Simulation Study on Wind Field Structure and Windbreak Efficiency of Double-Row Cyperus esculentus Belts at Different Harvest Intervals (Postprint)

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Abstract

Cyperus esculentus possesses a well-developed root system and demonstrates great potential as a windbreak and sand fixation crop. Investigating the windbreak and sand fixation benefits of Cyperus esculentus strips under different strip harvesting patterns is of great significance for the rational utilization of this crop for windbreak and sand fixation purposes. Using wind tunnel simulation, wind speeds at different positions in the wind tunnel were measured for three different Cyperus esculentus harvesting models—harvesting one strip after leaving one strip (H1), harvesting two strips after leaving one strip (H2), and harvesting three strips after leaving one strip (H3)—under three wind speeds of 6 m·s-1, 8 m·s-1, and 10 m·s-1, and the flow field characteristics, wind speed acceleration rates, and windbreak efficiencies of the different models were analyzed. The results showed that: (1) In all three Cyperus esculentus harvesting models, airflow was blocked by the Cyperus esculentus models near the bed surface, wind speed was sharply reduced, forming wind shadow zones of certain areas, and both the flow field structural stability and wind shadow zone area of H2 and H3 models were greater than those of the H1 model. (2) With increasing wind speed, the windbreak efficiency of all models decreased. The average windbreak efficiency on the leeward side of H2 and H3 models under different wind speeds showed no significant difference, but was significantly greater than that of the H1 model. Within the harvesting intervals, the windbreak efficiency of both H2 and H3 models was >50%, while that of the H1 model was <40%. (3) From the perspective of windbreak and sand fixation benefits and flow field stability, there was no significant difference between H2 and H3 models, and both were significantly greater than the H1 model. However, from the economic perspective, the harvesting interval of the H2 model decreased, resulting in reduced economic benefits. Considering both the ecological benefits of windbreak and

sand fixation and the economic benefits of Cyperus esculentus production, the H3 model is the recommended harvesting method. This study, by investigating the windbreak and sand fixation benefits of different Cyperus esculentus harvesting patterns, provides guidance for utilizing Cyperus esculentus for windbreak and sand fixation, and offers a theoretical basis for promoting the cultivation of Cyperus esculentus in arid and semi-arid regions to achieve greater ecological and economic benefits.

Full Text

Wind Flow Field Structure and Windbreak Efficiency Simulation of Double-Row Cyperus esculentus Belts with Different Harvest Intervals

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Abstract

Cyperus esculentus, with its well-developed root system, has great potential as a windbreak and sand-fixation crop. Investigating the windbreak and sand-fixation benefits of Cyperus esculentus belts under different strip-harvesting patterns is crucial for the rational utilization of this crop for wind erosion control. Using wind tunnel simulation, we analyzed the flow field characteristics, wind speed acceleration rate, and windbreak efficiency of three harvest models—harvest one belt and skip one belt (H1), harvest two belts and skip one belt (H2), and harvest three belts and skip one belt (H3)—under three wind speeds (6 m·s^{-1}, 8 m·s^{-1}, and 10 m·s^{-1}). The results showed that: (1) In all three models, airflow was blocked near the bed surface, causing sharp wind speed reduction and formation of wind shadow areas. The flow field stability and wind shadow areas of H2 and H3 exceeded those of H1. (2) As wind speed increased, windbreak efficiency decreased. The leeward-side efficiency of H2 and H3 was significantly greater than H1, with no significant difference between H2 and H3. Within harvest spacing, H2 and H3 efficiency exceeded 50%, while H1 was below 40%. (3) H2 and H3 showed no significant difference in windbreak/sand-fixation benefits, both outperforming H1. However, H2' s smaller harvest spacing reduces economic benefits. Considering both ecological and economic benefits, H3 is recommended as the optimal harvesting method. This study provides guidance for using Cyperus esculentus for windbreak and sand fixation and offers a theoretical basis for promoting its cultivation in arid and semi-arid regions to achieve greater ecological and economic benefits.

Keywords: harvest spacing; wind tunnel simulation; flow field structure; wind speed acceleration rate; windbreak efficiency

Introduction

China is one of the countries most severely affected by soil wind erosion and desertification [1], with rain-fed farmland being the most seriously impacted, which severely restricts economic and social development in western China [2]. Planting Cyperus esculentus in areas with severe wind erosion and desertification in northern China can not only effectively control soil wind erosion but also generate considerable economic income for local communities, promoting ecological improvement and socio-economic development.

Selecting a crop that is both adapted to sandy and drought conditions and can generate economic benefits is crucial for effectively utilizing desertified lands in the arid and semi-arid regions of western China, increasing local farmers' income, and improving ecological and economic benefits. Cyperus esculentus, a perennial herb of the family Cyperaceae native to Africa (grown as an annual crop), has a well-developed root system and strong tillering ability. It can adapt well to harsh environments in arid and semi-arid regions, its tubers can be pressed for oil and processed into food, and its aboveground stems and leaves can serve as high-quality animal feed, making it an eco-economic plant with both economic and ecological functions [3-5]. Generally, higher vegetation coverage leads to better windbreak and sand-fixation effects [6]. Previous studies have also shown that vegetation coverage below 30% cannot fully achieve windbreak and sand-fixation functions [7]. For eco-economic crops like Cyperus esculentus, it is necessary to obtain both ecological benefits from windbreak and sand fixation and corresponding economic benefits. After maturity, harvesting is required, which reduces vegetation coverage. However, the harvesting process inevitably causes some soil disturbance and reduces coverage, weakening the protective function of vegetation [8]. Strip-harvesting patterns can maximize both windbreak and sand-fixation benefits and Cyperus esculentus yield, making the determination of appropriate strip harvest spacing fundamental for obtaining ecological and economic benefits from this crop.

Generally, the smaller the interval between protection belts, the stronger the wind-sand protection effect [9]. For example, Yan Min et al. [10] studied the windbreak efficiency of Caragana korshinskii shelterbelts at different spacing intervals and found that the windbreak efficiency ranking was 4 m > 6 m > 8 m. However, other studies have shown that for different sand-blocking materials and models, models with smaller spacing did not achieve the maximum sand-blocking amount. For instance, Kang Xiangguang et al. [11] studied the windbreak effect of four different spacing intervals of sand-blocking nets using the net height H as the basic unit, finding that the 15H spacing yielded the maximum sand-blocking amount, while the 4H spacing yielded the minimum. Therefore, spacing has different effects on the windbreak and sand-fixation efficiency of different material models. However, current research on the effects of different strip-harvesting configurations on windbreak and sand-blocking efficiency has mainly focused on shelterbelts and nylon net sand barriers [10-11,13], with few studies on the windbreak efficiency of farmland plant belts with different harvest spacing configurations. This makes it difficult to provide scientific basis for obtaining greater ecological and economic benefits from strip-planting of Cyperus esculentus in arid and semi-arid regions.

For crops, although reducing harvest intervals increases vegetation coverage, it decreases economic benefits and fails to motivate farmers' planting willingness. Conversely, excessively large harvest intervals reduce the ecological benefits of windbreak and sand fixation. Therefore, studying the optimal strip-harvesting interval configuration pattern for Cyperus esculentus is important for reducing farmland wind erosion, obtaining greater yield, and reducing costs in arid regions. This study used strip-shaped Cyperus esculentus models and wind tunnel simulation experiments to measure wind speed changes and windbreak efficiency at the windward side, within the belt, and at the leeward side of Cyperus esculentus belts with different harvest spacing, aiming to elucidate the strip-harvesting spacing that can achieve maximum windbreak efficiency and economic benefits, and to provide theoretical basis for using Cyperus esculentus cultivation for windbreak and sand fixation and increasing farmers' economic income.

1 Materials and Methods

1.1 Experimental Equipment

The wind tunnel experiment was conducted at the Mosuowan Environmental Wind Tunnel Laboratory of the Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences. The wind tunnel is a direct-current open-circuit type with a total length of 16.2 m, an experimental section length of 1.0 m, and a cross-section of 1.3 m × 1.0 m. The adjustable experimental wind speed range is 0.5–20 m·s^{-1}. The experimental models were made of flexible simulated tall grass belts, with individual Cyperus esculentus model height of 7 cm and a scale ratio of 1:12.5 to field-grown plants. In actual field planting, the plant spacing is 8 cm and row spacing is 30 cm. To maximize simulation of field conditions, a three-row belt configuration was established with a belt spacing of 20 cm. Three different harvest pattern models of Cyperus esculentus were set up for wind tunnel experiments: harvest one belt and skip one belt (H1), harvest two belts and skip one belt (H2), and harvest three belts and skip one belt (H3).

1.2 Experimental Design

This experiment was conducted at three wind speeds: 6 m · s^{-1}, 8 m · s^{-1}, and 10 m · s^{-1}. Wind speeds were measured at the windward side, at the midpoint within the Cyperus esculentus belt, and at the leeward side at three heights in the vertical longitudinal profile of the wind tunnel: 10 cm, 15 cm, and 50 cm. The measurement points on the windward side were designated as negative values, while those within the belt and on the leeward side were positive. The corresponding measurement points were also expressed as multiples of the Cyperus esculentus model height. The specific measurement point locations and wind direction are shown in [Figure 1: see original paper]. The horizontal axis in the figure indicates the transverse coordinates of measurement points on the bed surface, with the pitot tube placed at the middle position of the bed surface during measurement. The 0 cm point marks the starting position of the Cyperus esculentus belt, with the model windward side located before the belt and the leeward side located after the second belt. In addition to measurement points set before and after the belt, midpoint measurements within the belt were also established to more accurately measure the effect of the belt on airflow (Figure 1). During measurement, different models and their spacing intervals were treated as an integrated unit. To measure windbreak efficiency and protection distance changes at equal distances before and after the model, the distance before the windward side was maintained at 72 cm and the distance behind the leeward side at 24 cm. Wind speed was measured using a micro-pressure sensor, with the pitot tube moved to each measurement point and held for 5 minutes.

1.3 Calculation Methods

1.3.1 Wind Speed Acceleration Rate The wind speed acceleration rate is a commonly used parameter representing the degree of airflow enhancement or reduction, which can effectively show the model’ s influence on airflow. When the wind speed acceleration rate > 1, it indicates that the Cyperus esculentus model accelerates airflow; when < 1, it indicates deceleration; and when $= 1$, it indicates no effect on airflow [9,17,20]. It is calculated as follows:

$$a_{klh} = \frac{v_{klh}}{v_{kh}}$$

where a_{klh} is the wind speed acceleration rate; k is the wind speed magnitude; l is the transverse coordinate of the measurement point; h is the vertical coordinate of the measurement point; v_{klh} is the measured value at point (l, h) under wind speed k; and v_{kh} is the control wind speed at the corresponding wind speed.

1.3.2 Windbreak Efficiency Windbreak efficiency is a primary indicator reflecting the model’ s wind speed reduction and is used to measure the degree of wind speed reduction by the model. It is obtained by comparing the average wind speed at each observation point with the initial wind speed at that point in the empty wind tunnel. The formula is as follows [9,17,20]:

$$E_{klh} = \frac{v_{kh} - v_{klh}}{v_{kh}} \times 100\%$$

1.3.3 Data Processing and Analysis Excel 2020 was used to organize and calculate wind speed acceleration rates and windbreak efficiency; Surfer 17.0 was used to plot flow field structure diagrams of Cyperus esculentus models with different belt spacing configurations; Origin was used to plot line graphs of windbreak efficiency changes at different positions and heights. SAS 9.4 software was used for one-way ANOVA of the data, and the least significant difference (LSD) method was used for significance testing ($P < 0.05$).

2 Results

2.1 Flow Field and Wind Speed Acceleration Rate Variation Characteristics

2.1.1 Flow Field Structure Distribution Characteristics As shown in [Figure 2: see original paper], [Figure 3: see original paper], and [Figure 4: see original paper], at the windward side of the three Cyperus esculentus model belts, relatively neat isovelocity lines perpendicular to the belts were formed. When approaching the plant models within the 0–20 cm height range, the isovelocity lines shifted downward, indicating an increasing wind speed trend. However, above this height, wind speed remained essentially unchanged. Within the 0–10 cm range near the bed surface, wind speed decreased sharply, forming wind shadow areas. Moreover, extremely weak wind speed vortices formed between the two Cyperus esculentus belts in all models, likely due to the blocking effect of the belt models creating static wind regions [15,17].

Within the 20–30 cm range above the belts, different models formed high wind speed areas of varying sizes. However, under wind speeds of 6 m·s^{-1} and 8 m·s^{-1}, these high wind speed areas were not closed, indicating weaker ability to reduce strong winds. Within the 0–10 cm range, wind speed gradually decreased, while in the 30–50 cm height range, wind speed remained essentially unchanged, showing minimal model influence.

Behind the second Cyperus esculentus belt in all three models, the intensity of near-bed wind shadow areas gradually decreased with distance. The wind shadow area intensity and area in H2 and H3 models were greater than in H1, indicating stronger airflow obstruction and reduction effects. Additionally, within the 24–32 cm range, all models again formed extremely weak wind speed vortices due to airflow blocking.

2.1.2 Wind Speed Acceleration Rate Variation Characteristics The variation characteristics of wind speed acceleration rates for different Cyperus esculentus models were similar across different wind speeds, so the 6 m·s^{-1} condition is used as an example. As shown in [Figure 5: see original paper], airflow formed a weak deceleration zone (acceleration rate < 1) near the bed surface before the Cyperus esculentus models. At the same height before the belt, the area with acceleration rate < 1 under H1 conditions was larger than under H2 and H3, indicating H1 had a relatively weaker wind speed reduction effect.

With increasing distance, within the 0–10 cm range, different belt-spacing models formed strong deceleration zones with acceleration rates all < 0.6. The blocking effect of the models on airflow was most pronounced near the bed surface. The area with acceleration rate < 0.6 under H1 was smaller than under H2 and H3, indicating that H2 and H3 had the strongest blocking effect on airflow in this region.

2.2 Windbreak Efficiency Analysis

2.2.1 Variation in Average Windbreak Efficiency Since the blocking effect of Cyperus esculentus models on airflow occurs mainly near the bed surface, and considering the model height and pitot tube measurement heights, this study calculated the windbreak efficiency on the leeward side of the models within the 0–10 cm height range at different wind speeds. According to , as wind speed increased, the average windbreak efficiency of all models decreased. On the leeward side of different harvest models, the windbreak efficiency of H2 and H3 models at experimental wind speeds of 6 m • s^{-1}, 8 m • s^{-1}, and 10 m • s^{-1} was significantly greater than that of H1, but there was no significant difference between H2 and H3 models. H1 showed the poorest wind speed reduction effect, while H2 and H3 showed no significant difference in windbreak effectiveness.

2.2.2 Protection Distance Analysis The variation characteristics of windbreak efficiency for different harvest spacing models were similar across different wind speeds. The 6 m • s^{-1} wind speed condition is used as an example for analysis on the leeward side of the models. H2 model showed a trend of first increasing then decreasing windbreak efficiency, reaching a maximum of 86.3% at 8 cm on the leeward side, then decreasing while remaining >50% at 48 cm. H3 model showed a similar trend, reaching a maximum of 91.1% at 8 cm on the leeward side, then decreasing while remaining >50% at 64 cm. H1 model had a belt spacing of only 16 cm, with windbreak efficiency <40% within the 0–8 cm range. H2 model had a spacing of 24 cm between the two belts, with windbreak efficiency >50% within the interval between the two belts. H3 model had a spacing of 32 cm, with windbreak efficiency >50% within the 0–24 cm range. H2 and H3 models were more effective at lifting the flow field, placing all areas between the two belts under protection.

3 Discussion

Previous studies have shown that due to friction and blocking effects of plant models [15,17], airflow is weakened. This is consistent with our results, where Cyperus esculentus models blocked airflow, causing rapid wind speed decay near the bed surface. However, above the Cyperus esculentus belts, all three models formed high wind speed zones. This occurs because when airflow encounters plant models, part of it is blocked and, influenced by the Venturi effect, passes over the models as "over-flow," merging with the original airflow above the models to form a higher wind speed region [15,17].

Many studies have shown that narrower spacing yields stronger airflow reduction by windbreak plant belts [9,10]. However, our results showed that wind shadow area intensity and area in H2 and H3 models were greater than in H1, consistent with Kang Xiangguang et al. [11] and possibly due to more stable airflow with larger intervals [21]. H2 model had a 24 cm spacing between belts with windbreak efficiency >50% in the interval; H3 model had 32 cm spacing with windbreak efficiency >50% within 0–24 cm. In practice, since Cyperus esculentus belts exist continuously during harvest, only the windbreak efficiency between the two belts needs consideration. These results indicate that H3 model provided more stable windbreak efficiency than H2. Additionally, wind field structures of different models were similar across wind speeds, showing that wind field variation is independent of wind speed, which only affects the intensity of acceleration and deceleration zones, consistent with previous research [17,20]. As wind speed increased, isovelocity line density increased in the three harvest models, and plant models' wind speed reduction effect weakened [11,20].

Previous studies indicated that when wind speed acceleration rate > 1, models accelerate airflow; when < 1, they decelerate airflow [9,17,20]. Our results showed that near-bed wind speed acceleration rates of different harvest spacing models were < 1, indicating deceleration, consistent with Yuan Xinxin et al. [20]. Near-bed acceleration rates decreased sharply, and as height increased, wind speed acceleration rates increased, following the wind speed decrement law [17,20]. Additionally, the area with acceleration rate < 0.6 under H1 was larger than under H2 and H3, while the area with acceleration rate < 1 was smaller, indicating that H2 and H3 had the best airflow blocking effects.

Plant models primarily achieve windbreak effects by lifting the flow field and blocking airflow passing through them [15,17]. Different models have different windbreak efficiencies under various wind speeds. Analysis of different Cyperus esculentus models showed that as wind speed increased, average windbreak efficiency of all models decreased, consistent with results. However, contrary to previous findings that larger shelterbelt spacing yields lower windbreak efficiency [9,10], our results showed H2 and H3 had significantly greater windbreak efficiency than H1. This may be because the overly close spacing of the two belts in H1 created unstable airflow, while the larger intervals in H2 and H3 suppressed sudden acceleration after airflow passed the first belt, avoiding near-surface turbulence [21] and improving stability. Additionally, H2 and H3 more effectively lifted the flow field, placing all areas between the two belts under protection.

4 Conclusions

(1) The flow field structures of Cyperus esculentus models under different harvest patterns were similar, all reducing airflow near the bed surface. The flow field structure stability of H2 and H3 models was greater than H1, and within the harvest spacing, the windbreak efficiency of H2 and H3 exceeded that of H1.

(2) As wind speed increased, the windbreak efficiency of all models decreased. The average windbreak efficiency on the leeward side of H2 and H3 showed no significant difference across wind speeds, but was significantly greater than that of H1. Within the harvest spacing, windbreak efficiency of H2 and H3 exceeded 50%, while H1 was less than 40%.

(3) In terms of windbreak and sand-fixation ecological benefits, H2 and H3 were optimal. However, from an economic perspective, H2' s smaller harvest area reduces economic income and cannot provide high economic benefits for farmers while obtaining windbreak and sand-fixation benefits.

(4) Therefore, considering both ecological benefits of windbreak and sand fixation and economic benefits of increased income, H3 is recommended as the optimal harvesting method. Additionally, as a study on windbreak and sand fixation by farmland crops, our model can also be applied to other crops similar to Cyperus esculentus, providing reference for research on using crops and economic plants for windbreak and sand fixation in arid and semi-arid regions.

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Note: Figure translations are in progress. See original paper for figures.