INFLUENCE OF THE THREE GORGES RESERVOIR ON THE VEGETATION OF ITS DRAWDOWN AREA: EFFECTS OF WATER SUBMERSION AND TEMPERATURE ON SEED GERMINATION OF XANTHIUM SIBIRICUM (COMPOSITAE)

ABSTRACT: Xanthium sibiricum, an annual weed, unexpectedly and dramatically occupied the exposed drawdown area after water had been impounded for the first time in the newly created Three Gorges Reservoir in China. In order to explain this phenomenon and establish an appropriate management strategy, the effects of constant submersion on seed viability and germination of X. sibiricum were investigated at two constant temperature regimes (25°C and 30°C) under artificial laboratory conditions. The results indicated that the seeds of X. sibiricum exhibited a high level of tolerance of submersion and up to 99% of seeds were viable in each treatment regime. The effect of submersion on germination was not obvious at 25°C until the submersion was prolonged for 180 days, while at 30°C the eventual germination rate of X. sibiricum, even after submergence for only one day, was significantly improved. The speed of germination was also consistently accelerated by prolonged periods of submersion. The proportion of seeds that germinated in all treatments combined was less that 56% due to seed dimorphism, thereby providing a seed bank. We conclude that the interaction between long-term winter flooding and high temperature in summer is the major reason that X. sibiricum was able to occupy the newly exposed drawdown area in the absence of competition. These findings provided further insight into how germination strategy and reservoir water-management regime contributed to this dramatic species outbreak.

KEY WORDS: Xanthium sibiricum, seed germination, submersion, temperature, drawdown area, Three Gorges Reservoir

1. INTRODUCTION

Riparian ecosystems are the most diverse, dynamic and complex biophysical habitats on the terrestrial Earth (Naiman et al. 1993, Naiman and Décamps 1997). Flooding, a disturbance that frequently occurs in natural riparian ecosystems has generally been considered to be the most important disturbance that maintains the diversity and vegetation of riparian habitats (Tiegs et al. 2005). Up to 2005, over half of the rivers in the world have been affected by the construction of dams, in order to meet human needs for water, energy, and transportation (Nilsson et al. 2005). Each year 160 to 320 new dams are being built in the world (Wu et al. 2003).

Reservoir impoundment and dam operations dramatically alter the hydrological regime of rivers, usually by reducing water-
level and flow-rate fluctuations and prolonging duration of flooding. Impoundment or prolonged flooding can alter soil structure, deplete dissolved oxygen, accumulate carbon dioxide, induce anaerobic decomposition of organic matter and reduce iron and manganese (Naiman et al. 1993, Naiman and Decamps 1997, Gomes et al. 2006). The altered conditions may cause die-back of existing riparian vegetation and simultaneously create open habitats for colonization by species that are resistant to flooding conditions (Jäkäläniemi et al. 2005, Ahn et al. 2007, Ishida et al. 2008, Van Uytvanck et al. 2010). Flooding can also significantly affect the germination of annual herbs, either positively or negatively. The effect is determined by the timing, duration, frequency and magnitude of floods as well as the properties of the seed in relation to dormancy, floating ability and germination requirements (Gomes et al. 2006, Nilsson et al., 2010). Many studies have demonstrated that flooding can result in high mortality and inhibition of germination of semi-terrestrial and terrestrial species (Guo et al. 1998; Hözelz and Otte 2004, Infante Mata and Moreno-Casasola 2005 Ferreira et al. 2007). On the other hand, submerged seeds of certain aquatic species could come out of dormancy and exhibit increased germination following the recession of floodwaters (Baskin et al. 2000, Kent and Johnson 2001, Hözelz and Otte 2004).

Temperature is the most reliable environmental signal to indicate the appropriate timing for germination (Baskin and Baskin 1988, Washitani and Masuda 1990) and can also affect seed germination in riparian ecosystems. Therefore, successful establishment of species in a flooded area significantly depends on the ability of its seeds to survive in water (Gomes et al. 2006) and its responses to the thermal regimes of potentially suitable sites (Nishihiro et al. 2004).

The Three Gorges Dam (TGD) in China, completed in 2006 after more than ten years of construction, is one of the largest such projects in the world. A reservoir (The Three Gorges Reservoir, TGR) with a maximum surface area of about 1080 km² (Wu et al. 2003) was created behind the dam when the reservoir was impounded to its full capacity in 2010. In order to control floods and decrease sediment deposition within the reservoir, water levels would be at their highest in winter (usually 175 m above sea level) and lowest during the summer rainy season (as low as 145 m above sea level), thereby producing a drawdown area of 348.93 km² having a vertical height of 30 m. The drawdown area of the TGR includes a previous riparian zone of the Yangtze River and its tributaries that was influenced by short term summer flooding prior to construction of the dam. Much (though not all) of the old riparian area is now completely submerged and the new drawdown area is submerged for up to six months annually, usually from October to May. Water regimes greatly influence the characteristics of riparian vegetation (Toner and Keddy 1997, Nilsson and Svedmark 2002, New and Xie 2008). Thus, changes of the vegeta-

Photo 1. Xanthium sibiricum growing in the drawdown area of the Three Gorges Reservoir at high density. Both pictures were taken during the summer of 2008. At the left image, an abandoned ferryboat has been overgrown by X. sibiricum.
Impoundment flourished *Xanthium sibiricum* in Three Gorges Reservoir

... (Photo 1).

*Xanthium* spp. are fast-growing annual herbs. They are monoeccious and wind-pollinated, and have a worldwide distribution, especially in subtropical and temperate regions (Rocha et al. 2007). *X. sibiricum* usually invades pastures, road banks, wastelands, floodplains and lakeshores in a similar manner to other *Xanthium* species (Sugiyama and Hirose 1991, Logarzo et al. 2002). However, at least in China, it generally exhibits a random or clumped spatial pattern of invasion and occupies small areas. *Xanthium* spp. are highly competitive for space, water, light and nutrients (Mcwhorter and Hartwig 1972). It is a troublesome weed and reduces yield of many crops, such as soybean, cotton and corn (Wapshere 1974, Bloomberg et al. 1982, Ellis and Camper 1995). In addition, *Xanthium* spp. contain carboxyatractyloside which is toxic to livestock and humans (Cole et al. 1980, Logarzo et al. 2002, Rocha et al. 2007, Gurley et al. 2010).

The extensive distribution of *X. sibiricum* inevitably introduces some environmental problems. It can cause economic losses of crop culture and animal husbandry in the drawdown area during exposure period. Moreover, in winter, decomposition of large biomass of *X. sibiricum* under water may deteriorate water quality and release toxic sesquiterpene lactones and strumaroside from its leaves, shoot and seeds. Therefore, the control of *X. sibiricum* is important and urgent for seasonal agricultural production in the drawdown area and water quality maintenance of the TGR.

Germination requirements of *X. sibiricum* have been studied in the past (Esashi and Leopold 1968, Esashi and Tsukada 1978, Norsworthy and Oliveira 2007), but little is known about the effect of flooding on its germination. Understanding the effect of flooding is very important to explain its outbreak and useful for establishing a management strategy. In the present study, we quantified the effects of water submersion on germination of *X. sibiricum* seeds at two constant temperature regimes (25°C and 30°C) under artificial laboratory conditions. The objectives of our study were to (i) determine whether the seeds of *X. sibiricum* are tolerant to simulated water submersion, (ii) examine how water submersion and temperature affect germination of *X. sibiricum*.

2. MATERIAL AND METHODS

2.1. Seed collection and treatment

Mature *X. sibiricum* burrs were randomly collected from entire plants in late September 2009 in the reservoir drawdown area in the Pengxi River region (31°08’N, 108°33’E), a tributary of the Yangtze River. The drawdown area in the Pengxi River basin is 55.47 km², almost sixteen percent of the total area of the drawdown area of the TGR. This region, like other valleys in the Three Gorges Reservoir Area, has a typical north subtropical humid monsoon climatic condition. Annual precipitation is between 992.5 mm and 1241.8 mm. Annual mean temperatures are 16.7–18.7°C. Usually, the temperature between late June and September is more than 30°C. Burrs were transported to the laboratory immediately and air-dried for seven days.

After that, *X. sibiricum* burrs were placed in uncovered large plastic containers filled with tap water (approx. 10 cm deep) in laboratory room conditions. In order to simulate *in situ* conditions, water was completely changed daily to prevent fungi from damaging the seed. Some burrs were retained as a control and were not submerged. Both seed viability tests and germination experiments were carried out on days 0 (control), 1, 7, 15, 30, 60, 120, 180, 240 and 300 days after submersion.

2.2. Seed viability test

For each treatment (i.e. submersion duration), seeds of five replicates (40 burrs per replicate) were extracted. Seed viability was tested using standard tetrazolium testing procedures (Egley 1980). The seeds were cut in half longitudinally without damaging the embryo and soaked in 0.1% solution of 2,3,5-triphenyltetrazolium chloride (TTC) solution at 30°C in dark for 24 h. After removed from the solutions, the seeds were washed with distilled water. The embryos of viable seeds...
exhibited reddish in colour. The seeds of control group were submerged in distilled water for 12 h before seed viability test. Most of the burrs contained two seeds. A very small number of them had only one seed, while some were imperfectly developed having an empty seed coat. Therefore, the viable seed percentage was calculated by dividing the number of viable seeds by the total number of fully developed seeds and then multiplying by 100.

2.3. Germination experiments

Germination experiments were carried out in two growth chambers at two temperatures (25°C and 30°C) respectively. Each treatment was replicated four times with 50 burrs per replicate. Burrs were sowed in 15 cm-diameter Petri dishes filled with 1 cm-thick wet river sand from the TGR. The sand was carefully washed using distilled water and dried at 120°C for 24 h before germination experiments.

Germination was defined as the emergence of an seedling from the sand. Germinated seeds were moved out of growth chambers every day after counting. If only one of them had germinated, the burr was marked by cutting the hooks at the end of the burr and replaced in the same Petri dish. If both seeds had germinated, the burr was removed from the growth chambers. Distilled water was added every day to maintain the sand wet. Thirty days after incubation, if no more germination had occurred over seven consecutive days, all seed in burrs were removed. The numbers of decayed and non-germinated seeds were recorded and their viability was tested as before.

2.4. Data analysis

The corrected germination rate index (CGRI) was calculated as:

\[ CGRI = \sum \frac{n_i}{d_i} / N \times 100\% \]

where \(d_i\) is the number of days after sowing, \(n_i\) is the number of seeds germinated on day \(i\), and \(N\) is the total number of sowed seeds (Song et al. 2008).

We used one-way and two-way ANOVA to determine the effects of temperature and duration of submersion on germination. Data were arcsine-square-root transformed if the assumption of homogeneous variance was not met. Duncan test was employed for post hoc comparisons for all treatments. Non parametric Kruskall-Wallis test was applied to determine the effect of submersion on seed viability as homogeneity of variance was not met even after being transformed. All the above analyses were performed with the SPSS 15.0 statistical package.

3. RESULTS

3.1. Seed viability

Seeds of X. sibiricum exhibited high tolerance of submersion and the mean percentage of viable seeds in each of the treatments was 99 % or higher (Table 1). The Kruskall-Wallis test indicated there were no significant differences among the treatments (\(P=0.383\)). The proportion of imperfectly developed seeds obtained from the burrs ranged from 1.25 to 12.5% with a mean of 6.78%.

3.2. Effect of water submersion and temperature

Results of ANOVA indicated that both germination percentage and germination rate were significantly influenced by the duration of submersion and temperature (Table 2). Interaction between the duration of submersion and the temperature was also significant (Table 2).

At 30°C, seeds of the control group showed the lowest germination percentage at 32.85%, while the seeds submerged for 300 days had a maximum of 55.4% germination (Fig. 1A). All germination percentages of submerged seeds were significantly higher than germination percentages of seeds of the control group at 30°C (\(P<0.05\)). This phenomenon clearly indicated that submersion promoted germination of X. sibiricum at 30°C. However, among the nine submersion treatments, submersion duration over prolonged periods of time did not induce an obvious and consistent increase in the percentage of germination, even if percentages of germination were statistically different (Fig. 1A). Germination percentages of
Impoundment flourished *Xanthium sibiricum* in Three Gorges Reservoir.

The submerged seeds for a duration ranging from 1 day to 180 days were not significantly different (*P*=0.133). In addition, germination percentage of the seeds with the longest submerged period of 300 days was not significantly different from that of the seeds submerged for seven days. At temperature of 30°C, the corrected germination rate index of seeds submerged for less than 15 days was less than 3%. However, the corrected germination rate index significantly increased to 7.6–22.3% for the seeds which had been inundated for more than 30 days (Fig. 1B). At 30°C, embryos of the seeds submerged for more than 30 days emerged readily from sand 24 hours after sowing, while the seedlings of other treatments, including the control group, did not emerge until the third day after incubation (Fig. 2B). It seemed that the effect of the duration of submersion had more effect on germination speed than on germination percentage at 30°C.

Germination percentage of the same treatment was significantly lower at 25°C than at 30°C (*P*<0.05, Fig. 1A, Fig. 2). At 25°C, the seeds submerged for a duration shorter than 120 days exhibited remarkably lower germination percentage (less than 1%) and three treatments (submerged for 1 day, 15 days and 120 days) did not germinate at all (Fig. 1A, Fig. 2A). At the same temperature, the seeds of three treatments which had undergone the longest submersion duration showed a significantly higher germination percentage and corrected germination rate index than other treatments (*P*<0.05, Fig. 1).

### Table 1. Viability of the seed of *Xanthium sibiricum* submerged for different durations. Values are means±S.E.

<table>
<thead>
<tr>
<th>Submersion duration (d)</th>
<th>Viable seed (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (control)</td>
<td>99.73±0.27</td>
</tr>
<tr>
<td>1</td>
<td>99.73±0.27</td>
</tr>
<tr>
<td>7</td>
<td>100.00±0.00</td>
</tr>
<tr>
<td>15</td>
<td>99.46±0.33</td>
</tr>
<tr>
<td>30</td>
<td>100.00±0.00</td>
</tr>
<tr>
<td>60</td>
<td>100.00±0.00</td>
</tr>
<tr>
<td>120</td>
<td>99.18±0.82</td>
</tr>
<tr>
<td>180</td>
<td>100.00±0.00</td>
</tr>
<tr>
<td>240</td>
<td>100.00±0.00</td>
</tr>
<tr>
<td>300</td>
<td>100.00±0.00</td>
</tr>
</tbody>
</table>

### Table 2. Summary of the two-way ANOVA on the effects of submersion duration and temperature on germination percentage and corrected germination rate index of the seeds of *Xanthium sibiricum.*

<table>
<thead>
<tr>
<th>Source</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>On germination percentage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Submersion duration (day)</td>
<td>0.980</td>
<td>9</td>
<td>0.109</td>
<td>33.223</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Temperature</td>
<td>6.896</td>
<td>1</td>
<td>6.896</td>
<td>2102.860</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Submersion duration (day) × Temperature</td>
<td>0.473</td>
<td>9</td>
<td>0.053</td>
<td>16.038</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Error</td>
<td>0.197</td>
<td>60</td>
<td>0.003</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>24.475</td>
<td>80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>On corrected germination rate index</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Submersion duration (day)</td>
<td>1.139</td>
<td>9</td>
<td>0.127</td>
<td>209.140</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Temperature</td>
<td>0.815</td>
<td>1</td>
<td>0.815</td>
<td>1347.739</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Submersion duration (day) × Temperature</td>
<td>0.087</td>
<td>9</td>
<td>0.010</td>
<td>15.948</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Error</td>
<td>0.036</td>
<td>60</td>
<td>0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>4.557</td>
<td>80</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4. DISCUSSION

4.1. Effect of flooding on seed viability and germination

The present research has revealed that seeds of *X. sibiricum* can tolerate submergence for at least ten months and recover with almost no damage. Flooding or submersion usually creates anoxic conditions (compared with air conduction) for seeds of riparian species. Anoxic stress is able to induce accumulation of toxic compounds of anaerobic metabolism, which may result in seed mortality during flooding if efficient mechanisms of removal of, or tolerance to, toxic compounds are not exhibited (Ferreira *et al.* 2007). Therefore, seeds of riparian species show important
Impoundment flourished *Xanthium sibiricum* in Three Gorges Reservoir.

Differences in flooding tolerance and germination after submersion. Seeds of riparian terrestrial species seem vulnerable to submersion. Guo *et al.* (1998) reported that embryo axes of the acorns of *Quercus velutina* were severely damaged after as little as 10 days of spring flooding. Kestring *et al.* (2009) found that only a few viable seeds could be extracted from fruits of *Mimosa bimucronata* after being submerged for 120 days. Generally seeds of aquatic plants are more tolerant of submer- sion. Voesenek and Blom (1992) tested the tolerance of *Rumex acetosa* to extended flooding and found that the percentage of viable achenes only declined 20% after immersion for two years. Baskin *et al.* (2000) found that nearly 100% of seeds of *Schoenoplectus purshianus* could germinate after flooding for 32 months at 35/20°C in light. However, there are also exceptions. Fogliatto *et al.* (2010) indicated that winter flooding for three months could result in as much as 95%
reduction in the germination rate of *Oryza sativa* because of seed decay. High moisture content has been considered to be harmful for the long-term storage of seeds in lower oxygen conditions (Infante Mata and Moreno-Casasola 2005). The burr and seed coat of *X. sibiricum* are highly permeable. In the seeds of *X. sibiricum*, passive and active water imbibition can be completed in 25 hours from the initiation of waterlogging (Esashi and Leopold 1968). The submerged seeds maintained high moisture content throughout the period of submersion. Therefore, there may be an efficient and undiscovered physiological mechanism of removal of toxic compounds of metabolism that protects the embryo of *X. sibiricum* from damage due to winter flooding of the TGR, and as a consequence, enough viable seeds are able to germinate and recolonize the drawdown area in the next exposure period. We don't know the maximum period of time which the seeds of *X. sibiricum* can endure continuous flooding. However, we suppose that it may not be as long as that of the seeds of *S. purshianus* and many other aquatic species, which are unable to imbibe water and subsequently germinate because of their waxy impervious seed coats (Clevering 1995).

Generally speaking, germination of many semi-terrestrial and terrestrial species has been shown to be inhibited by constant inundation, while germination of certain aquatic species is significantly facilitated (Hölzel and Otte 2004). Nevertheless, the results of our laboratory experiments suggest that germination of seeds of *X. sibiricum*, a typical terrestrial weed, is significantly improved by water inundation. This may be one reason that explains the ability of *X. sibiricum* to occupy natural riparian areas, shorelines and other similar habitats. *X. sibiricum* is frequently flooded in the summer in its normal habitat in the Three Gorges Reservoir region and usually exhibits a random or clumped spatial vegetation pattern. It usually occupies a small area because its shoots completely die if submerged for only a few days (personal observations). However, natural flooding of the Yangtze River and its tributaries in the TGR has been significantly constrained by operation of the TGD and the drawdown area is not subjected to cycles of submergence and emergence as frequently as was the former riparian area in summer. The newly created hydrological regime makes it more suitable for *X. sibiricum* to grow in the drawdown area during its growth period. This *X. sibiricum* outbreak phenomenon also reveals the importance of timing (season), magnitude and frequency, and characteristics of flooding for shaping riparian plant communities (Nilsson and Svedmark 2002).

Sesquiterpene lactones isolated from the leaf, stem, root and burr of *Xanthium* spp. possess active antiviral and antibacterial activities (Lavault *et al.* 2005) and are known to strongly inhibit the growth of the hypocotyl of wheat (Cutler and Cole 1983) and germination of lettuce seeds (Fratianne 1974). Water submergence is treated as a method to remove sesquiterpene lactones during the germination of the seed of *Xanthium* spp. (Waireng and Foda 1956, Tranel *et al.* 2003). Thus, we suppose that the decreased concentration of sesquiterpene lactones in the seed of *X. sibiricum* after water submergence may explain why its germination was accelerated. However, the extent to which the concentration of sesquiterpene lactones may have decreased in association with increasing period of inundation is not known. Further research should focus on this and its interaction with temperature.

4.2. Effect of temperature on germination

High temperature requirements for seed germination are very common in riparian and wetland flora (Thompson 1974, Grime *et al.* 1981, Hroudova *et al.* 1988; Jensch and Poschlod 2008) and have been considered to be an adaptation to germination in summer months when the water level recedes (Jensch and Poschlod, 2008). This is the similar case also for *X. sibiricum*. There was almost no germination at 25°C for the seed submerged for less than six months, while germination percentage for all treatments was significantly enhanced (more than doubled) when temperatures were increased from 25°C to 30°C. Moreover, seeds of *X. sibiricum* germinated significantly earlier and faster at 30°C (Figs 1 and 2) than at 25°C. Therefore it is clear that 30°C more ef-
Impoundment flourished *Xanthium sibiricum* in Three Gorges Reservoir

Effectively induces germination of *X. sibiricum* seeds than 25°C.

Air temperatures usually reach 30°C in May, just when the water level of the TGR declines to its lowest level and as a consequence its drawdown area is completely exposed. The temperature condition in May therefore favours germination of *X. sibiricum* and makes it easy for this plant to occupy available habitat successfully in the newly emerged drawdown area that is free of competing vegetation. Consequently the *X. sibiricum* population grows at high density and is widely distributed in the drawdown area. Its closed canopies formed by fast growing stems and leaves limit colonization of the stands by other floral species.

### 4.3. Seed dimorphism

Even at the relatively high temperature of 30°C, seed germination percentage for any treatment did not exceed 56%, and the percentage of burrs with both seeds germinated was no more than 8%, indicating that almost half of the seeds were still dormant. This phenomenon is probably explained by seed dimorphism in *X. sibiricum*, the burrs of which usually contain a pair of dimorphic seeds (Harper *et al.* 1970). The lower (larger) one has no innate dormancy and has high germination potential, while the upper (smaller) one is incapable of germinating at ordinary temperatures and defers germination considerably (Esashi and Leopold 1968, Shitaka and Hirose 1993). Thus, most of the germinated seeds in our experiment could be the lower one, although it was difficult for us to distinguish between the lower and upper seed when the seedling was formed, and by this means determine the proportion. Seed dimorphism is important for annual plants that grow in some environmental conditions (Imbert 2002) and the seed bank of non-germinated seeds is important for re-establishing the species (Cohen 1966). Considering its high endurance of flooding, we suppose that there may be a persistent seed bank consisting of non-germinated lower seeds of *X. sibiricum* in the former riparian zone. This seed bank is likely the origin of the rapid establishment of *X. sibiricum* in the drawdown area.

### 4.4. Management strategy

Although potentially beneficial, it will be difficult to eradicate *X. sibiricum* in the drawdown area due to the ability of its seed to germinate rapidly at high temperatures, its resistance to flooding, and its seed dimorphism. Traditional methods, such as weeding and spraying with herbicides, are either uneconomical or harmful to the environment. Some insects have been found to be biological control agents of *Xanthium* spp. (Logarzo *et al.* 2002, Shafique *et al.* 2007). However, their control and ecological effects will need to be tested if they are going to be introduced to the drawdown area. The reason for this is that it is not just the control of the weed that needs to be examined, but also the possibility of unwanted ecological effects if new organisms are introduced. The best way will be to find a biological agent that is already present in the TGR region and try to enhance it. The seeds of *X. sibiricum* usually mature in early October (personal observations) when the water of the TGR starts to rise. Therefore, advancing the impounding time to middle of September could be an effective method to depress seed yield and population size of *X. sibiricum* in the following exposure period. However, this has to be traded off against economic functions of the TGR and other environmental concerns, including land uses, transportation, control of sediment deposition, landslides and so on.

The TGR flooded to full capacity for the first time in the winter of 2010. Whether there will be any further change in the population and distribution of *X. sibiricum* is difficult to predict as the empirical database of the effect of winter flooding of the reservoir is sparse. Long-term observation and monitoring will be critical for establishing a feasible and efficient strategy to control this weed.

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