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Floating dynamics of *Beckmannia syzigachne* Seed Dispersal via Irrigation Water in a Rice Field

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ABSTRACT

Water is one of the main dispersal agents of plant seeds and influences plant population dynamics and community structure. Although a large proportion of paddy fields are subjected to irrigation, limited research has addressed weed seed dispersal via water in rice-based systems. In this study, safranin T-dyed *Beckmannia syzigachne* seeds were released and their movement was tracked to characterize their dispersal dynamics via water in an irrigation canal and in a rice field. *B. syzigachne* seeds, floating on the water surface, moved from their release point at the canal entrance via irrigation water along the irrigation canal. A well-simulated Gaussian plume model indicated that the seed dispersal of *B. syzigachne* conformed to a leptokurtic distribution, and the peak dispersal kernel showed that seeds moved along the irrigation water flow to approximately 800–1000 m away from the release point 36 h after release into the canal. When seeds were released in the center of a flooded field, a total of 60% of the released seeds were water-dispersed to the northwest corner by the southeast prevailing monsoon wind within 72 h. The well-fitted Gauss 2D-model illustrated the widening of the seed distribution range with time and dispersal pattern with an accumulation center in the field. Our study is the first to show that buoyant weed seeds are mainly dispersed by irrigation water in both the canal and field and that the water dispersal of seeds influences the spatial deposition and distribution of the weed seed bank and strongly affects weed occurrence patterns in irrigated fields.

1. Introduction

Seed dispersal is one of the most important aspects of plant population ecology (Schupp and Fuentes, 1995). The dispersal of plant seeds may influence short- and long-term population dynamics as well as range expansion, (re)establishment, diversity, community structure, genetic structure, and species interactions (Levin et al., 2003; Bohrer et al., 2005; Beckman et al., 2012; Emmerson et al., 2012). To understand plant dispersal, detailed knowledge of underlying processes and vectors is critical.

Plant dispersal vectors can be either biotic (e.g., animals, humans and agronomic practices) or abiotic, such as wind and water, which can transport seeds to various distances (Cain et al., 2000). Among these dispersal agents, the transport of propagules by water (hydrochory) is considered an important means of seed dispersal in natural and managed ecosystems (Davies and Sheley, 2007; Gurnell et al., 2008).

Existing studies of seed dispersal by water are mostly limited to rivers, streams, estuaries, floodplains, and swamps, which generally represent natural ecosystems (Danvind and Nilsson, 1997; Donnelly and Walters, 2008; Groves et al., 2009). Although paddy fields are an important form of land use and constitute large areas of aquatic agroecosystems, particularly in East and Southeast Asia, South America, and Central Africa, few studies have been conducted on the transport (dispersal) of weed seeds by water in these agroecosystems. Studies addressing weed seed dispersal via irrigation water in farmland settings are even more limited.

Current knowledge of seed dispersal by water gained from studies of natural aquatic environments may not be applicable to field situations in which the presence of rice stubble obstructs the free flow of water in the paddy fields. Moreover, compared to natural aquatic environments, irrigation water on arable land is typically much shallower. Therefore, specific studies are required to reveal the patterns of seed dispersal by water on agricultural lands.

The arable land of the Yangtze River basin in China is predominantly cropped in an annual rotation of rice and wheat or rapeseed oil (Li et al., 2012). In this cropping agroecosystem, frequent irrigation

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is necessary. The seeds of most weed species in paddies and summer crop (rape or wheat) fields can float on the water's surface for more than two days and be dispersed by the irrigation water, including *Beckmannia syzigachne* (American sloughgrass) (Li and Qiang, 2009). Since the 1990s, *B. syzigachne* has spread quickly in wheat fields and has become one of the dominant weeds in the continuous wheat-rice cropping system in the Yangtze River Basin and Southwest Region (Rao et al., 2009), particularly since it has evolved resistance to herbicides (e.g., chlorsulfuron, fenoxaprop-*P*-ethyl and pinoxaden) in winter crop fields (Li et al., 2013, 2014).It is reported that *B. syzigachne* can generally cause wheat yield losses of 10–30% and in some cases up to 50% (Li et al.,2010), particularly in low-lying fields. The ineffective control of *B. syzigachne* even in fields with a limited history of herbicide use may contribute to the spread of herbicide-resistant populations of *B. syzigachne* by irrigation water. *B. syzigachne* flowers in spring and sheds its seeds from May onward, surviving over the summer in the soil seed bank. Seeds of *B. syzigachne* have the highest floating density in summer crop fields, as they are able to float for over 7 days (Zuo and Qiang, 2008). The buoyancy of *B. syzigachne* seeds facilitates their dispersal by water, which may be helpful for understanding the uneven distribution of the weed populations in irrigated fields (Qiang, 2005) and its quickly spread. Knowledge of the spatial distribution of weeds associated with seed dispersal can guide effective weed management. Irrigation before rice planting most likely facilitates *B. syzigachne* seed dispersal. Thus, characterizing the dispersal of *B. syzigachne* by irrigation water may improve our understanding of its distribution patterns and provide a sound basis for establishing feasible weed management measures in local rice-wheat cropping systems. The objectives of the present study are to answer specific research questions: 1) How many seeds can be dispersed by water between fields during irrigation? 2) How far can the weed seeds be dispersed by water in an irrigation canal? 3) What is the dispersal trajectory of floating seeds driven by wind in a field? 4) How can the seed dispersal pattern be predicted or described? To address these questions, three experiments on *B. syzigachne* water seed dispersal were conducted both in an irrigation canal and in an irrigated field. Mechanistic and phenomenological models were developed separately to fit the experimental data and used to simulate and predict the seed dispersal process and distribution patterns.

2. Materials and methods

2.1. Study site

Field experiments were conducted at Baihu Farm, Anhui Province, China, in 2009 and 2010. Baihu Farm is situated in the transition zone between the warm-temperate and sub-tropical zones (from 31°13′12″N to 31°16′32″N and from 117°26′15″E to 117°29′22″E). The farm covers 11,300 ha, possesses a well-developed irrigation system, and has been almost entirely dedicated to rice-wheat cropping fields for more than 10 years. The soil is sandy to medium loamy, with 2.0–2.3% organic matter, 122–134 mg kg^{-1} of alkali hydrolysable nitrogen (N), 41–66 mg kg^{-1} of Olsen-phosphorus (P), 44–57 mg kg^{-1} of exchangeable potassium (K), and a pH of 6.4–6.7. The climate is temperate, with an average annual precipitation of 1220 mm, an average annual temperature of 12.5 °C, and 2035–2270 h of annual sunshine. A weather station nearby (31°13′ E, 117°27′ N, and altitude 6.6 m) records and provides real-time meteorological data.

B. syzigachne is prevalent in the wheat fields at Baihu Farm. Mature seeds of *B. syzigachne* were, in advance, collected in 2009 in Bauhu Farm for our seed release experiments.

2.2. Water-dispersal distance of dyed seeds in the irrigation canal (Experiment No. 1)

To determine how far the weed seeds could be dispersed via irrigation, an experiment on dispersal distance was conducted in a 2000-m-long concrete irrigation canal comprising equal lengths of main and branch canals. The cross section of the main canal was a U-groove with a 50-cm arc diameter and a 100-cm depth. The branch canal was trapezoidal with an upper width of 100 cm, a lower width of 80 cm, and a depth of 100 cm. There was a 60 × 60-cm water exit from the canal as well as a water entrance into the field. The position of the water entrance was slightly higher. There were no obstacles in the canal.

The experiment was conducted in June 2010. Mature seeds of *B. syzigachne* collected the previous year were dyed by immersion in 1% safranin T solution for one hour and then air dried at 30 ± 2°C for five days. A 1.0 × 1.2-m piece of 0.125-mm mesh nylon was set at the water exit before 1.08 kg of dry dyed *B. syzigachne* seeds (more than 1.2 million dyed seeds) were released at the canal entrance when the irrigation began. The irrigation water (0.18 $m^3 s^{-1}$) flowing at 0.5 m^{-1} was allowed to inundate the field. The irrigation process lasted for approximately one and a half days. The number of dyed seeds in a 15 × 15-cm quadrat of seed trap (as described above) was recorded 36 h after release at sites every 5 m along the direction of the irrigation water flow. The nylon net set at the water exit was taken back to the laboratory to determine the numbers of dyed weed seeds that reached the exit.

2.3. Dispersal trajectories of floating seeds driven by wind within a field (Experiment No. 2)

To determine the dispersal trajectories of floating seeds driven by wind within a field, the third experiment was conducted in June 2010 in an oblong field of 50 m (north-south direction) by 100 m (east-west direction) at Baihu Farm. Approximately 2.2 million (2.0 kg) dyed seeds of *B. syzigachne* were released at the center of the field after it had been inundated to a depth of approximately 15 cm with clean irrigation water. The water table was maintained for three days, after which the field was harrowed using a rotary cultivator in the flooded field. During the entire experimental period, the prevailing winds at the farm blew from the east or southeast, which was recorded by the weather station nearby. According to local meteorological data collected during the seed dispersal period, the prevailing wind blew from the east or southeast with a force of 3–4 (Beaufort scale) and a speed of 3-8 m s^{-1} (average 6.5 m^{-1}).

Floating seeds were sampled to track seed movement paths every 12 h until 72 h after the release. Then, an additional sampling was conducted to track the influence of harrowing on floating seeds after harrowing.

2.4. Modeling seed dispersal via irrigation water in the canal and in the field

A mechanistic model was developed from the experimental data to better understand the seed dispersal process and seed distribution after dispersal. Seed dispersal (the density/distance relationship) is typically described as a leptokurtic distribution, with negative exponential, negative power law, and Gaussian functions being the three most commonly represented (Nathan and Muller-Landau, 2000; Levin et al., 2003). Seed dispersal by either wind or water can be described using a leptokurtic single-modal curve with a long right-hand tail.

Previous studies have used tilted Gaussian plume models to describe seed dispersal in a fluvial environment (Greene and Johnson, 1989; Groves et al., 2009). However, there is no such report for seed dispersal in an irrigation canal. Therefore, in this study, we modified the unidirectional Gaussian plume model from Groves et al. (2009) to describe and predict the dispersal of seeds by the irrigation water in the canal. The canal's dimensions and flow variability were considered.

The model works by varying the mean distribution of the dispersing seed in response to changes in the canal dimensions, flow velocity, and time. The complete formula for the model is as follows:

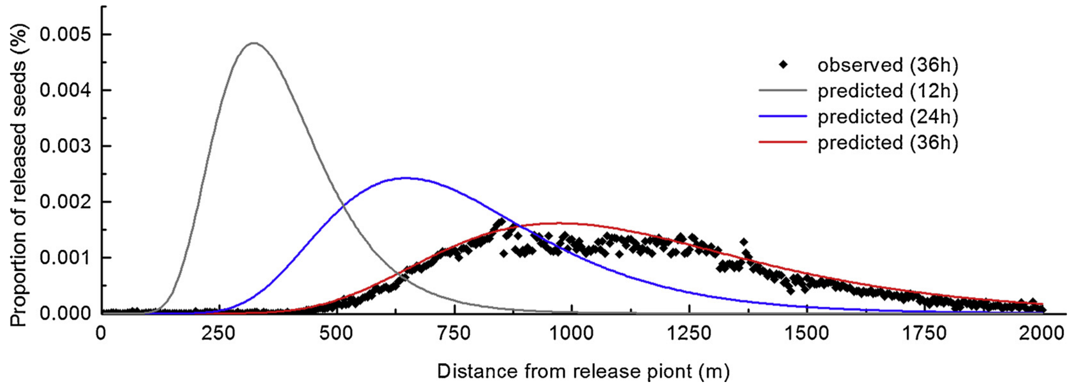

Fig. 1. Observed and predicted dispersal curves showing how the distribution of dyed *B. syzigachne* seeds released in the irrigation canal changed as the irrigation time increased.

$$\frac{N_x}{N_o} = \frac{1}{xC_2\sigma_u\sqrt{2\pi}} \exp\left(-\left[\frac{\ln(xC_1\sqrt{\bar{H}g}\,/(\bar{U}_g \times t)\bar{W})}{2C_2\sigma_u}\right]^2\right) \quad (1)$$

where x is the distance from release point;

C_1 and C_2 are empirically derived constants;

σ_u is the standard deviation of $\ln(\bar{U})$;

g is the acceleration due to gravity;

$(\bar{H})$ and $(\bar{W})$ are the average canal dimensions of depth and width, respectively;

$(\bar{U}_g)$ is the geometric mean of flow velocity;

t is the irrigation time after the seed is released at the water entrance;

N_x is the seed density along the canal at distance x away from the release point; and

N_0 is the original seed density at the release point.

A phenomenon model was used to fit the seed dispersal kernel in the field. The water surface can be treated as a two-dimensional (2D) plane; therefore, we attempted to describe the pattern and distribution of seed dispersal on the water surface using a 2D Gauss model. The dispersal density F at point (x, y) is

$$F(x, y) = Z + A \exp\left[-\frac{1}{2}\left(\frac{x - x_0}{a}\right) - \frac{1}{2}\left(\frac{y - y_0}{b}\right)^2\right] \quad (2)$$

where Z is the compensation value of the density, $(Z + A)$ is the peak value of the model, (x_0, y_0) is the coordinate of the peak value, and a and b are the adjusted values.

2.5. Data analysis

In the case of releasing dyed seeds at the canal entrance (Experiment No. 1), the water entrance was designated as the origin, the direction of irrigation water flow as the positive x-axis, and the number of dyed seeds recorded at each sampling site as the y-value. Based on the coordinates (x, y) of each sampling site, a scatter diagram of the distribution of dispersed dyed weed seeds along the irrigation canal could be drawn.

In Experiment No. 2, the seed release point (field center) was designated the origin, the east direction as the positive x-axis, and the north as the positive y-axis. As a result, the experimental fields were defined as a rectangular grid with a discretization of 1 m or 5 m (used in the seed bank survey). Then, each sampling site was positioned in the coordinate (x, y) grid. The number of dyed seeds recorded at each sampling site or the seed bank density of dyed seeds was designated as the z value. Based on the coordinates (x, y, z) of each sampling site, color fill maps were constructed to illustrate the distribution of dyed weed seeds using OriginPro 9.0 (OriginLab Corporation, Northampton, MA, USA).

In addition, in the center release experiment (Experiment No. 2), the distribution of dyed seeds from the center of the dispersal kernel was divided into eight directions (north-northeast, east-northeast, east-southeast, south-southeast, south-southwest, west-southwest, west-northwest, and north-northwest), and a modified pie chart (wind rose) was used to illustrate the relative dispersal distance we observed in the eight directions.

All statistical analyses were performed with SPSS 19.0 (IBM Corporation, Armonk, NY, USA), and all figures were drawn using OriginPro 9.0.

3. Results

3.1. Dispersal distance of floating seeds by irrigation water in the canal

Dyed *B. syzigachne* seeds were dispersed into the branch canal approximately 5 h after the irrigation started, and dyed seeds were present in the entire canal thirty minutes after irrigation stopped. Some dyed seeds were found adhering to the walls of the canal. The dyed *B. syzigachne* seeds in the sections of the canal from 750 m to 1500 m away from the seed release point accounted for approximately 20% of the total seeds present in the canal (Fig. 1).

3.2. The model of floating seed dispersal via the flow of irrigation water in the canal

The values of parameters required by the model were obtained from the observed data of the dyed *B. syzigachne* seed release experiment in the irrigation canal. The t value was 36, corresponding to the irrigation time. The results showed that $(\bar{U}) = 0.5$ m s^{-1}, $(\bar{H}) = 0.9$ m, $(\bar{W}) = 1$ m, and $\sigma_u = 0.12$. The constant values C_1 and C_2 derived from best fit were 0.006 and 2.0, respectively.

The dispersal curves derived from the seed release experiment fit the experimental data well, with a slight over-prediction of seed density at the right tail (Fig. 1). The model showed that most of the seeds were concentrated in the middle section of the irrigation canal, approximately 800–1000 m away from the release point, when the irrigation had lasted for approximately 36 h. The dispersal curve obtained from the model flattened, and the peak moved to the right as the irrigation time increased and seeds were dispersed further down the canal (Fig. 1).

3.3. Tracking the dispersal of released dyed seeds by wind and after harrowing in the field

Dyed *B. syzigachne* seeds were dispersed with a high-density center in a polygon, and the seed dispersal range expanded with time (Fig. 2). The floating dyed seed density within the dispersal kernel was as high as 62,000 seeds m^{-2} 12 h after release and decreased to approximately

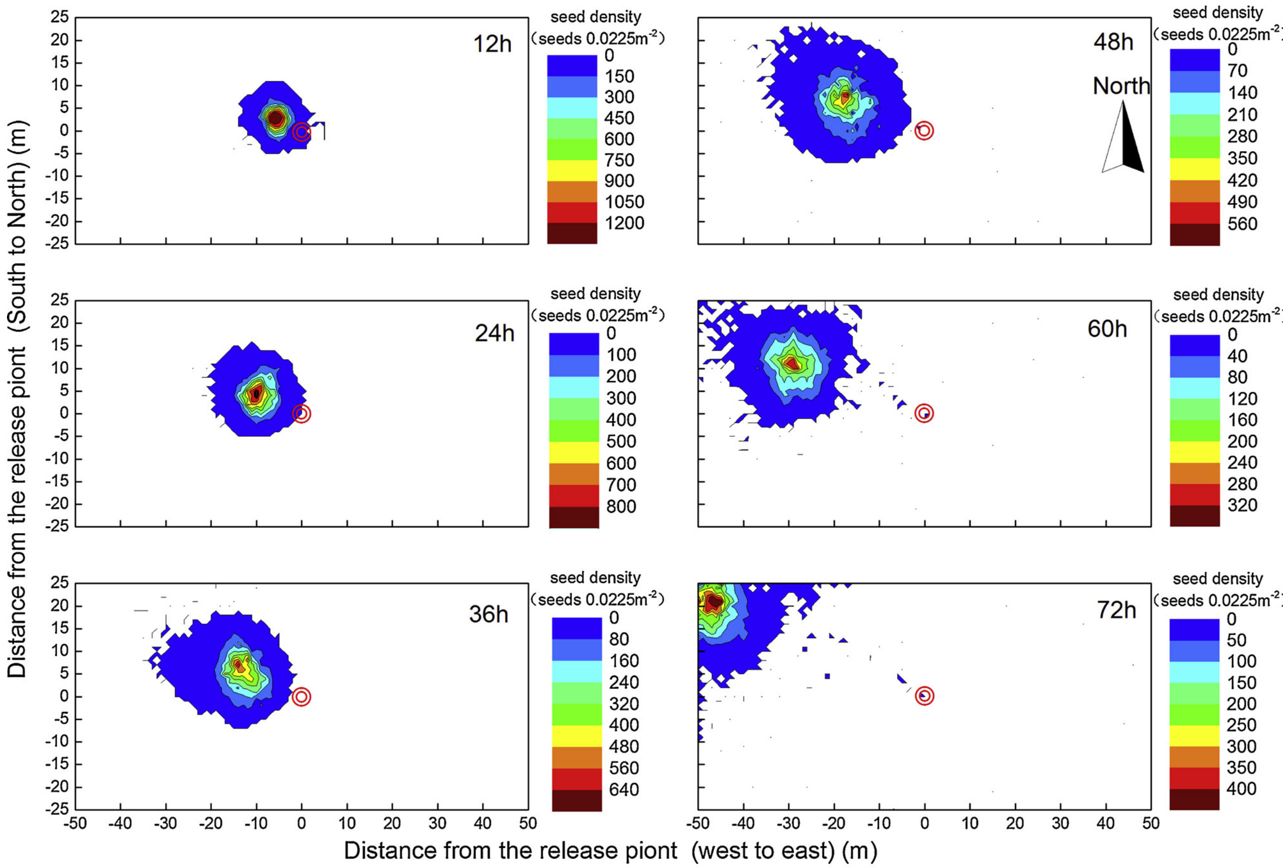

Fig. 2. Distribution of dyed *B. syzigachne* seeds (released at the center of the field) in the field when irrigated to a 15-cm water depth. The position at coordinate (0, 0) was the release point and is represented by "◎".

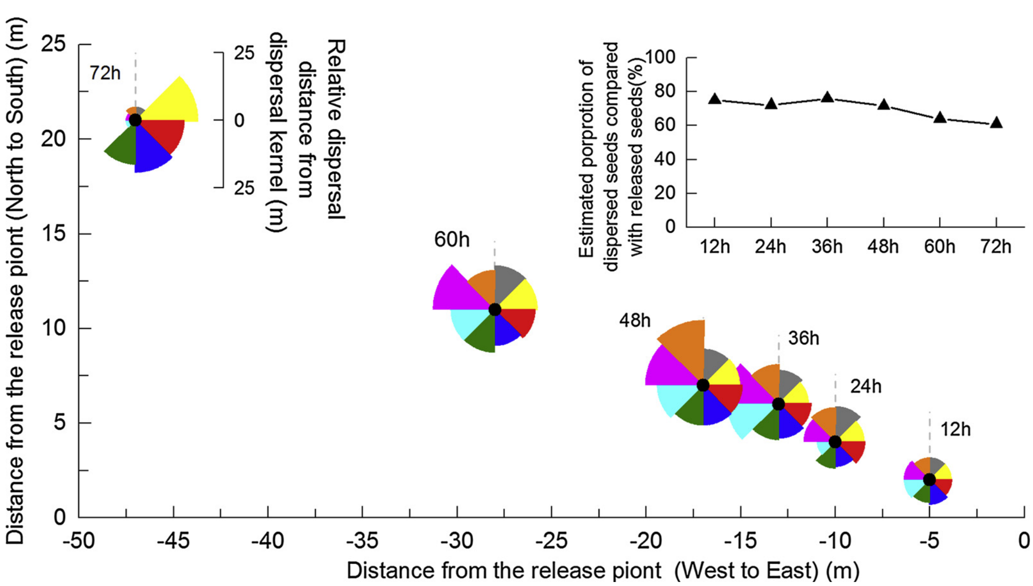

Fig. 3. Movement of the center of dispersal kernel of dyed *B. syzigachne* seeds. "●" represents the center of dispersal kernel; the radius of the sector for each direction in wind rose represents the relative dispersal distance from the center of dispersal kernel; each color in wind rose represents a corresponding dispersal direction of the dispersal kernel form the dispersal center.

13,000 seeds m^{-2} 72 h after release. However, there was still a seed accumulation center with the highest density. Twelve hours after release, the greatest distance dyed seeds had dispersed was approximately 15 m away from the release point but the dispersal center was at 5 m west and 2 m north; 60 h after release, the farthest dispersed seeds had reached the field edge but with the seed dispersal center at 11 m west and 28 m north of the release point. Finally, 72 h after release, a large number of dyed seeds accumulated at the corner of the field, approximately 47 m west and 21 m north. In general, over time, the center of the seed dispersal kernel had shifted northwest from the release point because of the prevailing southeast monsoon wind throughout the experiment, and the dispersal speed accelerated because the degree of seed accumulation decreased (Fig. 3). In addition, almost all dyed *B. syzigachne* seeds were floating on the water's surface when released. A total of 75% of dispersed seeds, approximately 1.65 million, were floating on the water's surface 12 h after their release; over 60%, approximately 1.34 million, remained floating after 72 h (Fig. 3).

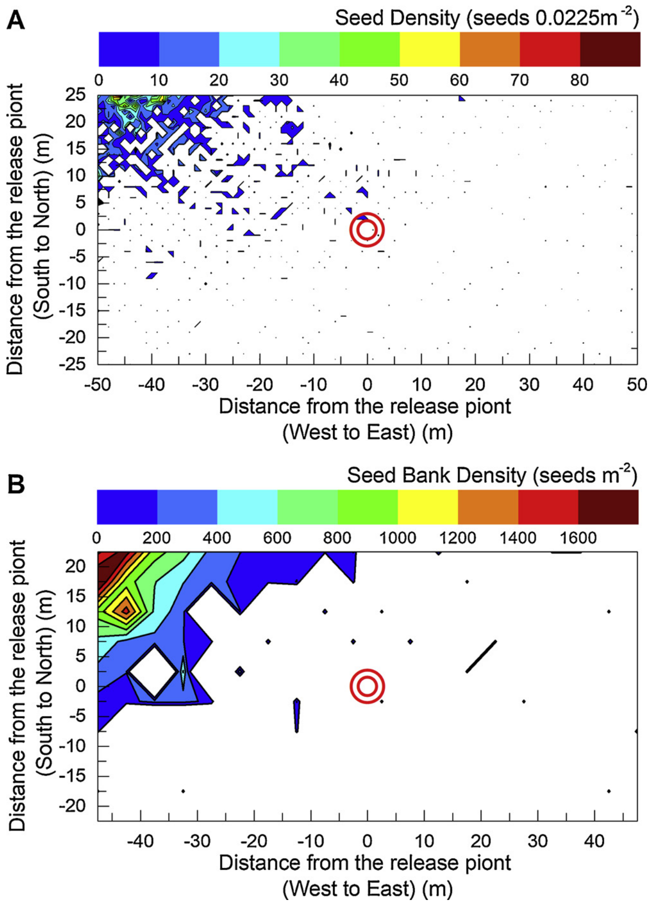

Fig. 4. A: distribution of dyed *B. syzigachne* seeds floating on water surface (released at the center of the field) after harrowing; B: distribution pattern of the seed bank of dyed *B. syzigachne* seeds dispersed by wind. The position at coordinate (0, 0) was the release point and is represented by "◎".

3.4. The distribution pattern of dyed weed seeds after harrowing

The results indicated that the dispersal range of dyed *B. syzigachne* seeds expanded considerably after harrowing to almost the entire field. However, the center and shape of the seed dispersal kernel became unclear after harrowing, and the density of dispersed seeds decreased to only approximately 3500 seeds m^{-2}, but the distribution area further expended. This result indicates that harrowing facilitated the deposition and expansion of the dispersal area of the dyed seeds (Fig. 4A).

Results show that the dyed seeds spread across almost the entire field; the seed bank density was highest at the field corner and nearby edge, where the seeds accumulated after harrowing and gradually decreased from the accumulation center to the periphery (Fig. 4B), indicating the distribution pattern of seed bank could be significantly influenced by the dispersal pattern.

3.5. The phenomenological model for floating seed dispersal in the field

The dispersal of floating seeds was influenced by both wind and water, and the distribution pattern of seed dispersal on the water's surface changed over time. The results showed that the 2D Gauss model fit the field data well ($R^2 > 0.87$). The peak value of the model decreased over time, while the range of the distribution of dispersed seeds extended. The position of the peak value of the model shifted toward the northwest over time (Fig. 5).

4. Discussion

4.1. Water is major agent for seed dispersal under the wheat/rape-rice cropping agroecosystem

The above results on dispersal distance, long duration and large number of floating seeds of *B. syzigachne* suggest that water is a predominant vehicle for the dispersal of *B. syzigachne* seeds in wheat/rape-rice cropping fields in the middle and lower reaches of the Yangtze River. *B. syzigachne* seeds have evolved in their adaptation to traits needed for floating, i.e., having a flat shape, light weight and special structure with saccate glumes. Specifically, the saccate glumes of *B. syzigachne* forming two advanced air chambers, makes the specific gravity of the seed lighter than water; the flat shape makes the seed have large surface area which could provide large stressed area on water surface against the gravity. All the traits facilitate the floating of *B. syzigachne* seeds on water that give the seeds the opportunity for water dispersal. Furthermore, previous field survey studies found that more than 74 weed species belonging to 20 families floated during irrigation, including almost all dominant weed species in paddy and wheat or rape fields (Zuo et al., 2007; Zuo and Qiang, 2008; Li and Qiang, 2009). The dominant weeds in wheat or rape fields—*B. syzigachne*, *Alopecurus aequalis*, *A. japonicus*, and *Polypogon fugax*,—and in paddy fields, including *Echinochloa crus-galli*, *Monochoria vaginalis*, *Cyperus difformis*, and *Eclipta prostrata*, which are mainly dispersed by water, are all hygrophytes or hydrophytes (Qiang, 2002 and 2005). Most species came from the Poaceae family, accounting for 15 species, including 20% of the observed floating weed species (Zuo et al., 2007; Zuo and Qiang, 2008; Li and Qiang, 2009). This finding is mainly attributed to the caryopses of gramineous weeds having specialized structures with lightweight glumes.

4.2. Long-distance dispersal of B. syzigachne seeds

In the present experiment, a Gaussian plume model effectively described and predicted the dispersal processes of floating *B. syzigachne* seeds in the irrigation canal. As simulated by the model, when the irrigation lasted for only 36 h, 5% of the *B. syzigachne* seeds dispersed more than 2000 m along the irrigation canal via irrigation water flow. Considering the seed floating capacity of *B. syzigachne*, it is possible that a longer dispersal time would have resulted in much greater dispersal distance. In the middle and lower reaches of the Yangtze River, irrigation usually lasts for more than 3 days in preparation of rice planting, and the flow velocity of irrigation water generally ranges between 0.2 m s^{-1} and 1.0 m s^{-1}. We can speculate that under the specific experimental conditions presented in our model, if the irrigation had been extended to 3 days, approximately 10% of the seeds would have been dispersed more than 3000 m. Likewise, if the water velocity had been doubled to 1.0 m s^{-1}, 25% of the seeds' dispersal distance would have covered 5000 m. The simulation results indicated that irrigation canals may be corridors for long-distance dispersal, with the dispersal duration and flow velocity being the two important influencing factors. Moreover, seeds can be transported over considerably greater distances in rivers (Andersson et al., 2000).

In the Yangtze River Basin, in recent years, *B. syzigachne* has evolved resistance to herbicides (e.g., chlorsulfuron, fenoxaprop-P-ethyl and pinoxaden) in winter crop fields (Li et al., 2013, 2014) resulting from the continuous use of the same herbicide or herbicide class. In vast farmland with a well-developed canal irrigation system, because of the conventional irrigation practices, plant seeds can be carried by irrigation water along ditches to a new field far from the parent plant's location. In this case, the seeds produced by herbicide-resistant populations of *B. syzigachne* can also be spread via irrigation water, which may lead to the establishment of the resistant weed even in fields far from their starting place with a limited history of herbicide use. Thus, seed dispersal via irrigation water eventually contributes to the expansion of

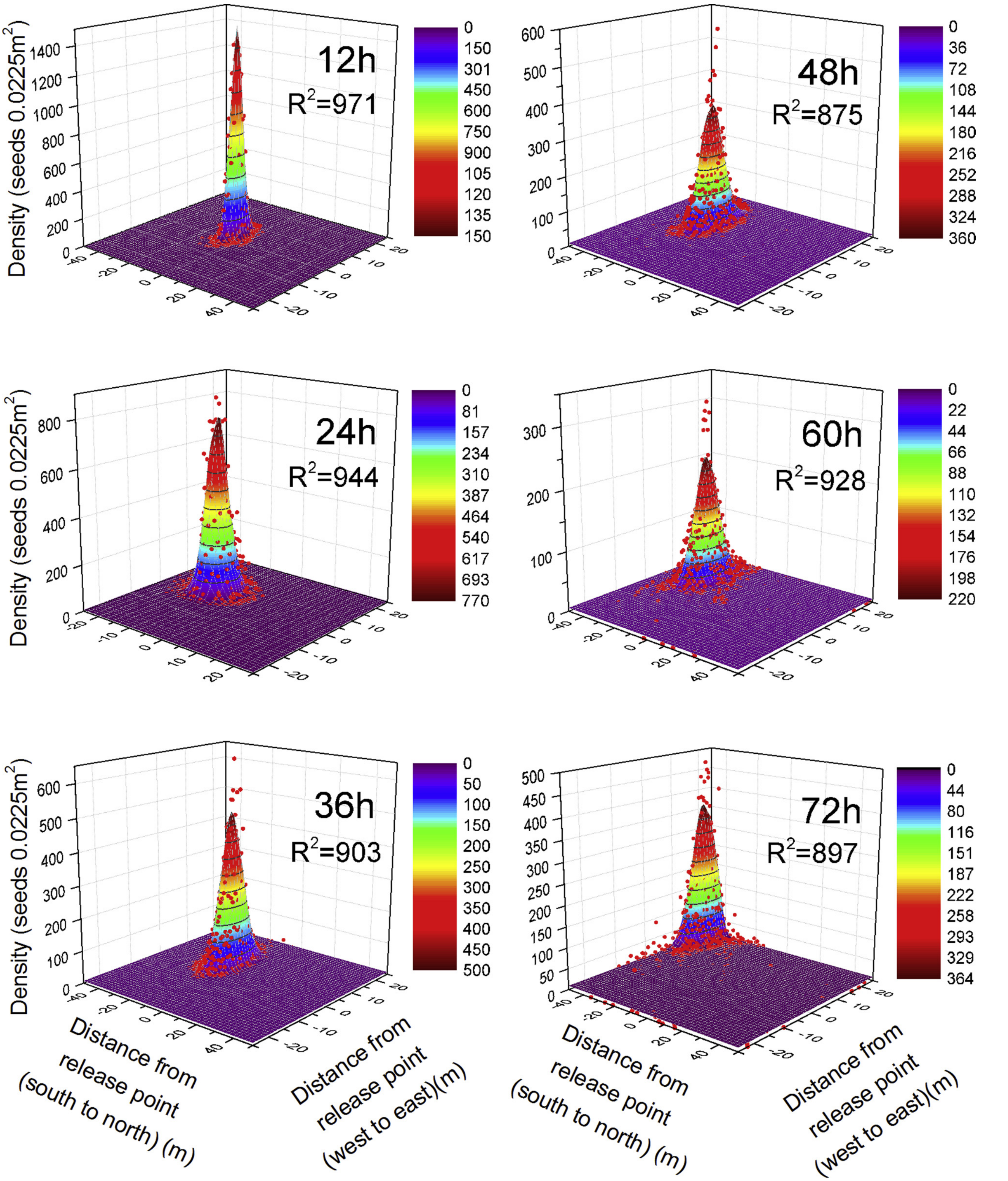

Fig. 5. A 2D Gauss model of the field distribution pattern of dyed *B. syzigachne* seeds (released at the center of the field). The position at coordinate (0, 0) was the release point and is represented by "◎".

herbicide-resistant *B. syzigachne* populations into new fields and the aggravation of weed problems. The water outlet of irrigation ditches usually connects with river systems, which provide the condition for the weed seeds to disperse via river flow, resulting in a longer-distance dispersal of weed seeds.

4.3. Seed water-borne dispersal influences the seed distribution in the soil seed bank

A Gauss 2D model was established to describe the distribution of floating *B. syzigachne* seeds within a submerged field. The seed dispersal process via water in such submerged fields (lentic systems) appears to be directly influenced by wind speed and direction. During the irrigation of field, the floating seeds can move in the downwind direction relatively freely by means of wind blowing over the water surface without obstacles. Under the conditions of the present study, after 72 h of wind blowing, with the average wind speed of 6.5 m s^{-1}, over 75% of the weed seeds remained floating on the water surface but accumulated at the northwest corner of the field and nearby field levees, as the predominant wind was the southeast monsoon during the rice planting season in this region. The floating seeds moved approximately 55 m. If the wind speed increased to 10 m s^{-1}, the time it took the floating seeds to accumulate in the field corner and ridge would be shortened to 2 days. In another case, if the water level was not high enough to submerge the wheat stubble, some of the seeds would gather around the wheat stubble and the aggregating process of floating seeds would be impeded. As the water level fell, the floating seeds were deposited onto the ground, forming the seed bank. Furthermore, the deposited and floating seeds can be redistributed by plowing and harrowing. The co-relationship analyses indicated that the dispersal of *B. syzigachne* seeds by irrigation water in the wheat-rice cropping system significantly influenced its seed bank, and the farming operations also affected the seeds' distribution pattern in the soil seed bank. Such a relationship between seed dispersal and the seed bank may help us to understand the population structure and distribution pattern in farmland.

4.4. Weed seed water-borne dispersal and weed management

Weed seed dispersal, or spread, is recognized as an important biological factor that can affect weed control and should be included in weed management plans (Ghersa and Roush, 1993; Jordan, 1992; Maxwell and Ghersa, 1992). Specific weed management measures should focus on controlling the primary factors that influence seed dispersal and distribution (Davies and Sheley, 2007). The present and previous studies have shown that weed seeds are predominantly dispersed and spread by water in wheat/rape-rice cropping agroecosystems. This notion may be integrated into weed control strategy, but available control measurements are still limited.

Because weed seeds can be dispersed by irrigation water in the irrigation channel and into and out of fields, before the first irrigation after the harvest of wheat/rape, we recommend that the irrigation channels be cleaned, filters be installed at the water entrances of irrigation channels and fields to intercept weed seeds and clean irrigation water be used in order to prevent weed seeds from entering as well as exiting a field.

During the soaking of field in preparation for rice planting, weed seeds could be removed, most of which float on the water surface. However, at the beginning of irrigation, the elimination of weed seeds is impracticable, difficult and time consuming because the seeds are scattered over the entire field. When maintaining the water layer for a day or longer, the floating weed seeds will congregate to the corner of the field through the prevailing southeast monsoon in the downwind direction. This is the appropriate time to fish the floating seeds out with a tuck net. Because of differences in field size, wind speed and direction, the timing of implementation of fishing out seeds will vary. In general, according to our practices, with an approximate field area of 1000 m^2, it usually takes 2 days for 80% of the floating weeds to be concentrated, and then it takes 15 min to fish out 90% of the concentrated seeds. In addition, the water table in the field should be maintained at a higher level than the wheat stubble (usually > 15 cm) during field soaking.

In sum, the setting of water filters and fishing out of seeds should be appropriately implemented before the first irrigation and before harrowing, respectively, in wheat/rape-rice cropping fields. These measures may be effective, simple and easy to operate.

5. Conclusion

B. syzigachne seeds can be dispersed by irrigation water both between fields and within fields. The weed seeds on the water surface are dispersed by prevailing monsoon winds and congregate at the corners of the field. The water-driven seed dispersal influences the seed distribution in the soil seed bank and further influences the distribution and structure of the weed communities in the field. The seed dispersal pattern may be beneficial for the adoption of environmentally friendly weed management practices such as setting water filters and fishing out of dispersal seeds using nets. However, considering the variety of weed seeds, further empirical studies on additional weed species should be conducted to verify the water-borne seed dispersal and its practical value for weed control in arable fields.

Acknowledgments

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agee.2019.02.008.

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