A new model of two-sown regime for oat forage production in an alpine region of northern China

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Abstract
Demand for high forage production and quality has been increased markedly by development of animal husbandry in China. The lack of efficient planting regimes and key technologies greatly limits production of high-quality forage. Oat has become an important forage in animal husbandry in China due to its high nutritional value and forage yield as well as its great adaptation to harsh environment. To maximize oat forage production in an alpine region, we developed a new model of oat forage production known as two-sown regime, i.e., the first spring-sown and the second summer-sown, during a single growing season in an alpine region of Hulun Buir, Inner Mongolia Autonomous Region, China, using two early-matured oat species, Avena sativa (cv. Qinghai444, winner oat cultivar) and A. nuda (cv. Huazao2, spring oat cultivar). The key technologies and the underlying agronomic mechanisms were investigated across three experimental years of 2017–2019. The main results were as follows: (1) dry weight yield, crude protein yield, and relative feed value of forage in the two-sown regime were significantly increased by 53.6%, 48.9%, and 70.6% relative to traditional one-sown regime across the 3 years, respectively; (2) forage production was mainly achieved by an increase in plant height at the first spring-sown; and (3) forage yield resulted mainly from an increase in tiller density by increasing seeding rate under no-tillage treatment in the second summer-sown.

The key technologies of the two-sown regime were the first spring-sown at the soil thawing depth 10–13 cm, followed by the second summer-sown with increasing seeding rate under no-tillage treatment. These findings highlight that the two-sown regime of oat forage can be widely used as an effective planting regime to maximize forage production in large alpine regions of northern China as well as in regions with similar climates.

Keywords Oat (Avena Linn.) forage · Summer-sown · Cold regions · Sowing regime · Forage production

Introduction

Oat (Avena Linn.) is an important cereal crop in the world, and represents a major source of forage for livestock around the globe (Fraser and McCartney 2004; Favre et al. 2019). Oat is mostly grown in cool climate in latitudes from 35 to 65 °N (Suttie and Reynolds 2004) and in alpine regions of China (Zhou et al. 2018). In recent years, the demand of oat forage by animal husbandry has been increased markedly in China (Fang et al. 2018; Kuang et al. 2018), as evidenced by rapidly increasing import of oat forage from 0.15 × 10^4 tons in 2008 to 30.81 × 10^4 tons in 2017 (Tao et al. 2018) and expanding growth area of oat forage from 5.5 × 10^4 ha in 2008 to 10.2 × 10^4 ha in 2015 in China (Hou et al. 2019). In addition, traditional planting regime and corresponding technologies greatly limited oat forage production (Yang et al. 2019). Therefore, development of novel sowing and
harvest regimes to maximize forage production and quality is urgently needed.

Cold regions accounting for one third areas of the territory are the traditional animal husbandry base in China (Zhang et al. 2018). Their traditional agricultural systems are one crop production of late spring-sown and early autumn-harvested in the regions with frost-free period of 90–125 days, referring to as the one-sown regime (Zhou et al. 2018; An et al. 2020). Grain production requires growing period of 70–120 days, while oat forage production needs a shorter growing period of 50–80 days for the optimal harvest at growing stage ahead of grain ripening (Maloney et al. 1999; Steve 2005; Favre et al. 2019). To improve the utilization of fallow period, the two-harvest regimes of forage and grain (also known as dual purpose model), harvest for twice grains or twice forages have been developed in some cereal crops, e.g., wheat (Triticum aestivum), barley (Hordeum vulgare), rice (Oryza sativa), and oat based on one planting (Frischke et al. 2015; Lyu et al. 2018; Yang et al. 2019; Hou et al. 2021). However, few studies have focused on the two-sown regime in those regions distinguished by short-growing period in Northern China. In this context, we developed a two-sown regime of oat forage, referring to as two-sown regime in the cold regions of northern China. Briefly, the regime included the first spring-sown and the second summer-sown sowing oat in spring and harvesting in summer and thereafter sowing oat again in summer and making harvest in late autumn.

To achieve the maximal oat forage production by the two-sown regime, optimizing sowing date in spring is crucial, which determined the onset of the oat growing. It has been demonstrated that sowing in early spring can avoid less favorable conditions of high temperatures in late June to mid-July in Ohio (Gooding and Lafever 1991), keep full utilization of optimal growth in early summer in Korea (Han et al. 2018), and reduce crown rust (Puccinia coronata) infection in the Canadian prairies (May et al. 2004). In contrast, sowing in late autumn improved forage yield by minimizing summer heat and drought stress in Wisconsin (Coblentz et al. 2011). Therefore, determination of optimal sowing date needs to consider minimizing environment stress and maximizing forage production (Han et al. 2018). We thus postulate that sowing as early as possible in spring would also improve seedling growth and forage production under limited growing seasons.

Effective soil preparation and optimizing seeding rate may directly determine the output of the second sowing in summer. Previous studies have reported that no-tillage oat sowing can enhance forage production by improving soil properties of nutrients, enzymatic activities, and soil microbial C, N, P concentrations (Wang et al. 2016a, 2016b; Guo et al. 2012). In contrast, there are reports that no-tillage inhibited oat growth by increasing soil bulk density and weed density (Wang 2014; Zhang et al. 2014). We postulate that no-tillage is a better management practice in the second summer-sown for reducing cost and time, thus protecting soil from erosion. Seeding rate has also been suggested to be one of the important factors in improving oat forage production, and increasing seeding rate can enhance oat forage and grain production, especially in hot conditions (Wang 2009; Vinod et al. 2012; Zhao et al. 2016). Previous studies showed that increasing seeding rate improved forage quality due to a decrease in thickness of stem and an increase in leaf biomass (Contreras and Albrecht 2006; Xiao et al. 2017). Thus, we postulate that increasing seeding rate for the summer-sown oat would increase forage production through increasing tiller density.

In the present study, three experiments associated with the two-sown regime of oat across 3 consecutive years in a cold region of northern China were conducted. Specifically, we firstly optimized timing for the first spring-sown (Experiment 1). We then determined seeding rate in the second summer-sown (Experiment 2). We finally compared yield and quality of oat forage, resource use efficiency, and benefit between the two-sown regime and traditional one-sown regime across 3 constructive years of 2017–2019 (Experiment 3). The objectives of this study were to (1) evaluate the new two-sown model of oat forage and (2) determine the key technologies in the first spring-sown and the second summer-sown and their underling agronomic mechanisms.

Materials and methods

Study site

The experiments were conducted in Xieertala farm (49°11′-49°31′ N, 119°47′-120°18′ E, altitude 612–790 m), the key farm of Hulun Buir State Farm Conglomerate, located in Hulun Buir, Inner Mongolia, China (47°05′-53°20′ N, 115°31′-126°04′ E, altitude 200–1700 m). The frost-free period ranged from 110 to 125 days, with crop-growing season in early May to middle August. The mean annual temperature and mean annual precipitation are −1.3 °C and 348.4 mm, respectively, and the annual accumulated temperature in ≥ 0 °C and ≥ 10 °C is 2279–2647 °C and 1856–2274 °C, respectively (Hou et al. 2021). Soil type is chestnut soil. The basic soils (0–20 cm layer) were sampled prior to sowing in spring and their chemical characteristics were measured: soil pH 6.45 ± 0.23, organic matter 31.1 ± 1.0 g kg−1, total N 1.82 ± 0.12 g kg−1, inorganic N 94.6 ± 4.5 mg kg−1, available P 15.1 ± 4.5 mg kg−1, and available K 161 ± 36 mg kg−1.

The dynamic change in monthly precipitation and mean monthly temperature exhibited a single-peaked curve in growing season of Apr.–Sep. in experiment year and 30-year
mean (Fig. S1). Compared to the 30-year mean of the total precipitation (310.6 mm), year of 2018 (326.2 mm) and 2019 (295.0 mm) are normal, while year of 2017 (117.6 mm) is dry year. For each growing season, the temperature and precipitation in the early growing season (Apr. to Jun.) were lower than those in the later growing season (Jul. to Sep.) (Fig. S1).

**Experimental design**

Insufficient high-quality forage is a key limited factor in sustainable development of animal husbandry in cold regions of northern China (Zhang et al. 2018). Thus, development of novel plant and harvest regime in forage production is an effective way to solve the problems. Given the relative short duration in oat forage production, oat can quickly germinate and grow in summer sowing (See introduction; Tian and Zhang 2016; Zhou et al. 2018); we developed a two-sown regime of oat in short growing season with long cold winner in northern China (Fig. 1). In the two-sown regime, two key technologies were developed and evaluated. In the experiment 1, sowing at varying dates was conducted. In the experiment 2, the different sowing regimes were done in second summer-sown. Finally, in the third experiment, the forage yield and quality, resource use efficiency and economical income in two-sown regime were assessed compared to traditional one-sown regime in consecutive growing seasons of 2017–2019 (Table 1).

**Experiment 1: optimization of sowing date determination in the first spring sown**

Sowing in spring as early as possible can advance the start of growing season. However, the optimal sowing date may be determined by both environmental conditions and crop growing characters. In 2017, a randomized block design with four replicates was conducted to study the effect of sowing date (every 10 days from 1 Apr. to 20 May) in early-spring on oat germination and emergence, agronomic characteristics, and forage qualities in Xieertala farm. Each plot was 4 m × 5 m. The thawing depth in soil was measured (Table S1). Oat cultivar of *A. sativa* cv. Qinghai444 (abbreviated as QH444), an early-maturation cultivar widely planted as forage and grains in cold regions of northern China, was used.

![Fig. 1 The diagram of two-sown regime and one-sown regime during growing season](image)

**Table 1** Experimental design and cultivars used to develop two-sown regime of oat

| Exp. # | Design                                      | Cultivars                  | Water regime | Year   |
|-------|--------------------------------------------|----------------------------|--------------|--------|
| 1     | The optimum date of spring-sown            | *Avena sativa* cv. Qinghai444 (QH444) | Irrigated    | 2017   |
| 2     | The technology in summer-sown              | *Avena nuda* cv. Huazao2 (HZ2)     | Irrigated    | 2017   |
| 3     | Two-sown regime vs One-sown regime         | QH444 + HZ2                | Irrigated    | 2017–2019 |
used (Zhou et al. 2018). The seed germination rate of Qinghai444 was 88.5%, with 1000-grain weight 33.2 g. The soil was ploughed in the autumn of previous year with oil crop of rape (Brassica campestris). Oat seeds were sown with a row space of 15 cm, depth of 5 cm in soil, and seeding rate at 225 kg ha\(^{-1}\), and mixture base fertilizers of 42 kg N, 24 kg P, and 24 kg K per hectare were applied.

**Experiment 2: effects of soil regimes and seeding rate on forage production and quality in the second summer sowing**

Traditionally, oat was sown in the spring soils that were ploughed and raked in the previous autumn in northern China (Tian and Zhang 2016). Soil tillage was affected by weather and soil moisture, which would delay the sowing in summer, and it has been suggested that seedling rate should be increased by 20% for late planting under warm conditions (DAFF 2015). Thus, we conducted a split-plot experiment to compare the effects of soil regimes and seeding rates in summer sowing. Main plots were the soil regimes (tillage vs no-tillage) and subplots were the seeding rates (210, 225, 240 kg ha\(^{-1}\)) with subplot unit of 4 m \(\times\) 5 m for four replica-tions (Table S2). Oat cultivar of A. nuda vs. Huazao2 (HZ2), an early-maturation cultivar also widely planted as forage and grains in cold regions of northern China was used (Tian and Zhang 2016). The seed germination rate of Huazao2 was 96.5%, with 1000-grain weight 23.5 g. The oat seeds were sown with a row space of 15 cm, depth of 3 cm in soil, and mixture base fertilizers of 18 kg N, 23 kg P per hectare were applied. Previous studies indicated that shallower planting can ensure more rapid emergence and early seedling establishment (Steve 2005). We thus adopted to sow the oat seeds at 3-cm depth rather than the traditionally sowing at 5–6 cm depth in spring-sown.

**Experiment 3: comparison in forage production, resource use efficiency, and economical income between two-sown regime and one-sown regime**

On the basis of results obtained from the experiment 1 and experiment 2, the two-sown regime was demonstrated in field conditions, and the traditional one-sown regime was considered as controls. Forage yield and quality were determined. The corresponding resource use efficiency and economical income were calculated. In 2017, the data were the optimal combination of experiment 1 (sowing date of 20 April) and experiment 2 (no-tillage and seedling rate of 240 kg ha\(^{-1}\)) for the two-sown regime. In 2018 and 2019, the data were measured in fixed four experiment plots (10 m \(\times\) 10 m for each) in a large area of about 40 ha demonstration plot in the two-sown regime and one-sown regime, respectively. The details in sowing and management were shown in the Table 2.

**Measurement and calculation of indexes**

Plant height (PH) was determined with arithmetic average of measuring randomly selected ten main tillers in each plot. Tiller density (TD) was calculated as mean tiller number ([No. (m·row)\(^{-1}\)\] \(\times\) 6 (rows), as 6 rows in 1 m \(\times\) 1 m quadrat. Mean tiller number was arithmetic average of 3 sections in each plot (Yang et al. 2019).

Dry weight of aboveground biomass (DW) was determined by drying fresh weight at 80 °C for 48 h in an oven and scaled up to 1 ha. The fresh weight was cut at a 10-cm stubble height with a 1 m \(\times\) 1 m quadrat.

Crude protein concentrations (CP, %) were estimated by CP = total nitrogen \(\times\) 6.25 as described by Silva et al. (2013). Total nitrogen contents were measured by Kjeltec2200 (FossTM2200, Denmark).

NDF and ADF were determined following the protocols of Nie et al. (2009). Relative feed value (RFV) is calculated as following protocols described by Rohweder et al. (1978):

\[
RFV = \text{DDM}\% \times \text{DMI}\% \times 0.775
\]

### Table 2 Experiment 3: Sowing and management of oat in growing season of year 2017–2019

| Year | Sowing regime | The first sowing (spring-sown) | The second sowing (summer-sown) |
|------|---------------|-------------------------------|--------------------------------|
|      |               | Sowing date | Emergence date | Harvest date | Growing stage | Sowing date | Emergence date | Harvest date | Growing stage |
| 2017 | Two-sown      | 20 Apr      | 7 May          | 27 Jun       | GS68          | 30 Jun      | 7 Jul         | 12 Sep       | GS73          |
|      | One-sown      | 11 May      | 21 May         | 20 Aug       | GS92          |            |              |              |              |
| 2018 | Two-sown      | 24 Apr      | 6 May          | 24 Jun       | GS72          | 27 Jun      | 4 Jul         | 12 Sep       | GS69          |
|      | One-sown      | 11 May      | 20 May         | 29 Jul       | GS92          |            |              |              |              |
| 2019 | Two-sown      | 25 Apr      | 7 May          | 27 Jun       | GS65          | 30 Jun      | 8 Jul         | 13 Sep       | GS68          |
|      | One-sown      | 12 May      | 24 May         | 23 Aug       | GS92          |            |              |              |              |
where DDM is digestible dry matter expressed by % of dry matter and DMI is dry matter intake expressed by % of animal body weight (Hu et al. 2019) (St. Luce et al. 2020).

**Data statistical analysis**

Firstly, all data were tested for normality and homogeneity prior to statistical analysis and thereafter were log-transformed when necessary. One-way ANOVA was used to evaluate the effects of sowing date on measured and calculated indexes in the first sown of the two-sown regime (Exp. 1). The data collected in the second-sown were analyzed by a general linear model with different soil regimes and seeding rates as fixed factors and the field blocks (n = 4) as random factors (Exp. 2). Two-way ANOVA was used to evaluate the effects of year (2017–2019) and sown regime (two-sown regime, one-sown regime) on forage production and quality, resource use efficiency index, and economic indexes.

\[
\text{DDM} = 88.9 - (0.77 \times \text{ADF})
\]

\[
\text{DMI} = \left(\frac{120}{\text{NDF}}\right)
\]

Crude protein yield (CP yield, \(\text{tha}^{-1}\)) = \(\text{CP} \times \text{DW yield (tha}^{-1}\))

Relative feed value yield (RFV yield, \(\text{tha}^{-1}\)) = \(\text{RFV} \times \text{DW yield (tha}^{-1}\))

Oat growing days = the harvest date – the emergence date

Water use efficiency (WUE, kg mm\(^{-1}\)) = \(\frac{\text{DW yield}}{\text{Precipitation + irrigation}}\)

N fertilizer use efficiency (FUE, kg kg\(^{-1}\)) = \(\frac{\text{CP yield (kg ha}^{-1}\)}{\text{Fertilizer N application (kg ha}^{-1}\)}\)

Gross income (US$ ha\(^{-1}\)) = \(\text{Forage price (US$ t}^{-1}\) \times \text{DW yield (tha}^{-1}\)

\[
\text{Gross cost (US$ ha}^{-1}\) = \text{Cost of seed + Fertilizer + mechanical operation (Rotary tillage prior to the first spring sown, sowing, irrigation, cutting and harvesting, transport, depreciation of machinery)}
\]

\[
\text{Net income (US$ ha}^{-1}\) = \text{Gross income} - \text{Gross cost}
\]

Increased percentage of Indexes of two-sown regime over one-sown regime (IP, %) = \(\frac{(\text{Indexes of two-sown regime} - \text{Indexes of one-sown regime})}{(\text{Indexes of one-sown regime})} \times 100\)

where the Indexes include dry weight yield, crude protein yield, relative feed value yield, growing days, water use efficiency, N fertilizer use efficiency, gross income, and net income.

In the first spring sowing, the Z-score was used to compare the change trend in agronomic characteristics (PH, TD), forage qualities (CP, NDF, ADF, RFV), and yields (DW yield, CP yield, RFV yield) under different sowing date treatments. The Z-score is the number of standard deviations a given data point lies from the mean. Z-score was calculated as:

\[
Z - \text{score} = \frac{(x - \mu)}{\sigma}
\]

where \(x\) is measured value (original value), \(\mu\) is the mean of all data in each index, and \(\sigma\) is the standard deviation of all data in each index.
Results

Experiment 1: effects of sowing date on forage yield and quality of the first spring-sown

Except tiller density \((P = 0.939)\), sowing date had significant effects on all indexes of agronomic characters, forage qualities and yields in first spring-sown (Table 3, all \(P < 0.001\)). The highest values for dry weight yield, crude protein yield, and relative feed value yield were observed for those sowing date at 10–30 April, 20–30 April, and 20–30 April, respectively (Table 3). The Z-score results showed that sowing at 20–30 April had higher yield in dry weight, crude protein, and relative feed value with the corresponding thawing depth of soil at 10–13 cm (Fig. 2a). As sowing date delayed, similar to the three yield indexes, the dynamic change in plant height showed a unimodal curve, while the forage quality-related indexes including crude protein and relative feed value decreased, but increases in NDF and ADF were detected (Fig. 2b-c).

The three yield indexes were significantly correlated to plant height (all \(P < 0.01\)), while no significant correlation between the indexes and tiller density was detected (Fig. 3a, all \(P > 0.05\)). SEM model revealed that sowing at early dates enhanced dry weight yield \((R^2 = 0.890)\) by increasing plant height \((R^2 = 0.774)\) and increased relative feed value yield \((R^2 = 0.984)\) by increasing dry weight yield and relative feed value \((R^2 = 0.962)\) (Fig. 3b). Though earlier sowing significantly increased crude protein \((R^2 = 0.953)\), the crude protein yield was not linearly correlated to the change in crude protein (Fig. 3b).

### Table 3

Experiment 1: Agronomic characters, forage quality and yield among different spring-sown date in 2017. PH plant height, TD tiller density, CP crude protein, NDF neutral detergent fiber, ADF acid detergent fiber, RFV relative feed value

| Sown date | Agronomic characteristics | Forage qualities | Yields |
|-----------|---------------------------|------------------|--------|
|           | PH (cm)                   | TD (No./m²)     | CP (%) | NDF (%) | ADF (%) | RFV | DW yield (t ha⁻¹) | CP yield (t ha⁻¹) | RFV yield (ha⁻¹) |
| 1 Apr     | 100±2b                    | 698±17a         | 10.8±0.3d | 56.3±0.6a | 32.9±0.9a | 105±0e | 8.84±0.15b | 0.95±0.03c | 924±16c |
| 10 Apr    | 104±2ab                   | 702±8a          | 11.0±0.3d | 55.8±0.7a | 31.6±0.9b | 107±1e  | 9.72±0.23a | 1.07±0.06b | 1042±27b |
| 20 Apr    | 105±4a                    | 701±17a         | 11.6±0.3c | 53.1±0.9b | 31.1±0.6b | 113±2d  | 9.87±0.34a | 1.14±0.06a | 1118±44a |
| 30 Apr    | 101±3ab                   | 695±6a          | 11.9±0.3c | 51.4±0.8c | 28.9±0.3c | 120±2c  | 9.56±0.24a | 1.13±0.03a | 1148±24a |
| 10 May    | 90±2c                     | 698±10a         | 13.2±0.1b | 48.3±0.7d | 26.4±0.3d | 132±2b  | 7.86±0.25c | 1.04±0.03b | 1034±33b |
| 20 May    | 85±2d                     | 696±5a          | 14.4±0.2a | 45.1±0.7c | 23.7±1.0c | 145±3a  | 6.39±0.12d | 0.92±0.03a | 929±13c  |
| F value   | 38.38                      | 0.24            | 134.27   | 111.06   | 18.59     | 135.03  | 93.62     | 231.14    | 43.40    |
| P value   | <0.001                     | 0.939           | <0.001   | <0.001   | <0.001   | <0.001  | <0.001   | <0.001    | <0.001   |
| Sig       | **                         | ns              | **       | **       | **       | **      | **       | **        | **       |

Data are means ± standard deviation \((n = 4)\). Different lowercase letters indicate significantly differences in each column, respectively.

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Fig. 2 Experiment 1: the dynamic change in forage yields, qualities and agronomic characteristics of spring sown oat
Experiment 2: effects of soil regimes and seeding rate on forage yield and quality of summer-sown oat

Soil regimes had no significant effects on all those of agronomic characters, forage quality, and yield indexes (Table S3, all $P > 0.05$). In contrast, seeding rate had significant effects on tiller density, NDF, relative feed value, dry weight yield, crude protein yield, and relative feed value yield (Table S3, all $P < 0.05$). Seeding rate at 240 kg ha$^{-1}$ had significantly higher tiller density, relative feed value, dry weight yield, crude protein yield, and relative feed value yield, but it had significantly lower NDF than at those other seeding rates (Table 4).

All the three yield indexes were positively correlated to tiller density (Fig. 4a, all $P < 0.01$). Crude protein was significantly correlated to crude protein yield ($r = 0.60$, $P < 0.01$). Relative feed value had significant relationship with relative feed value yield ($r = 0.71$, $P < 0.01$). SEM model indicated that high seedling rate increased dry weight yield ($R^2 = 0.530$) by increasing tiller density ($R^2 = 0.425$), increased relative feed value yield ($R^2 = 1.000$) by increasing

![Diagram](image-url)

Fig. 3 Experiment 1: Pearson correlation coefficients (a) and structural equation models (b) among indexes of agronomic characters, forage quality and yield under spring-sown (n = 24). Values associated with single-headed arrows are the direct path coefficients. * and ** indicate significant difference at $P < 0.05$ and $P < 0.01$, respectively. PH plant height, TD tiller density, CP crude protein, NDF neutral detergent fiber ADF acid detergent fiber, RFV relative feed value

Table 4 Experiment 2: Comparison of mean agronomic characteristics, forage quality and yield under soil regimes and seeding rates in summer-sown in 2017

| Treatments | Agronomic characteristics | Forage qualities | Yields |
|------------|---------------------------|-----------------|--------|
|            | PH (cm)                   | TD (No./m²)     | CP (%) | NDF (%) | ADF (%) | RFV | DW yield (t ha$^{-1}$) | CP yield (t ha$^{-1}$) | RFV yield (ha$^{-1}$) |
| Soil regimes |                            |                 |        |         |         |     |                   |                    |                     |
| No-tillage | 84 ± 1a                    | 473 ± 15a       | 11.1 ± 0.2a | 54.8 ± 0.9a | 32.2 ± 0.4a | 108 ± 2a | 6.70 ± 0.37a | 0.75 ± 0.05a | 726 ± 49a |
| Tillage    | 84 ± 2a                    | 467 ± 12a       | 11.2 ± 0.2a | 54.6 ± 0.4a | 31.9 ± 0.4a | 109 ± 1a | 6.66 ± 0.19a | 0.75 ± 0.02a | 727 ± 24a |
| Seeding rates |                      |                 |        |         |         |     |                   |                    |                     |
| 210 kg/ha  | 85 ± 2a                    | 460 ± 11b       | 11.1 ± 0.2b | 54.9 ± 0.7a | 32.2 ± 0.4a | 108 ± 1b | 6.41 ± 0.21c | 0.71 ± 0.03c | 694 ± 29c |
| 225 kg/ha  | 84 ± 2a                    | 469 ± 10b       | 11.1 ± 0.2ab | 55.0 ± 0.5a | 32.0 ± 0.5a | 108 ± 2b | 6.68 ± 0.13b | 0.74 ± 0.02b | 723 ± 18b |
| 240 kg/ha  | 84 ± 2a                    | 481 ± 11a       | 11.3 ± 0.1a | 54.2 ± 0.7b | 31.9 ± 0.3a | 110 ± 1a | 6.95 ± 0.21a | 0.78 ± 0.03a | 764 ± 26a |

Data are means ± standard deviation (n = 12 for soil regime, n = 8 for seeding rate). PH plant height, TD tiller density, CP crude protein, NDF neutral detergent fiber, ADF acid detergent fiber, RFV relative feed value. Different lowercase letters indicate significantly differences at $p < 0.05$ in each column under soil regime or seeding rate, respectively.

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dry weight yield and relative feed value ($R^2=0.212$). An increase in seeding rate led to increased crude protein ($R^2=0.242$) by increasing tiller density (Fig. 4b).

**Experiment 3: the yield, resource use efficiency, and profits in the two-sown regime**

Compared to one-sown regime, dry weigh yield, crude protein yield and relative feed value yield were significantly increased by 46.8–66.4%, 37.1–66.3%, and 63.4–87.6% in the two-sown regime across three consecutive years of 2017–2019, respectively (Table 5).

Year, sowing regime, and their interaction all had significant effects on water use efficiency and N fertilizer use efficiency (Table 5, all $P<0.001$). Compared to one-sown regime, oat growing days were increased by 29.7–65.3%, water use efficiency was increased by 2.2–35.6%, and N fertilizer use efficiency was increased by $-4.1$ to $16.4\%$ in two-sown regime across year of 2017–2019, respectively (Table 5).

Two-way ANOVA showed that year, sowing regimes had significant effects on gross income and net income (Table 5, all $P<0.001$). Compared to one-sown regime, gross income was increased by $57.0$–$78.1\%$ and net income was increased by $48.0$–$73.7\%$ in two-sown regime across experiment year of 2017–2019, respectively (Table 5).

**Discussion**

**Oat forage yield and its driving factors in the first spring-sown of two-sown regime**

Our results demonstrated that spring-sown oat at thawing depth of 10–13 cm soil was an optimal condition for higher dry weight yield, crude protein yield and relative feed value yield in the first spring-sown of the two-sown regime (Table 3 and Fig. 2a). The optimal sowing date is dependent on harvest objective (grain or forage), utilization of limited natural resource (short growing stage, light, temperature, precipitation in rain-fed regions), and environmental factors (cool temperature, hot, drought environment) (Jehangir et al. 2013; Huang et al. 2020; Vitantonio-Mazzini et al. 2020). In the present study, spring-sown date at soil thawing 10–13 cm depth may maximize utilization of temperature and light compared with later sowing regime and prevent oat germination and emergence from environmental stresses (Fig. 1, Table S1). When soil thawing depth was less than 10 cm, the alternation of freezing–thawing by temperature fluctuation would damage the germinated oat seeds in soil layer of 5–6 cm, thus imposing negative effects on the subsequent growth.

Plant height was the main driving factor in dry weight yield in the first spring-sown (Fig. 3b). This result is consistent with previous studies that plant height was the main drivers of oat forage in limited growing duration of autumn-sown in Northern Arkansas (Gunsaulis et al. 2008). In the oat plant development progresses, dry weight significantly
increased with increasing plant height, especially in stem elongating stage (Irfan et al. 2016), meaning that early-matured cultivars with taller canopy should be chosen under insufficient growing days (Coblentz et al. 2011).

No-tillage and higher seeding rate increasing oat forage yield in the second summer-sown

Summer-sown would ensure oat germination, emergence, joint, stem elongation booting, and head by extending the growing season (Fig. 1, Table S2), which is in line with previous studies that oat sown in summer and autumn could joint, elongation and head, compared to other cereal crops (e.g., wheat and rye) that often failed to stem elongation (Gunsaulis et al. 2008; Coblentz and Walgenbach 2010; Coblentz and Bertram 2012). Similar to other cereal crops, oat is also a long-day plant, requiring at least 12 h of daylight to flower and head development (Steve 2005; Coblentz and Walgenbach 2010). However, compared to other cereals, oat was shorter season in growth period with low accumulative temperature (May et al. 2004) and grew quickly in the vegetative growth, which can ensure stem elongation in summer-sown and autumn-sown with limited cumulative temperature and short growing season (Steve 2005; Gunsaulis et al. 2008; Coblentz and Walgenbach 2010). The characteristics of stem elongation, flowering, and heading in summer-sown oat can produce significantly higher dry weight of aboveground biomass relative to those cereals failed to stem elongation (Coblentz and Bertram 2012). As shown in our results, the summer-sown regime was an effective method in harvesting higher forage production and quality of oat (Table 4).

Our findings showed that no-tillage had no significant effect on the oat indexes in agronomy, quality, and yield under synchronous summer-sown, compared to the tillage sowing (Table 4). The positive effects of no-tillage include reducing cost and saving time, protecting soil by stubble remaining from previous crop and diminishing disturbance (Page et al. 2006), and suppressing weed by allelopathic compounds (Valenzuela and Smith 2002). Previous studies reported that no-tillage planting increased soil moisture (Page et al. 2006; Hao 2015; Wang et al. 2016c), availabilities of nutrients in soils (Wang et al. 2016a), enzymatic activities in soils (Wang et al. 2016b), and soil microbial C, N, and P concentrations (Guo et al. 2012), thus benefiting oat germination, emergence, and subsequent seedling growth. The negative effects of no-tillage include increased soil bulk density and weed density, which may mainly result from long-term no-tillage (exceeding 3 years), especially in dry rain-fed areas (Wang 2014; Zhang et al. 2014). In the two-sown regime, soil was ploughed in previous autumn, and no-tillage treatment only occurred in the summer-sown as well as irrigation management (see methods). It has been reported that early autumn-sown produced more forage by

### Table 5: Effects of sowing regimes on dry weight (DW) yield, crude protein (CP) yield, relative feed value (RFV) yield, growing days, water use efficiency (WUE), N fertilizer use efficiency (FUE), gross income (GI) and Net income (NI) across three growing seasons of 2017–2019

| Year Sown | DW yield kg ha⁻¹ IP % | CP yield kg ha⁻¹ IP % | RFV yield kg ha⁻¹ IP % | Growing Days IP % | WUE kg mm⁻¹ IP % | FUE kg kg⁻¹ IP % | GI US$ ha⁻¹ IP % | NI US$ ha⁻¹ IP % |
|-----------|------------------------|------------------------|------------------------|-------------------|------------------|------------------|-----------------|-----------------|
| 2017 Two  | 16.98a                 | 46.8                   | 1.94a                  | 23.7              | 1900a            | -4.1             | 36.4            | 32.4            |
| One       | 11.57c                 | 4.12                   | 1163c                  | 91                | 63.4             | 63.4             | 1718            | 1420            |
| 2018 Two  | 14.79b                 | 47.5                   | 43.4                   | 1034d             | 87.6             | 35.6             | 24.4            | 28.3            |
| One       | 10.02d                 | 37.1                   | 3.62                   | 663b              | 65.3             | 65.3             | 1300F           | 2774b           |
| 2019 Two  | 14.30b                 | 66.4                   | 1.70b                  | 632b              | 87.6             | 35.6             | 24.4            | 28.3            |
| One       | 8.59e                  | 1.18                   | 870e                   | 72                | 40.9c            | 40.9c            | 33.00d          | 1839c           |

P value

- Year (Y) < 0.001
- Sown (S) < 0.001
- Y × S 0.057

Data are means (n = 4). Different lowercase letters indicate significantly differences in each column, respectively. IP, increase percentage.
increase stem elongation and subsequent growth relative to late autumn-sown (Coblentz and Bertram 2012; Dar et al. 2014). Therefore, we can conclude that no-tillage summer-sown can improve forage production by extending oat growing time and decrease cost.

As seeding rate was increased from 210 kg ha$^{-1}$ to 240 kg ha$^{-1}$, the dry weight yield, crude protein yield, and relative feed value yield all reached peak values (Table 4), suggesting that increasing seeding rate benefits forage yield and quality in summer-sown oat, thus strengthening previous results that increasing seeding rate can lead to higher production of forage yield (DAFF 2015; Zhao et al. 2016). High seeding rates promoted aboveground biomass by increasing tiller density (Fig. 4b; Ayub et al. 2011; Vinod 2012). Under hot conditions in summer, oat contributed less to tillering and quickly growth in height (Gooding and Lafever 1991). Furthermore, increasing seeding rate also contributed to increase in crude protein through enhancing tiller density and relative feed value of forage (Table 4; Fig. 4b), thus leading to reduction in the thickness of stems and leaf to stem ratio (DAFF 2015; Xiao et al. 2017). Therefore, the mechanisms underlying the high seeding rate-induced improving yield and quality in summer-sown may be accounted for by increasing tiller density and crude protein and relative feed value through decreasing thickness of stem.

**The significance in the two-sown regime over one-sown regime**

In cold regions of northern China, a significant increase in oat forage yield and quality in the two-sown regime can meet the demand of sustainable development of animal husbandry (Table 5; Fang et al. 2018; Zhang et al. 2018). Furthermore, the oat forage harvested in summer by the two-sown regime can have additional benefits to the local animal husbandry as the forage harvested in the previous autumn would be run out and the maximal forage production from the natural grasslands has not occurred in summer yet (Fang et al. 2018). The supply of oat forage in summer can also make less dependence of local animal husbandry on natural grasslands, thus protecting the grasslands from degradation (Kuang et al. 2018). In addition, the increases in plant growing days, water, and nitrogen use efficiency can enhance utilization of resources and prevent soils from erosion (Fig. 1; Table 5; Valenzuela and Smith 2002; Gunsaulis et al. 2008; Coblentz and Bertram 2012; Vinod 2012).

**Conclusions**

We developed a two-sown regime for oat forage production in a cold region with long winter of northern China. The key technologies of the two-sown regime for oat forage include sowing time at soil thawed depth 10–13 cm in the first spring-sown and increasing seeding rate under no-tillage treatment in the second summer-sown. Compared to traditional one-sown regime, oat forage yield and quality were significantly increased in the two-sown regime. The benefits of the two-sown regime were extending plant growing days, enhancing utilization of resources, and increasing net income. Therefore, the two-sown regime of oat forage can be widely used in alpine regions of northern China as well as other regions with similar climates.

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**Data availability** The datasets used and/or analyzed during the study are available from the corresponding author on reasonable request.

**Declarations**

**Ethics approval and consent to participate** No applicable.

**Consent for publication** No applicable.

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**References**

An P, Chen S, Meng L, Jiang L (2020) Determination of standard farming system in cultivated land classification of the third national land survey. J China Agric Univ 25:61–72. https://doi.org/10.11841/j.issn.1007-4333.2020.08.07 (in Chinese with English abstract)

Ayub M, Shehzad M, Nadeem M, Perven M, Muhammad N, Sarwar N (2011) Comparative study on forage yield and quality of different oat (Avena sativa L.) varieties under agroecological conditions of Faisalabad. Pakistan Afr J Agr Res 06:3388–3391. https://doi.org/10.5897/AJAR11.411

Coblentz W, Walgenbach R (2010) Fall growth, nutritive value, and estimation of total digestible nutrients for cereal-grain forages in the north-central United States. J Anim Sci 88:383–399. https://doi.org/10.2527/jas.2009-2224

Coblentz W, Bertram M, Martin NP (2011) Planting date effects on fall forage production of oat cultivars in Wisconsin. Agron J 103:145–155. https://doi.org/10.2134/agronj2010.0350
Vitantonio-Mazzini L, Borrás L, Garibaldi L, Pérez D, Gambin B (2020) Management options for reducing maize yield gaps in contrasting sowing dates. Field Crop Res 251:107779. https://doi.org/10.1016/j.fcr.2020.107779

Wang L (2009) Effect of different cultivating methods on growth and yield of oat. Inner Mongolia Agricultural University, Huhhot, China (in Chinese with English abstract)

Wang Y (2014) The influence of tillage methods on naked oats growth and soil properties in cold and arid regions of north Hebei. Hebei Agricultural University, Baoding (in Chinese with English abstract)

Wang R, Liu J, Zhang Z, Liu H (2016a) Effects of No-tillage with different mulching methods on soil water and temperature in rainfed oats field. J Irrig Drain 35:69–73. https://doi.org/10.13522/j.cnki.ggpps.2016.11.013 (in Chinese with English abstract)

Wang R, Zhang Z, Liu J, Liu H, Liu J, Wu J (2016b) Effects of No-tillage with mulching on soil nutrient content and microbial biomass in oat field. J Soil Water Conserv 30:183–193. https://doi.org/10.13870/j.cnki.stbcxb.2016.04.031 (in Chinese with English abstract)

Wang R, Zhang Z, Liu J, Liu H, Zhao B (2016c) Effects of No-tillage with stubble mulch on soil nutrients, soil enzyme activities and oat yield. Crops 31:134–138. https://doi.org/10.16035/j.issn.1001-7283.2016.03.025 (in Chinese with English abstract)

Xiao X, Zhou Q, Chen Y, Du Z, Bai X, Tian L, Peng X (2017) Effect of seedling rate on production performance and photosynthetic characteristics of Avena sativa cv. LINA in alpine pastoral regions. Pratacul Sci 34:761–771. https://doi.org/10.11829/j.issn.1001-0629.2016-0364 (in Chinese with English abstract)

Yang J, Hou L, Bai W, Yan J, Hao J, Tao J, Luo Y, Zhang J, Zhang W (2019) A Dual-purpose model for spring-sown oats in cold regions of Northern China. Agronomy 9:721. https://doi.org/10.3390/agronomy9110721

Zhang L, Zhang L, Wu D, Zhang J (2014) Effect of tillage patterns on the structure of weed communities in oat fields in the cold and arid region of North China. Ying yong sheng tai xue bao = J Appl Ecol 25:1725–1732. https://doi.org/10.13287/j.1001-9332.20140415.005 (in Chinese with English abstract)

Zhang W, Hou L, Yang J, Song S, Mao X, Zhang Q, Bai W, Pan Q, Zhou Q (2018) Establishment and management of alfalfa pasture in cold regions of China. Chin Sci Bull 63:1651–1663. https://doi.org/10.1360/N972017-01181 (in Chinese with English abstract)

Zhao H, Ma Z, Zhang C, Lei Z, Yao B, Zhou H (2016) The reproductive allocation of Arena sativa under different planting densities and nitrogen addition treatments. Pratacul Sci 33:249–258. https://doi.org/10.11829/j.issn.1001-0629.2015-0361 (in Chinese with English abstract)

Zhou Q, Gou X, Tian L, Chen Y, Gao S, Bai W, Zhang W (2018) Performances of early and late maturing oat varieties in cold regions. Chin Sci Bull 63:1722–1730. https://doi.org/10.1360/N972018-00343 (in Chinese with English abstract)

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