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ORIGINAL ARTICLE

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Fruit consumption and seed dispersal by birds in native vs. ex situ individuals of the endangered Chinese yew, *Taxus chinensis*

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Abstract The conservation success of endangered trees may depend on re-establishing or replacing the mutualisms that were important in their native habitats. In this study, we quantified avian frugivore diversity on individuals of the endangered Chinese yew (*Taxus chinensis*) in a botanical garden and at a natural site. We found that frugivore species diversity was lower in the botanical garden than in the natural site. In spite of the relatively low frugivore diversity, however, the ex-situ population of Chinese yew attracted similar disperser species to those in the natural population, and trees in the ex-situ population were visited more frequently than those in the natural population. Furthermore, the different perching behavior of dispersers resulted in different dispersal efficiencies. Although the Chinese bulbul (*Pycnonotus sinensis*) was the most common forager in the botanical garden, its dispersal efficiency was the lowest, and thus it could not like the role played by the mountain bulbul (*Hypsipetes maclellandii*) in the natural site. Only the red-billed blue magpie (*Urocissa erythrorhyncha*) provided a high-quality dispersal service in both sites. Our results highlight the ability of the Chinese yew to recruit seed dispersal agents in new habitats. However, if the newly recruited species is a low-quality disperser, the plants will depend more heavily on other avian vectors for regeneration.

Keywords Seed dispersal · Dispersal effectiveness · *Taxus chinensis* · Ex-situ population · Nature population

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Introduction

When endangered plant species are transplanted to botanical gardens in order to restore populations (Guerrant et al. 2004), their interactions with resident organisms may determine whether they establish successful (Carroll and Fox 2008). Non-native establishment is limited by competition with, or herbivory by, resident species (Cogni 2010). In contrast, mutualisms with pollinators or dispersers may permit population establishment in new environments (Bascompte and Jordano 2007; Morales et al. 2013).

Generally, many endangered fleshy-fruited plant species can easily attarcted native birds to dispersal its seeds (Howe and Smallwood 1982; Bacles et al. 2010; Carnicer et al. 2009). These seed dispersal are generally diffuse: many bird species interact with the plant species (Bascompte and Jordano 2007; Breitbach et al. 2010), although dispersal efficiency clearly differs among the different bird species (Jordano et al. 2007; Spiegel and Nathan 2007; Calviño-Cancela and Martín-Herrero 2009). It is vitally important for ex-situ plants to form mutualistic interactions with effective dispersers in botanical gardens; however, botanical gardens, which are subjected to a relatively high degree of human interference (Maunder 1992; Guerrant et al. 2004; Carroll and Fox 2008), differ significantly from natural sites. This difference may result in distinct variations in the seed dispersal.

Previous studies have shown that several alien fleshy-fruited plants could easily attarcted native birds to dispersal their seed in the new habitats (Gleditsch and Carlo

2011; Caughlin et al. 2012; Cruz et al. 2013). These plants can successfully establish in these habitats and may even become invasive (Gosper et al. 2005; Aslan 2011; Heleno et al. 2013). However, there are few reports regarding the seed dispersal of ex situ plants in new habitats.

The Chinese yew (*Taxus chinensis*) is a typical gymnosperm plant that is endemic to China. It has been listed as an endangered (EN) species by the IUCN (Thomas et al. 2013) and a first-class national protected plant in China. The regeneration of wild populations is limited (Deng et al. 2008) due to low pollination rates, seed-predator pressure, weak competitive ability of seedlings, and scarcity of microhabitats for recruitment (Li et al. 2000,2014a). To protect this endangered tree species, 11 seedlings were transplanted from their native area, the Lu Mountains in Jiangxi Province, to the Nanjing Botanical Garden Memorial Sun Yat-Sen in Jiangsu Province in the 1950s. These trees formed cones and produce seeds in the 1980s, and a regenerated population established that relies on avian dispersers (Lu et al. 2008). In this study, we quantified avian frugivore diversity on individuals of the endangered Chinese yew (*Taxus chinensis*) in a botanical garden and at a natural site. We addressed the following scientific questions: (1) How do bird dispersers differ in fruit consumption in native vs. ex situ individuals of Chinese yew, thus affecting seed removal in two sites? (2) How do bird dispersers perch after foraging in two sites, thus affecting seed dispersal effectiveness of Chinese yew?

Materials and methods

Species and study site

The Chinese yew has been listed as an endangered (EN) species by the IUCN (Thomas et al. 2013); it is a dioecious and wind-pollinated species that is distributed in evergreen broadleaf forests. Every year, female plants bear axillary cones which, in autumn, develop into fleshy arils (commonly, although incorrectly, referred to as ‘‘fruits’’) that contain a single seed. An average tree bears more than 4000 of these ‘‘fruits’’ (Lu et al. 2008; Thomas et al. 2013).

We selected two sites with dense populations of Chinese yew—one was a natural population in Anhui Province and the other was a ex situ population introduced into Jiangsu Province.

Anhui Province is an important native area for Chinese yew. The study site, Shuangkeng village (30°00′N, 117°18′E; AL: 540 m), is located on Xianyu Mountain in the southern part of Anhui Province. The annual average temperature is 16 °C, with a mean annual precipitation of 1626.4 mm. Human-modified patches of fir (*Cunninghamia lanceolata*) and bamboo (*Phyllostachys heterocycla*) and natural patches (broadleaf forest, mixed coniferous-broadleaf forest) are interlaced with plantations of tea (*Camellia sinensis*) to form a heterogeneous mosaic. The only mature population of yew in the area occupies approximately 2.33 ha in a human-modified bamboo patch located at the far end of the village. Seedlings and saplings were found in the patch in which mature trees were distributed (Deng et al. 2008).

An ex situ population of Chinese yew at the Sun-Yat Sen Memorial Botanical Garden, Nanjing, Jiangsu Province, China (32°5′N, 118°48′E; AL: 30–50 m), was also investigated. The garden covers a fenced area of approximately 186 ha at the south foot of the Purple Mountain, Jiangsu Province. No wild Chinese yew populations exist in Jiangsu Province. This ex situ population consisted of five females and four males. Seedlings and saplings were found on a hillside in an approximately 0.5-ha area that was separated from the mother trees by a small stream. The vegetation was dominated by *Pterocarya stenoptera* and *Quercus acutissi*, mixed with other species such as *Q. variabilis, Liquidambar formosana, Cryptomeria fortunei, Pinus thunbergii, Lindera glauca, Ilex purpurea, Photinia serrulata, Ilex cornuta, Cyrtomium fortunei, Asplenium incisum,* and *Milletia reticulata* (Li and Yin. 2004; Lu et al. 2008).

Frugivorous bird diversity in the botanical garden and natural site

To quantify the avian frugivore diversity in the vicinity of the population of Chinese yew, we estimated the species richness, diversity, and total abundance of frugivorous birds during the fruiting season using line transects. In both study sites, a 50-m-wide, 3-km-long transect was set across the plant population and two further transects (50 m wide, 3 km long) were set 100 m either side of, and parallel to, the first transect. Two investigators walked along the lines between 0700 and 1000 and 1600 and 1800 hours on two separate days and counted frugivorous birds (Gil-Tena et al. 2007). Each line transect was surveyed four times by the same observers. In total, each site was surveyed for 240 h over 2 years.

For each frugivore species, we retained for each species the highest of the three values recorded during three censuses. We then used the Shannon-Wiener index, Pielou species evenness index, Sorensen similarity index, and Simpson's dominance index to compare frugivore species diversity between the two habitats under investigation (Magurran 1988; Sutherland et al. 2004).

Fruit consumption of frugivorous birds in the botanical garden and natural site

We observed mother trees during two fruiting seasons (from late October to early December). Five mother trees were observed between 20 October and 10 December in 2011 and 2012 at the botanical garden and the natural site. Each mother tree was observed for an 8-h period starting at sunrise. Observations were made with binoculars from a hide placed at least 20 m from the trees. Observations ended when no more fruits remained on the mother trees. All observations were made in good weather.

For each bird that visited a mother tree, we recorded the species, time spent foraging in the tree, number of fruits foraged during the visit, and the fruit-handling behavior from the time of the bird's arrival until it left the tree. If a group of conspecific birds visited the tree and the behavior of all birds could not be observed simultaneously, we focused on the individual that was most visible (Altmann 1974; Breitbach et al. 2010). Seed dispersers were defined as bird species that were observed swallowing fruits or carrying fruits away in their beaks (Traveset 1994). We used *t* tests to compare the visiting frequency of both frugivorous bird species and disperser species at the botanical garden with those at the natural site (Quinn and Keough 2002).

Seed dispersal effectiveness of bird dispersers in the ex situ and natural populations

Previous studies have shown that the seeds of Chinese yew are mainly dispersed by Corvidae and Pycnonotidae (Lu et al. 2008; Li et al. 2014a). In our study, we focused on bird species in these two families and their post-foraging behaviors were tracked. The effectiveness of seed dispersal was evaluated by the spatial correlation between bird perching frequency and the quantity of 1-year-old seedlings, because the seedling numbers and its distribution are significantly affected by disperser behavior in patchy environments (Breitbach et al. 2010). A strong, positive spatial correlation between perching frequency and 1-year-old seedlings indicates that the bird is able to transport a relatively large number of seeds to seedling habitats, thereby contributing to the quality component of dispersal effectiveness (Breitbach et al. 2010, 2012; Puerta-Piñero et al. 2012).

Initially, 10×10 m^2 habitat cells were used to digitize two study sites. The 1-year-old seedlings ($H \leq 10$ cm) in each cell were then located. In all, we surveyed 48 sampling cells in the botanical garden and 72 cells in the natural site. We modeled seedling distribution at both sites using the biharmonic-spline surfaces interpolation method (Quinn and Keough 2002).

We observed the post-foraging behaviors of avian dispersers and recorded the habitat cells in which birds perched after they left the study trees. The perching locations of each bird were recorded every 30 s until the bird was lost from sight (Breitbach et al. 2010). These perching locations were used to identify characteristic landmarks near the study trees for later verification of estimates through measuring on maps. Spearman's rank correlation coefficient indices and a simple regression model were used to test the correlation between bird perching and seedling numbers at each study site (Quinn and Keough 2002).

Table 1 Diversity comparison of frugivore birds in a natural site and a botanical garden

Measure of diversity	Natural site	Botanical garden
Shannon-Wiener diversity	1.580	1.524
Species evenness index	0.682	0.654
Simpson's dominance index	0.045	0.800
Sorensen similarity index (%)	57.630	

Results

Frugivorous bird diversity in the botanical garden and natural site

During the fruiting seasons, we observed 32 and 27 frugivore species in the natural site and botanical garden, respectively. The composition of frugivore species overlapped between the sites (Similarity index 57.63 %), but species diversity differed between sites. There were fewer dominant species in the natural site than in the botanical garden, whereas frugivore species richness and total abundance was lower in the botanical garden than at the natural site (Table 1, Table S1).

Fruit consumption of frugivorous birds in the botanical garden and natural site

During 324 h of tree observations at each site, we recorded 324 visits of nine bird species that foraged seeds in the natural site and 576 visits of five such species in the botanical garden. The visiting frequency of frugivorous birds was significantly higher in the botanical garden (576 visits) than in the natural site (324 visits) ($t = -4.250$, $df = 2$, $P = 0.005$). Moreover, the species composition of the frugivorous birds differed between the two sites. In the natural site, the main foraging species were mountain bulbul (*Hypsipetes maclellandii*; 151 visits), red-billed blue magpie (*Urocissa erythrorhyncha*; 76 visits), and chestnut bulbul (*Hemixos castanonotus*; 43 visits) (Table 2). In the botanical garden, the main foraging species were Chinese bulbul (*Pycnonotus sinensis*; 406 visits), red-billed blue magpie (118 visits) and azure-winged magpie (*Cyanopica cyana*; 32 visits).

During the fruiting season, five bird species dispersed seeds following 244 visits in the natural site and four bird species were observed to disperse seeds following 563 visits in the botanical garden. The composition of disperser species differed between the two sites and the visiting frequency was significantly higher in the botanical garden than in the natural site ($t = -3.850$, $df = 2$, $P = 0.001$; Table 2).

Seed dispersal effectiveness of bird dispersers in ex situ and natural populations

In the seedling census, 221 and 208 seedlings were found in the natural site and botanical garden, respectively. All

Table 2 Frugivorous birds visiting *Taxus chinensis* in the botanical garden and natural site

Bird visitor	Feeding pattern	Visiting frequency		Feeding amount per visit		Feeding amount per unit time	
		Natural site	Botanical garden	Natural site	Botanical garden	Natural site	Botanical garden
Seed disperser							
Pycnonotus sinensis	S	×	406	×	5.1 ± 1.3	×	20.7 ± 13.3
Urocissa erythrorhyncha	S	76	118	6.2 ± 1.0	7.8 ± 1.3	4.7 ± 3.3	9.2 ± 7.8
Cyanopica cyanus	S	×	32	×	3.6 ± 1.7	×	1.2 ± 2.0
Zoothera dauma	S	5	7	5.6 ± 1.5	5.8 ± 5.0	0.3 ± 1.2	0.4 ± 1.6
Hypsipetes maclellandii	S	151	×	6.1 ± 2.0	×	9.2 ± 4.8	×
Hemixos castanonotus	S	43	×	5.5 ± 2.0	×	2.4 ± 1.6	×
Dendrocitta formosae	S	4	×	6.8 ± 2.6	×	0.3 ± 1.2	×
Pulp consumers							
Tarsiger cyanurus	P	×	13	×	1.5 ± 1.0	×	0.2 ± 1.2
Alcippe morrisonia	P	31	×	3.5 ± 1.0	×	1.1 ± 1.2	×
Abroscopus albogularis	P	30	×	5.1 ± 1.0	×	1.5 ± 1.4	×
Yuhina castaniceps	P	3	×	1.5 ± 1.6	×	0	×
Stachyris ruficeps	P	20	×	3.5 ± 1.5	×	0.7 ± 1.3	×
Total		324	576				

S swallow, P peck. Seed dispersers are those birds that swallow entire fruits, defecating or regurgitating the seeds. Pulp consumers are those species that peck the fruit pulp and discard the seed (Traveset, 1994). Unit time is an 8-h period starting at sunrise. Results are presented as the mean ± SE. x, species not recorded at a site

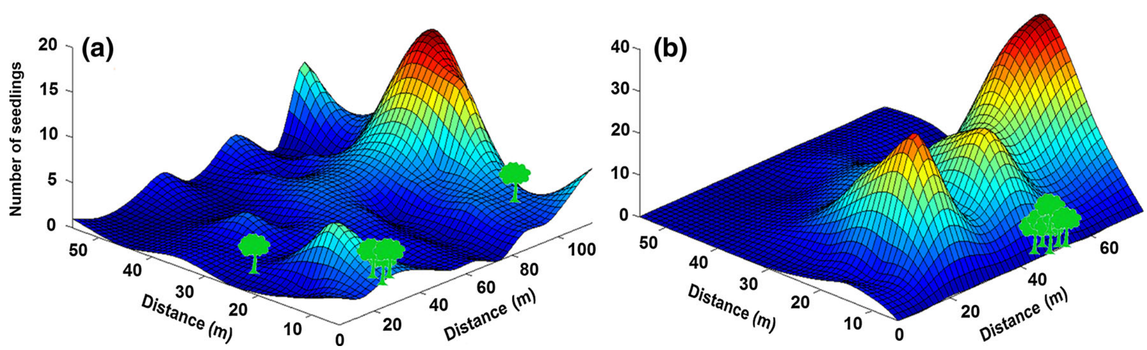

Fig. 1 Distribution of 1-year-old seedlings and mother trees of Chinese yew (*Taxus chinensis*) in a natural site **a** and a botanical garden. **b** Peaking values increase with the number of seedlings in the habitat cell. *Green* trees repesent mother trees (color figure online)

seedlings were aggregated within 100 m of mother trees (Fig. 1) showing a bird-dispersed pattern (Li et al. 2014a). The different perching behaviors of the main dispersers was associated with differences in dispersal effectiveness (Fig. 2).

At the natural site, both mountain bulbul and red-billed blue magpie provided a high-quality dispersal service. The perching frequencies of these birds were significantly correlated with seedling numbers (mountain bulbul: r = 0.428, P = 0; $y = 0.382 + 0.049x$, $R^2 = 0.544$, $df = 52$, $F = 60.799$, P = 0.001; red-billed blue magpie: r = 0.407, P = 0; $y = 0.374 + 0.054x$, $R^2 = 0.486$, $df = 52$, $F = 48.277$, P = 0.001; Fig. 2a, b).

In the botanical garden, the forager with the highest visit frequency, the Chinese bulbul, had low dispersal quality and its perching frequency was not significantly related to seedling numbers (r = −0.299, P = 0.064; $y = 0.912 - 0.310x$, $R^2 = 0.096$, $df = 24$, $F = 2.440$, P = 0.072; Fig. 2d). In contrast, the red-billed blue magpie was a high-quality disperser, as its perching frequency was significantly correlated with seedling numbers (r = 0.702, P = 0.001; $y = 0.755 + 0.164x$, $R^2 = 0.480$, $df = 24$, $F = 21.236$, P = 0; Fig. 2c).

Discussion

Seed dispersal system in the botanical garden and natural site

Establishment of seed dispersal system between ex situ plants and local birds implies successful ex situ conservation. Previous studies suggest that it is easy for bird-dispersed tree species to establish seed dispersal system in new habitats (Aslan 2011; Magdalena et al. 2011). With regard to the Chinese yew, the ex situ population surveyed in this study was able to attract local birds to forage seeds and form a seed dispersal system that included several avian dispersers (Table 2). However, there were some differences in the seed dispersal systems of the ex situ population and the natural population.

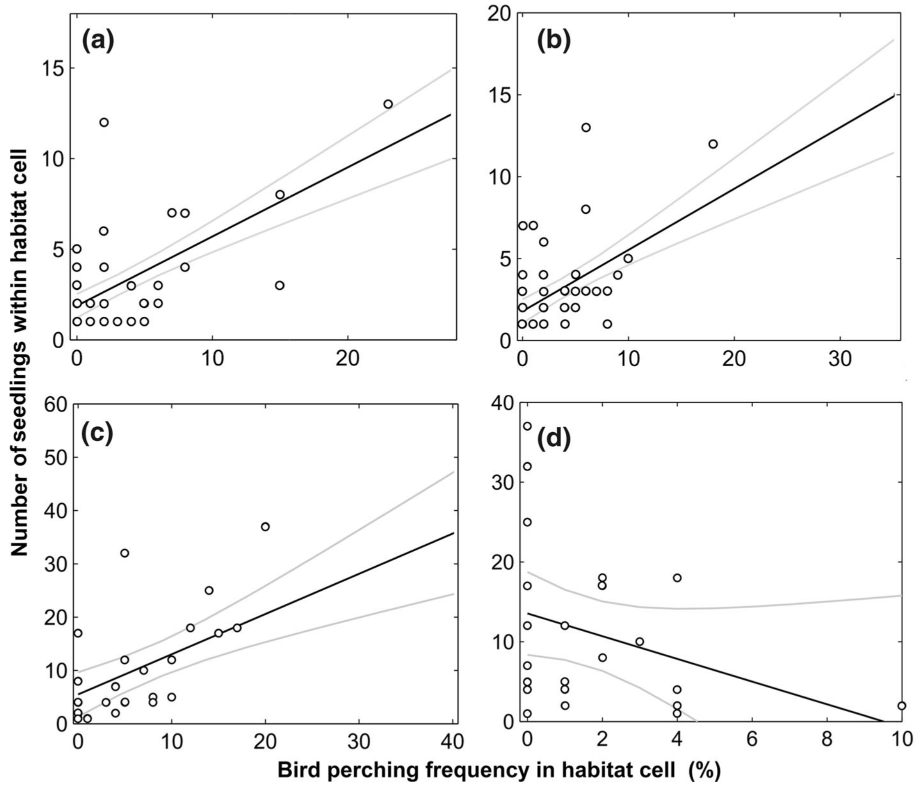

Fig. 2 Post-foraging perching behaviors of two main avian dispersers in a natural site (**a**, **b**) and a botanical garden (**c**, **d**) and their spatial correlation with the number of Chinese yew (*Taxus chinensis*) seedlings. The mountain bulbul *Hypsipetes maclellandii* (**a**), red-billed blue magpie *Urocissa erythrorhyncha* (**b**), red-billed blue magpie *U. erythrorhyncha* (**c**) and Chinese bulbul *Pycnonotus sinensis* (**d**). *Open circles* repesent observed data; *black lines* indicate the correlation between perching frequency and seedling number; *gray lines* indicate the 95 % confidence interval

In both seed dispersal systems, Chinese yew populations established seed dispersal systems with birds of the Pycnonotidae and Corvidae families (Table 2), similar to those in the Chinese yew populations in Zhejing and Fujiang (Li et al. 2014a, b). Stability of disperser species facilitates the formation of seed dispersal mutualisms (Bascompte and Jordano 2007). Moreover, Pycnonotidae and Corvidae have a relatively wide distribution and a relatively high degree of adaptability. These may be the main reasons why the ex situ study population was successfully established and may permit wider distribution of Chinese yew populations (Gao 2006). Our results suggest that disperser features should be considered before transporting endangered plants to new habitats (Burns 2003).

Disperser composition and visiting frequency are primarily affected by habitat structure and were different in the two seed dispersal systems studied. In the botanical garden, the forests consisted of artificial plants with a simple community structure, and there were relatively few shrub species (Li and Yin. 2004; Lu et al. 2008). This resulted in the absence of some frugivorous birds that require a shrub layer (Table 1, Table S1). These birds were therefore also missing from the seed dispersal system of the ex situ population (Table 2). In contrast, there are numerous broad-leaved, coniferous, and mixed forests in the vicinity of the natural site. In addition, the natural site has rich species diversity and the community structure is complex (Deng et al. 2008). This attracted a greater variety of frugivorous birds to the seed dispersal system in the natural site than in the botanical garden (Table 2, Table S1). However, the simple habitat structure of the botanical garden did not disrupt the seed dispersal mutualisms of the ex situ population. The visiting frequency of disperser species was higher in the botanical garden than in the natural habitat ($t = -3.850$, $df = 2$, $P = 0.001$). Two factors may contribute to the high frequency of visits in the botanical garden. First, the seed removal rate might be higher in the structurally simple habitat due to amplified fruit advertisement. This view is supported by a study of wild cherry (*Prunus avium* L.) (Breitbach et al. 2010). Second, in structurally complex habits, the relatively high dominance of disperser species may facilitate a high seed removal rate (Schupp et al. 2010). In the case of Chinese yew, more individuals of frugivore species may have joined the seed dispersal system of the ex situ population of plants (Table 1, Table 2, Table S1), thereby increasing seed removal rate.

Effects of post-foraging behaviors of bird dispersers on Chinese yew regeneration

After foraging, dispersers must decide how to move between habitats and how to select habitats. These decisions determine where seeds are deposited and, consequently, affect the spatial patterns of 1-year-old seedlings (Schupp et al. 2010). However, if the utilization of habitat by avian dispersers is highly consistent with the habitat that is suitable for plants, the dispersal efficiency of the birds is high (Breitbach et al. 2010; Schupp et al. 2010).

In the case of Chinese yew, the seedling distribution of ex situ populations and that of natural populations reflected a bird-dispersed pattern, but the aggregation peaks of seedlings in the two types of habitat were different (Fig. 1). The seedling distribution in the two sites was mainly influenced by the post-foraging behaviors of the seed dispersers (Fig. 2). In the natural site, most foraging Pycnonotidae and Corvidae birds efficiently dispersed seeds to regeneration habitat (Fig. 2a, b); disperser species from both families provided a good seed distribution service for yew regeneration. Once plants form a seed dispersal system with the primary foragers at a natural site, they can easily regenerate because most of their seeds are dispersed (Loiselle et al. 2007; McConkey and Brockelman 2011; Bueno et al. 2013). However, trees in botanical gardens must depend upon a different assemblage of avian vectors than those in natural habitats. In the present study, the Chinese bulbul was the primary forager in the botanical garden (Table 2). However, after foraging, this species transported the majority of seeds to an unsuitable habitat for regeneration (Fig. 2d), and is therefore an inefficient disperser. This suggests that in the botanical garden, the Chinese bulbul is not a key disperser. On the other hand, the red-billed blue magpie foraged less than the Chinese bulbul in the botanical garden, but often used habitat suitable for regeneration of the plants (Fig. 2c), thereby facilitating plant regeneration in the botanical garden. Seed dispersal systems in which the main disperser is a low-quality disperser not only exist in botanical gardens but also in natural sites, causing low regeneration rates of plants and affecting the dynamics of plant communities (Sethi and Howe. 2009; Wotton and Kelly 2011).

Our results highlight the ability of the Chinese yew to recruit seed dispersal agents in new habitats. However, if the newly recruited species is a low-quality disperser, the plants will depend more heavily on other avian vectors for regeneration.

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