergence. * indicates significant difference \((p < 0.05)\) between Bayou6 and Qinghai444 under the same treatment. Significant differences are shown by different lowercase letters under cutting stage in each oat cultivar at \(p < 0.05\). CK is control that was harvested without cutting. Data are means ± SE \((n = 4)\).

3.8. Field Demonstration for the Dual-Purpose Model

To verify the results obtained from the field trials, we also collected data from field demonstration in 2017 and 2018 in the same area as the field trials. The results showed the overall dry weight and seed yield for the two oat species under cutting at 30 days after emergence was significantly higher than their corresponding controls across the two consecutive years (Table 5). In contrast, cutting at 40 days after emergence led to significant decreases in the seed yield for the two oat species (Table 5).
Table 5. Field demonstration of the dual-purpose model for the two oat species of Bayou6 and Qinghai444.

| Species     | Year | Emergence Days | Plant Height | Tiller Density | Dry Weight | Plant Height | Tiller Density | Dry Weight | Overall Harvest |
|------------|------|----------------|--------------|----------------|------------|--------------|----------------|------------|-----------------|
|            |      | days | cm  | No. m⁻² | kg ha⁻¹ | cm  | No. m⁻² | kg ha⁻¹ | kg ha⁻¹ | kg ha⁻¹ |
| Bayou6     | 2017 | 40   | 82.4 ± 1.9 a | 738 ± 18 a | 4819 ± 158 a | 85.3 ± 1.8 c | 678 ± 12 c | 9967 ± 558 bc | 14,786 ± 784 a | 4436 ± 493 bc |
|            | 2018 | 30   | 71.1 ± 1.5 b | 726 ± 12 a | 4011 ± 147 b | 95.3 ± 1.3 b | 756 ± 18 a | 10,677 ± 347 b | 14,688 ± 487 a | 5848 ± 419 a |
|            | 2017 | 40   | 79.3 ± 1.8 a | 708 ± 18 a | 4725 ± 189 a | 83.3 ± 1.6 c | 726 ± 18 ab | 11,798 ± 445 a | 11,798 ± 698 b | 5249 ± 568 ab |
|            | 2018 | 30   | 72.1 ± 1.3 b | 720 ± 12 a | 4034 ± 166 b | 94.2 ± 1.4 b | 726 ± 18 ab | 9887 ± 466 bc | 13,930 ± 587 a | 4935 ± 387 b |
| Qinghai444 | 2017 | 40   | 73.1 ± 1.5 b | 726 ± 12 a | 4011 ± 147 b | 95.3 ± 1.3 b | 756 ± 18 a | 10,677 ± 347 b | 14,688 ± 487 a | 5848 ± 419 a |
|            | 2018 | 30   | 72.1 ± 1.3 b | 720 ± 12 a | 4034 ± 166 b | 94.2 ± 1.4 b | 726 ± 18 ab | 9887 ± 466 bc | 13,930 ± 587 a | 4935 ± 387 b |

Note: Data are means ± SE (n = 4). “–” indicates no harvesting. Different lowercase letters indicate significant differences in each column.
4. Discussion

Plant height and fresh weight in aboveground biomass for both oat species peaked at 50 days after emergence, while the maximal dry weight occurred at 70 days after emergence under our experimental conditions (Figure 1). This means that the growth in height may have stopped at the time of 50 days after emergence, and that accumulation of dry weight is accounted for by an increase in stem and spike as well as a decrease in ratio of leaf to stem [21]. In the present study, we found that dry weight of aboveground biomass for oat Bayou6 was significantly higher than that for Qinghai444 in both the field experiment and field demonstration (Figure 1c, Table 5). This difference may result from discrepancies in their agronomic characteristics associated with photosynthetic rates, and nutrient usage efficiency between the two oat species [17,22]. In addition, the differential adaptability to local climatic and edaphic conditions may also contribute to the observed differences in growth and dry weight between the two oats.

The two oat species used in the present study showed a similar dynamic change in CP across growing seasons, that is a decrease followed by an increase with the lowest value at 50–60 days of emergence (Figure 2a). This result is in contrast to previous studies on oats [10,23,24]. For example, it has been reported that CP in oats was decreased as the growing stage proceeded [10,23]. Several possible explanations may account for the difference. Firstly, the sampling time used for measuring CP differed among those studies. In the present study, CP concentrations across different developmental stages, until the full-ripe, were determined. In contrast, the sampling for CP measurements was often conducted at filling or milk stage in other studies [10,23]. Secondly, the differences in genetic diversity associated with breeding objectives, i.e., those used for grain, forage, and for both may also underpin the difference [25]. Finally, field managements including irrigation and application of fertilizers between our studies and those in the literature may also affect oat agronomic traits and qualities, thus leading to the differences in CP contents [26]. The decrease in CP during the early growth stages may result from a decrease in leaf-stem ratio [24], while the increase in maturation may result in an increase in seed weight, which in turn may contribute to the observed higher CP [12]. Therefore, the lowest CP value at 50 and 60 days after emergence may be explained by an increase in stem relative to leaf. The peak CP value was observed at 90 days after emergence (full-ripe stage) in our study. In contrast, it has been reported that the highest CP content occurred at blooming stage for oat (A. nuda cv. Bayou3) [24], and at jointing stage for four oat cultivars [10]. The difference is likely to result from no measurements of CP in maturation stage for the two studies. Furthermore, the different oat species and/or cultivars and field managements can also partly account for this difference [24,26].

The NDF and ADF in the growing stage increased rapidly and remained relatively constant across the full-ripe stage (Figure 2b,c). This result is consistent with those of previous studies [10,23]. The rapid increase in NDF and ADF during the early stages is due to an increase in dry weight of stem and stem-leaf ratio [24]. At the maturation stage, three mechanisms may underpin the constant NDF and ADF contents. Firstly, a great amount of carbohydrates would be transported to seeds at the expense of leaves and stems, leading to an increase in seed weight with a concurrent decrease in weight of leaves and stems [10,27]. Secondly, the stem/leaf ratio increased, and ADF and NDF increased in straw as the maturation progressed [24]. Thirdly, an increase in seed amount can also contribute to reductions in ADF and NDF relative to the straw [12].

One important finding in the present study is that spring-sown oats are capable of re-growing, and that the ability to re-grow decreased with delay in cutting times as evidenced by decreases in plant height, tiller density, and accumulation of aboveground biomass dry weight (Figure 3a–c, Table 5). Similar results have been reported for autumn-sown oats in different climatic regions [10,28]. Oats can re-grow again following grazing or cutting by maintaining intact apical meristems in the early growth stages [29]. In the present study, we found that plant height of re-growth reached as high as that for the un-cut plants for Qinghai444 (Figure 3a, Table 5). In contrast, plant height of re-growth was significantly lower than that of un-cut plants for Bayou6 (Figure 3a, Table 5). The reasons may be that cutting in the early stage (30 days after emergence) did not damage the apical meristems in
tillers, which confers its re-growth after cutting [2]. The stubble will re-grow quickly to compete for light, thus contributing to the growth in height [30]. The observation that the tiller density was constant at cutting at 30 days after emergence (Figure 3b, Table 5) is in line with the understanding that the tiller can continue re-growth after cutting [2]. A significant reduction in the tiller density by cutting after 40 days emergence may result from damage to apical meristems [2]. The apical meristems would be elevated as vegetative growth was delayed [31]. Previous studies have shown that re-growth ability was weakened by damage to apical meristems in oats [2]. Therefore, our results highlight the maintenance of apical meristems as an important mechanism for re-growth of spring-sown oats.

Cutting is an example of physical damage to plants, and re-growth after cutting is an important strategy for plant survival [30]. Furthermore, dry weight of regrowth aboveground biomass was decreased as the cutting time delayed (Figure 3c), which is in line with plant height and tiller density of re-growth (Figure 3a,b). Cutting at 30 to 40 days after emergence enhanced the stubble to maintain the vegetative growth compared to the control without any cutting (Figure 3c). The re-growth is likely to be determined by quickly growing of re-grown plant and constant tiller density (Figure 3a,b). Indeed, both of plant height and tiller density were positively correlated with dry weight of aboveground biomass (Figure 6). Moreover, the ability to re-grow requires a combination of several growth-related traits. These include (i) storage organs (roots, stubbles) containing reserves of carbohydrates, amino acids, and nutrients [30]; (ii) increased photosynthetic rates in residual tissues [32]; (iii) transport and utilization of the photosynthates in newly re-grown tissues [33], and (iv) photosynthesis by the newly-grown tissues [2]. Previous studies have demonstrated that oats can re-grow once proper stubble height is maintained [29]. In this study, cutting was done across the period of vegetative growth from June to July in which the most rain and the highest temperature occurred (Table 3). However, cutting 50 days and beyond after emergence significantly decreased dry weight in aboveground biomass for Qinghai444. This result may result from a significant decrease in its tiller density (Figure 3b). In addition, some molecular and physiological mechanisms associated with re-growth have been reported, but most studies have focused on perennial leguminous and poacea so far [34–36]. For example, the contents of crude protein, amino acids, and nitrate were changed with re-growth after cutting in orchard grass (Dactylis glomerata L.) [34]. The vegetative storage proteins changed in tap roots of alfalfa (Medicago sativa L) after cutting, which can be indirectly affected by changes in the source-sink relation [35,36]. Thus, the corresponding mechanisms underlying the regulation of re-growth of oats after cutting warrants further studies in the future.

Our results showed that cutting at 30 and 40 days of emergence enhanced overall dry weight of aboveground biomass for both oat species (Figure 4b, Table 5). The relatively rapid re-growth ability after cutting and extension of vegetative growth time may account for the increase in the overall dry weight (Figure 5, Table 4). Our results revealed that oats can maintain a normal growth process after cutting in the early vegetative stage (Figures 3 and 5). The agronomic characteristics associated with cutting-induced re-growth were similar with those of control without cutting, thus contributing to a large proportion of biomass dry weight for overall production across the whole growing season (Figure 3c). Similar results have been reported in many dual-purpose crops by sowing in autumn [2,9]. The extension of vegetative growth following cutting can maintain higher photosynthesis by efficient usage of natural resources, for example light, temperature, and soil water and nutrients [9]. Delay in vegetative growth by cutting can allow for oat plants to reach full growth in July with the optimal precipitation and temperature (Table 3, Figure 5). It has been reported that re-growth may result in more biomass than the un-cut control under certain favorable conditions [30]. Thus, our dual-purpose spring-sown oat model would lead to an overall higher dry weight of aboveground biomass. The model can extend the growing period from 70 days up to 120 days. This would allow oat plants efficient utilization of sunlight, water, and heat resources (Table 4). The increased growing period can not only contribute to enhanced forage production (Figure 3b), but it may also protect the environment by maximizing land cover (Table 4).
Another important finding in the present study is that cutting during early vegetative growth (30 days after emergence) did not influence seed yield relative to the un-cut control for the two oat species in both field trials and field demonstration (Figure 3c, Table 5). There are reports showing that cutting led to an increase [1], a decrease in seed yield [37], as well as no effect on seed yield [38] in autumn-sown cereal crops [2]. Three possible explanations may account for the similar seed yield between cutting at 30 days after emergence and the un-cut control in our studies. Firstly, dry weight of re-grown aboveground biomass under cutting at 30 days after emergence was significantly decreased (Figure 3b, Table 5), however, the grain harvest index was significantly increased compared to the control (Figure 8). This would offset the negative effects on dry weight of aboveground biomass. It has been reported that defoliation by grazing or cutting can change grain harvest index [31]. Secondly, the tiller density remained constant under cutting at 30 days after emergence (Figure 3b, Table 5), thus ensuring the number of spikes in the ripening. Thirdly, cutting at 30 days after emergence extended the vegetative growth in July with maximal precipitation and temperature (Tables 3 and 4). Previous studies have demonstrated that matching crop phenology to environmental conditions can positively affect grain production in cereals [2,9,39].

In contrast to cutting at 30 days after emergence, cutting at 40 days after emergence significantly reduced the seed yield in our field trials and field demonstration for the two oat species (Figure 4c, Table 5), highlighting that an optimal cutting time is critical for the dual-purpose spring-sown oat model. A similar result has also been reported for autumn-sown dual-purpose cereal crops [2,35,40]. The reduction in tiller density by cutting at 40 days after emergence may lead to damage to apical meristems [41]. Removal of apical meristems has been reported to result in loss of viable tillers and seed yield [2]. The delayed cutting will affect the yield components of the re-growth, including the number of kernels per spike, kernel size, and weight [37,38], thus leading to reductions in seed yield (Figure 8).

Based on our results, the dual-purpose patterns for oat planting can be more flexible in the second harvest period depending on the demands for oat forage and climatic features. For example, in the dry years, forage supply from natural grassland will be reduced, and more forage from artificial pasture is needed to meet the demand for animal husbandry, thus harvesting the oat forage in the second harvest is of importance. Furthermore, in the years when the frost occurs earlier, the growing season may not be long enough to ensure the seeds reach full maturity for the second harvest, harvesting of oat forage can also be a good choice. Therefore, the dual-purpose model for spring-sown oats in the cold regions of northern China can allow us to harvest either oat forages or oat cereals depending on the demands for forages and/or cereals as well as local climatic conditions.

5. Conclusions
We developed a dual-purpose model for spring-sown oats by studying the growth dynamics and re-growing mechanisms in a cold region with long winters in northern China in both field trial experiments and field demonstration across two consecutive years. Our results showed that cutting at 30 days after emergence significantly enhanced overall dry weight of aboveground biomass (forage production) without influencing seed yield and forage quality. The application of this novel model can lead to great forage supply for animal husbandry and improve the environment for sustainable development in the regions with long, cold winters.

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