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Nannophya pygmaea (Odonata: Libellulidae), an Endangered Dragonfly in Korea, Prefers Abandoned Paddy Fields in the Early Seral Stage

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ABSTRACT To characterize habitats of *Nannophya pygmaea* Rambur (the northern pygmyfly; Odonata: Lilbellulidae), which is endangered in Korea, we analyzed characteristics of surface water and soil, landscape properties, and vegetation types in 22 habitats in eight areas of Korea where nymphs *of N. pygmaea* have been found since 2005. We divided the habitats into two groups: DS (dwelling site) habitats, where *N. pygmaea* was observed at the time of the study, and PDS (past dwelling site) habitats, where *N. pygmaea* recently lived but is no longer found. The habitats were mostly located in former paddy fields on mountain slopes that have been abandoned for 3–7 yr. The main water sources for these habitats were ground water and surface runoff, and the water level was stable at 3–7 cm in depth. The habitats ranged from 300 to 1000 m^2 and were dominated by *Juncus effusus*, which formed tussock mounds. According to the hydrosere model of succession, *N. pygmaea* appeared mostly in the early stages of plant succession (the period ≈3–7 yr after the initiation of succession in former paddy fields) and *N. pygmaea* preferred habitats displaying the water and soil characteristics that are typical of the early stages of succession in abandoned paddy fields. These results indicate that the primary habitats of *N. pygmaea* in Korea are recently abandoned paddy fields that are in an oligotrophic state. As succession proceeds in these habitats, *N. pygmaea* disappears. A habitat management program should be launched to conserve the habitats and populations of *N. pygmaea*.

KEY WORDS habitat characteristics of *Nannophya pygmaea, Juncus effusus*, oligotrophic state of water, succession in abandoned paddy fields

Since the 1960s, Korea has experienced unprecedented economic growth and a dramatic increase in population, both of which have led to increasing environmental stress. The loss of species diversity is one of the most important problems resulting from environmental changes in Korea (Korean Ministry of Environment 2002). Economic development without concern for habitat destruction has caused sharp declines in the populations of many species. Accordingly, 221 species of wild plants and animals have recently been designated as endangered species (Korean Ministry of Environment 2006).

Fragmentation and loss of habitat severely threatens the survival of many species (Rouquette and Thompson 2005). In particular, wetlands are transitional zones between aquatic and terrestrial environments and provide habitats for aquatic insects such as dragonflies and damselflies (Mitsch and Gosselink 2000). Aquatic organisms are particularly sensitive to habitat destruction, degradation of water quality from drainage and pollution, and other environmental problems. All odonates (i.e., dragonflies and damselflies) require aquatic habitats for larval development and oviposition by mature adult females. Odonates are relatively widespread in freshwater habitats, and as top predators, they are important elements in freshwater ecosystems (Corbet 1962, Steytler and Samways 1995). They are also vulnerable to changes in environmental conditions (Oertli et al. 2002). Thus, Odonata have been suggested as valuable bioindicators of water quality and environmental disturbance (Watson et al. 1982, Castella 1987).

Nannophya pygmaea Rambur, designated by the Korean Ministry of Environment as an endangered species, is distributed in East Asia and is one of the smallest (≈16 mm in length) and most beautiful Anisoptera species (Bae et al. 1999). Although *N. pygmaea* is widely distributed in central China and southern Japan, *N. pygmaea* is rare in Korea, and the number of individuals is believed to be decreasing (Kim 1997, Won et al. 2005). In addition, *N. pygmaea* is a less efficient flier than other dragonfly species, which makes it more difficult for them to disperse from isolated habitats. Consequently, inbreeding by *N. pygmaea* in isolated pockets of suitable habitat might cause the loss of genetic diversity in the long term. A

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genetic map produced by the Korean National Institute of Biological Resources showed a higher genetic diversity index (GDI) for *N. pygmaea* in a larger and less fragmented area of habitat in Mungyeong (GDI: 0.56) than in a smaller, more isolated habitat in Muui-do (GDI: 0.00) (Kim et al. 2007). Thus, Kim et al. (2007) suggested that habitat loss might lead to local extinction of *N. pygmaea.* Although *N. pygmaea* is beautiful, rare, and an important indicator of habitat quality, very few scientific studies have examined the ecology and habitat characteristics for this species (Bae et al. 1999). Until now, most studies on *N. pygmaea* have focused on morphology and distribution (Fujita et al. 1978, Kim 1997, Bae 1998, Bae et al. 1999) or breeding patterns (Tsubaki et al. 1994, Tsubaki and Ono 1995, Kim et al. 2006). There has been little scientific study of the factors leading to declining populations in Korea. Understanding the relationship between a species and its environment is crucial for conservation or restoration/recovery of endangered species.

Detailed information about the physical and biotic conditions in *N. pygmaea* habitats will be necessary to design appropriate management plans for their conservation and restoration. In the absence of detailed autecological information, the best approach is to examine a variety of habitats that vary in water conditions and aquatic/marginal vegetation to determine which features are associated with the presence of a healthy Odonata fauna (Steytler and Samways 1995). This study analyzed environmental conditions including topographic features, vegetation, and physical and chemical characteristics of soil and water in abandoned paddy fields where *N. pygmaea* had recently dwelled or was present at the time of the study. The results of this study provide basic data for use in designing effective conservation and restoration programs for *N. pygmaea* habitat.

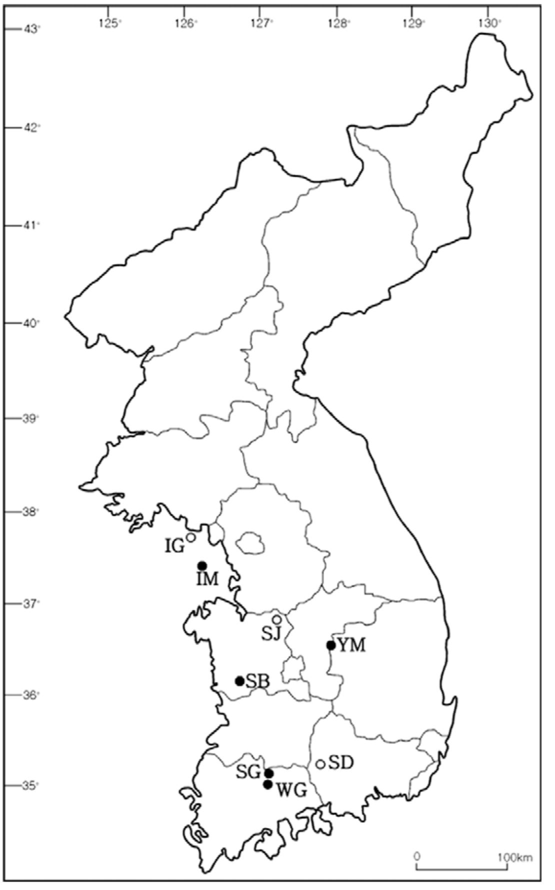

Fig. 1. Location of the eight study sites in Korea. *N. pygmaea* DS and PDS. IM, Incheon Muui-do; SG, Singi-ri Gokseong; YM, Yoolsu-ri Mungyeong; WG, Wolbong-ri Gokseong; SB, Suckdong-ri Buyeo; IG, Incheon Gyodong-do; SD, Sancheong Dunchul mountain; SJ, Sanggae-ri Jincheon; ●, DS; ○, PDS.

Materials and Methods

Study Sites. We selected 22 habitats in eight areas spanning the range of climatic conditions and geographic regions in South Korea for this study based on media reports and national surveys (Korean Ministry of Environment, unpublished data). We divided the habitats into two groups: one included 16 habitats designated as dwelling sites (DS) where *N. pygmaea* were recorded as present in 2006, and the other included 6 habitats where *N. pygmaea* was recorded as absent in 2006 (Korean Ministry of Environment, unpublished data) but had been recorded in the preceding years, designated as past dwelling sites (PDS; Fig. 1). All sites were terraced paddy fields in mountain valleys (Table 1). The age of the fallows was determined from interviews with local farmers combined with tree ring counts from woody species established in the older fields. Water sources at the sites included surface run-off from rainfall and ground water. The water level does not exceed ≈15 cm because of the banks around the paddy fields. The study of habitat characteristics was performed mainly in 2006 from May to August, when *N. pygmaea* adults appear and oviposition occurs. One habitat (Suckdong-ri Buyeo) was additionally studied in 2007.

Topographical Features and Plant Community Surveys. The habitats were surveyed for studying the topographical features including the size and surface of the habitats. After determining the borders for the wetlands, we studied vegetation communities and drew the vegetation maps at 1-m intervals along the longitudinal and latitudinal lines. Identification of plant species followed Lee (2003, 2006). The maps were converted into digital data using the computer-aided design (CAD 2007) program, and the size of habitats and the area of each plant community at each site was calculated.

Soil Analysis. We sampled the soils from overall 22 habitats of DS and PDS. Considering the habitat size or total length of the habitats, we took three to five samples at each habitat. Top soils from a depth of 0–5 cm were taken by using a soil hand auger. We mixed the soil samples from each habitat, removed gravel and large organic items from the sample, and passed it through a 2-mm sieve (standard sieve #10).

Table 1. Brief descriptions of *N. pygmaea* habitats surveyed in eight areas of South Korea

	Habitat no.	Inhabitation	Habitat size (m^2)	Ratio of vegetation cover (%)	Fallow age (yr)
Incheon Muui-do	1	DS	1,153.1	52.4	3
	2	DS	126.0	40.5	
Singi-ri Gokseong	1	DS	208.9	100.0	3–5
Yoolsu-ri Mungyeong	1	DS	182.6	100.0	3–5
	2	DS	366.9	100.0	
	3	DS	203.0	100.0	
	4	DS	113.9	100.0	
	5	DS	232.2	100.0	
	6	DS	165.0	100.0	
	7	DS	98.2	100.0	
Wolbong-ri Gokseong	1	DS	749.0	94.3	6
	2	DS	745.2	100.0	
	3	DS	712.0	91.2	
	4	DS	542.3	76.3	
Suckdong-ri Buyeo	1	DS	105.4	99.9	7
	2	DS	148.5	92.5	
Incheon Gyodong-do	1	PDS	1,736.2	100.0	7
	2	PDS	2,664.3	91.9	
Sancheong Dunchul mountain	1	PDS	1,127.0	100.0	7–8
	2	PDS	302.1	100.0	
Sanggae-ri Jincheon	1	PDS	377.1	100.0	7–8
	2	PDS	1,304.6	100.0	

We measured PO_4-P, NO_3-N, NH_4-N, and moisture from the fresh soil samples and then measured soil texture, organic matter content, airdry moisture content, pH, conductivity, total dissolved solids, total H, total N, total C, and cations (K^+, Ca^{2+}, Na^+, Mg^{2+}) after air-drying the samples in the laboratory. The soil texture was determined using hydrometer analysis and the texture triangle (Sheldrick and Wang 1993). The organic matter content was analyzed using the loss on ignition method (LOI; Boyle 2004). Soil moisture was measured as both fresh water moisture, which counts the total amount of water in the sample, and airdry moisture, which reflects the ability of the soil particles to retain moisture (Topp 1993).

We made soil solutions by mixing soil with distilled water at a mass ratio of 1 to 5 and measured soil pH using a pH meter (model AP 63; Fisher, Pittsburgh, PA) and conductivity and total dissolved solids (TDS) using a conductivity/TDS meter (model 311 checkmate II; Corning, Corning, NY).

Nitrate N and ammonium N were extracted with a 2 M KCl solution and measured colorimetrically by the hydrazine and indophenols method (Murphy and Riley 1962; Kamphake et al. 1967). PO_4–P was extracted with Bray No.1 solution (Bray and Kurtz 1945) and measured colorimetrically by the ascorbic acid reduction method (Solorzano 1969). Total carbon (T-C), hydrogen (T-H), and nitrogen (T-N) were determined with an element analyzer (model EA1110; CE Instruments, Wigan, United Kingdom) at the National Center for Inter-University Research Facilities, Seoul National University. Extractable Ca, Mg, K, and Na were extracted with 1 N ammonium acetate solution (Allen et al. 1974) and measured with an atomic absorption spectrometer (model AA240FS; VARIAN, Mulgrave, Australia).

Water Analysis. We measured the water depth (WD) and turbidity (TUR) of the sites in the field. WD was defined as the distance from the water table to the soil surface; it was positive when the soil surface was below the water table and negative when the soil surface was above the water table. TUR was measured using a turbidimeter (HACH 2110P; HACH, Loveland, CO). Dissolved oxygen (DO), conductivity (CON), and total dissolved solids (TDSs) were measured in the field using a Corning checkmate (model 311 checkmate II; Corning, Lowell, MA), and the water pH was measured using a pH meter (model AP 63; Fisher).

We collected duplicate samples of water from each site and filtered each sample with a membrane filter (pore size, 0.45 μm) before analysis in the laboratory. We measured NO_3-N, NH_4-N, and PO_4-P in the water samples using the hydrazine method (Kamphake et al. 1967), the indo-phenol method (Murphy and Riley 1962), and the ascorbic acid reduction method (Solorzano 1969), respectively. The contents of K^+, Ca^{2+}, Na^+, and Mg^{2+} in the samples were measured using an atomic absorption spectrometer (model AA240FS; VARIAN).

Data Analysis. The studied plant communities were classified as stage I, II, and III according to seral stages of abandoned paddy fields (Lee et al. 2002). The seral stage was determined according to the water level: Stage I is open water; the water is deeper in stage I than in the other stages. Stage II has water levels from 0 to 15 cm—including areas that can be inhabited by *N. pygmaea* nymphs (Jeong 2007). Stage III is areas where soil is exposed to air.

We used multivariate analysis of variance (MANOVA) to test for significant differences between DS and PDS in soil and water characteristics using the SPSS program (v. 13.0) with a significance level of 0.05.

Results

Topographical Features. *Nannophya pygmaea* were mostly found in abandoned terraced paddy fields in

Table 2. Major dominant plant communites in successional stages modifed from Lee et al. (2002) in the habitats of *N. pygmaea*

Successional stage	Major dominant plant communities
Stage I	Open water with submerged grass
	Monochoria vaginalis var. *plantaginea* (Roxb.) Solms
	Scirpus juncoides var. *hotarui* (Ohwi) Ohwi
Stage II-1	*Juncus effuses* var. *decipiens* Buchen
	Typha orientalis C. Persl
Stage II-2	*Juncus effuses* var. *decipiens* Buchen
	Persicaria thunbergii H. Gross
	Gramineae.
Stage III	*Salix koriyanagi* Kimura
	Alnus japonica Stedu.
	Artemisia princeps Pamp.
	Phragmites communis Trin.

mountain valleys that had been left fallow for 3–8 yr (Table 1). The average size of the habitats studied was 607.4 m^2. These habitats had an average altitude of 180.3 m above sea level and typically comprised two to seven consecutively terraced fields that were irrigated by ground water and surface run-off. The water level in these habitats generally ranged from 10 to 15 cm during the period from May to August because the drainage was regulated artificially by banks at the rim of the habitats. However, the water level in *Juncus*- and *Persicaria*-dominated microhabitats, where *N. pygmaea* larvae were found, ranged from 3 to 7 cm.

Plant Community. Average percent plant coverage in the habitats was 90.4% at DS and 98.7% at PDS (Table 1). The study sites included 70 grass and 10 rush communities. The plant communities were classified after a modified version of the hydrosere model of succession of Lee et al. (2002) (Table 2). Stage I refers to open water areas with submerged grass and water levels >15 and floating leaved plant community. Stage II habitats are comprised of grass and rush communities with water levels ranging from 0 to 15 cm. Stage III habitats include woody and land plants, with no surface water. Water levels for stage II were appropriate for nymphs of *N. pygmaea,* so we divided stage II into two substages, II-1 and II-2, depending on the presence of *N. pygmaea;* major plant communities where *N. pygmaea* appeared were designated as stage II-1 and other stage II communities were designated as stage II-2. There were no plants in stage I, stage II-1 was dominated by *Juncus effusus,* stage II-2 was dominated by *Persicaria thunbergii* and *Typha orientalis,* and stage III was dominated by *Artemisia princeps* and *Phragmites communis.* The *Juncus* species, which was dominant in stage II-2 PDS, showed larger tussocks at stage II-2 sites than stage II-1 sites. Although the tussocks in DS are generally 10–15 cm in diameter and <65 cm in height, the tussocks in PDS are 30–45 cm in diameter and >100 cm in height. The cover ratio of the plant communities of stage I and II-1 in DS is higher than PDS (Fig. 2). In contrast, the ratio of stage II-2 and III in PDS is higher than DS. This result leads to the discussion on the relationship between the presence of *N. pygmaea* and the succession of the habitats.

There were 68 plant communities in DS, but most *N. pygmaea* nymphs were observed in 23 stage II-1 plant communities. Among these 23 plant communities, the *Juncus* community had the largest coverage (38.3% of the total area), whereas the *Typha orientalis–Juncus effusus* community comprised 14.1% of total area, the *Juncus effusus–Leersia japonica* community comprised 12.7% of total area, the *Persicaria* community comprised 8.1% of total area, and the *Juncus effusus–Persicaria thunbergii* community comprised 5.5% of total area. Also, annual plant species, including *Persicaria thunbergii, Aneilema keisak,* and *Persicaria hydropiper,* were common in these areas. In DS stage II-1 plant communities, there were thick organic matter layers composed of entangled roots and dead roots, and small tussocks were starting to develop, separated by areas of open water ≈15 to 30 cm in diameter. The height of the plants in these early stage tussocks was <100 cm.

Soil and Water Characteristics. MANOVA on the soil and water variables indicated that fresh moisture, LOI, conductivity, EMg, NO_3-N, and total H in the soil

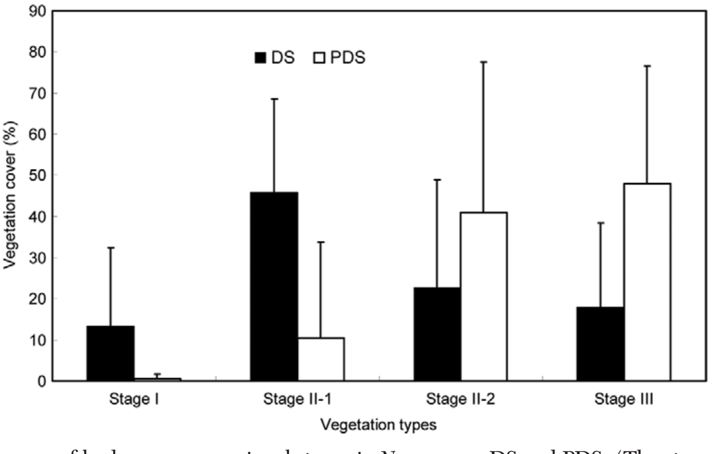

Fig. 2. Vegetation cover of hydrosere successional stages in *N. pygmaea* DS and PDS. (The stages of vegetaion type for plant communities were refered from Lee et al. 2002.)

Table 3. Descriptive statistics and MANOVA test for DS and PDS environmental variables

	Dependent variable	DS/PDS	Minimum	Maximum	Mean	SE	F	P
Soil	Fresh moisture (%)	DS	24.857	43.640	35.284	1.908	8.078	0.010[a]
		PDS	31.264	64.577	45.666	3.115		
	Airdry moisture (%)	DS	0.851	9.081	3.764	0.675	0.047	0.831
		PDS	1.624	11.138	4.044	1.102		
	LOI (%)	DS	2.242	6.862	4.874	0.842	5.281	0.032[a]
		PDS	5.174	21.083	8.580	1.375		
	Conductivity (μS/cm)	DS	9.567	51.767	28.355	2.948	16.033	0.001[a]
		PDS	25.600	69.000	50.960	4.814		
	pH	DS	4.710	5.363	5.026	0.051	3.247	0.087
		PDS	4.558	5.080	4.851	0.083		
	EK (cmol/kg)	DS	0.026	0.077	0.045	0.004	3.437	0.079
		PDS	0.033	0.103	0.060	0.007		
	ECa (cmol/kg)	DS	0.627	2.640	1.654	1.876	2.827	0.108
		PDS	1.383	38.277	7.695	3.064		
	ENa (cmol/kg)	DS	0.006	0.122	0.067	0.014	0.412	0.528
		PDS	0.006	0.204	0.084	0.023		
	EMg (cmol/kg)	DS	0.014	0.321	0.175	0.037	6.800	0.017[a]
		PDS	0.046	0.605	0.360	0.060		
	PO_4-P (mg/kg)	DS	13.862	356.925	154.931	29.683	0.247	0.625
		PDS	50.363	386.392	126.680	48.472		
	NO_3-N (mg/kg)	DS	2.029	8.060	5.060	0.536	5.731	0.027[a]
		PDS	4.156	12.532	7.515	0.875		
	NH_4-N (mg/kg)	DS	1.425	43.272	11.272	3.707	2.356	0.140
		PDS	3.339	61.321	22.168	6.054		
	Total N (%)	DS	0.022	0.178	0.113	0.035	1.562	0.226
		PDS	0.058	0.734	0.197	0.057		
	Total C (%)	DS	0.527	2.928	1.741	0.573	3.317	0.084
		PDS	1.326	12.592	3.739	0.935		
	Total H (%)	DS	0.295	0.752	0.527	0.067	5.883	0.025[a]
		PDS	0.565	1.750	0.839	0.110		
Water	Conductivity (μS/cm)	DS	23.467	80.920	35.616	4.058	0.636	0.435
		PDS	22.067	79.125	41.811	6.627		
	Total dissolved solid (mg/liter)	DS	11.697	40.380	18.155	1.837	0.333	0.571
		PDS	11.270	32.765	20.183	2.999		
	Turbidity (NTU)	DS	2.785	31.567	13.021	4.933	3.967	0.060
		PDS	3.490	98.200	31.833	8.055		
	pH	DS	5.003	6.595	6.084	0.085	0.278	0.604
		PDS	5.757	6.277	5.998	0.139		
	K (cmol/kg)	DS	0.149	0.873	0.306	0.069	3.745	0.067
		PDS	0.157	1.368	0.561	0.112		
	Ca (cmol/kg)	DS	0.447	2.310	1.443	0.188	1.855	0.188
		PDS	1.016	3.996	1.934	0.308		
	Na (cmol/kg)	DS	1.647	8.696	3.530	0.485	0.125	0.727
		PDS	2.328	4.628	3.859	0.792		
	Mg (cmol/kg)	DS	0.177	0.774	0.383	0.092	3.927	0.061
		PDS	0.223	1.772	0.732	0.150		
	PO_4-P (mg/kg)	DS	0.000	0.047	0.020	0.003	0.021	0.887
		PDS	0.000	0.030	0.020	0.005		
	NO_3-N (mg/kg)	DS	0.005	0.196	0.053	0.013	0.009	0.924
		PDS	0.017	0.077	0.050	0.021		
	NH_4-N (mg/kg)	DS	0.001	0.042	0.021	0.011	4.873	0.039[a]
		PDS	0.008	0.183	0.066	0.018		

Degree of freedom: 1 (group), 20 (error), 21 (total).
[a] $P < 0.05$.

characteristics showed significant differences at the level of $P < 0.05$ (Table 3). The water characteristics have significant differences in the content of NH_4-N. The above environmental variables were lower in DS than in PDS.

Soil texture is an important determinant of environmental conditions affecting nymphs of *N. pygmaea.* DS soils were comprised of 70% sandy loam, 25% loam, and 5% loamy sand. Silt loam was not found in DS soils. In PDS soils, sandy loams and silt loams each comprised 42% of soils, whereas loamy sand comprised the remaining 16%.

Discussion

Relationship Between Succession of Abandoned Paddy Fields and Use of These Habitats by *N. pygmaea.* *Nannophya pygmaea* has been observed only in relatively small abandoned paddy fields in Korea compared with the area of paddy fields in plains. In general, paddy fields in plains are ≥3,000 m^2 and have large area in Korea, but paddy fields in a mountainous valley are relatively small and could have a potential of the habitats given the fields abandoned. Small abandoned paddy fields are generally located in relatively undisturbed areas of mountains in Korea, and they function in a similar manner to natural wetlands (Park et al. 2006). Features of the watershed and the location of an abandoned paddy determine whether the terraced fields remain flooded (Byun et al. 2008). Generally, abandoned paddy fields in mountain valleys have greater drainage than those located on plains, because levees on the slopes gradually collapse if they are not maintained. The vegetation communities also change with the environmental change and secondary succession is accelerated. Thereafter, the vegetational change in the *N. pygmaea* habitats could alter the habitability of the environment.

Vegetation is also one of the major factors affecting habitat selection by Odonata as well as habitat size (Oertli et al. 2002). Secondary succession is a complex multifactorial process (Bazzaz 1990, Peet 1992, Lee et al. 2002) that is difficult to generalize. In our study, the original environments before the initiation of secondary succession were all abandoned paddy fields that were fairly similar to each other, which made it easier to collect data reflecting the return to a more natural state in a systematic way. Many previous studies have described plant distribution in abandoned paddy fields and the resulting changes in the physical environment associated with secondary succession (Kim and Jung 1995, Na et al. 1996, Comin et al. 2001, Lee et al. 2002, Kang et al. 2003). Accordingly, biotas can be differentiated along a chronosequence from cultivated paddy to native woodland (Han et al. 2007); the distribution of biota is affected by the successional stage.

Our results of the plant community survey on the PDS and DS suggest that the inhabitation of *N. pygmaea* can be related to the chronosequence of paddy field succession as well (Fig. 2). The present habitats of *N. pygmaea* are in the early seral stage of succession in abandoned paddy fields, indicating that *N. pygmaea* tend to appear in abandoned paddy fields of the early seral stages. As succession of habitats proceed and they become unpreferable for inhabitation, *N. pygmaea* could locally go extinct or leave for other habitats of early seral stage.

In addition, succession in abandoned paddy fields of early seral stage can cause another effect. The succession of habitats generally leads to the change of environmental factors and the appearance of new animal species. The immigration of other species causes an increase in abundance of carnivore species such as Coleoptera or Amphibia, which are predators of *N. pygmaea* (Jeong 2007). *N. pygmaea* may also be outcompeted by other, newly arrived species (Schaffner and Anholt 2004). Indeed, the Shannon- Weaver diversity indices (H') for aquatic invertebrates at Incheon Muui-do and Yoolsu-ri Mungyeong were 1.74–1.99 and 1.04–2.00, respectively, indicating that the values were relatively low (Y. J. Bae, unpublished data).

Major Plant Group Characteristics of *N. pygmaea* Habitats. The plant groups most commonly associated with *N. pygmaea* were the tussock-forming rush, *Juncus effusus*, and the annual forb. These dominant species in the DS have been shown to facilitate colonization by nonaerenchymatous species without gas spaces in the leaf (Ervin 2005), a process that is likely mediated through characteristics of the tussock mound, such as accumulation of large quantities of detritus from senescent culms (Wetzel and Howe 1999, Kuehn et al. 2000). Oxygenation of these accumulating sediments by *Juncus* roots and rhizomes could create favorable microhabitats for colonizing species in *J. effusus*–dominated wetlands. Previous research has suggested that established wetland plants may enhance recruitment of new species by providing a stable substratum for rooting and protection from water movements (Wilson and Keddy 1986) and increased local temperatures (Chapin et al. 1979, Ervin 2007). Thus, *Juncus* tussocks may provide *N. pygmaea* nymphs with safe and warm microhabitats that are buffered against changes in the water level. The canopy height of *J. effusus* varies across seasons (Ervin 2005). *N. pygmaea* usually flies slowly ≈30 cm above the water surface, and *Juncus* tussocks provide suitable perching sites for both nymphs and adults. Adults preferentially choose these plants for perching sites while searching for mates and copulating and for oviposition, because eggs are laid in the water near the roots of "phalanx" (Tsubaki et al. 1994). Also, because of their tendency to accumulate sediments, *Juncus* tussocks grew larger in older abandoned paddy fields. Therefore, *J. effusus* may be an indicator of the suitability of habitat for *N. pygmaea* because they reflect the biological age (or rather, stage) of the habitat.

Emergent dicots and the roots of in-channel emergent dicots were preferred by the damselfly, *Coenagrion mercuriale* for its developing larvae (Rouquette and Thompson 2005), and an annual forb, *Persicaria thunbergii* (height = 30–45 cm), is also able to provide shelter and potential perching sites for *N. pygmaea.* Adults preferentially choose such plants for oviposition, because eggs are laid directly into the stems of submerged and emergent plants. *Persicaria* grows in water of 5−10 cm depth (Lee 2003), which is in the range favored by *N. pygmaea* (3–7 cm). Accordingly, the presence of *Persicaria* can indicate water levels appropriate for *N. pygmaea.* However, as the area of coverage by *Persicaria* increases, oviposition by *N. pygmaea* becomes more difficult. *N. pygmaea* seems to avoid habitats containing reeds and willow shrubs, probably because they cast shade onto the watercourse, reducing the temperature and water level (Rouquette and Thompson 2005).

Abiotic Characteristics of *N. pygmaea* Habitats. Fresh water moisture and LOI of PDS soils were higher than those of DS soils, and soil textures in PDS were finer, containing less sand and more silt. These physical characteristics reflect the local plant community, as the soils form the substrate of the habitat for *N. pygmaea* nymphs. In wetlands, variation in soil organic matter and water content is closely related to the succession of vegetation (Nilsson et al. 1989, Kim and Jung 1995). The soil texture is affected by the processes of soil genesis and plant adaptation and determines the productivity, development, and the permeability of organic and inorganic matter in the soil (Kim and Jung 1995). As succession proceeds in abandoned paddy fields, the water content, and organic matter in the soil increase and soil particles became finer (Yun 2007). That is, the soils in DS could be more oligotrophic than the soils in PDS. Significant differences in soil characteristics like LOI, conductivity, and NO_3-N and water characteristics like NH_4-N, in *N. pygmaea* habitats suggest that DS are in a more oligotrophic state than PDS.

Conclusion and Conservation Implication. The distribution of wetland plants is dependent on soil and water environmental factors (Heegaard et al. 2001). The hydrological gradient (from permanently dry to permanently wet) is one of the main determinants of the distribution of plant species (Riis and Hawes 2002, Kwon et al. 2007). In our study, the distribution of *N. pygmaea* could be associated with the plant succession and the nutrient contents of soils and water in abandoned paddy field habitats. The results of this study suggest that *N. pygmaea* is likely to inhabit abandoned paddy fields in earlier successional stage. Therefore, the management of *N. pygmaea* habitats should be performed under considering the following.

1. The habitats where *N. pygmaea* persist are in earlier stage of hydrosere succession in abandoned paddy fields compared with the habitats where *N. pygmaea* disappear. Thus, the development of the habitats of *N. pygmaea* might need the areas where hydrosere succession just begins.
2. The plant compositions of the present habitats of *N. pygmaea* consists of mainly a tussock-forming rush, *J. effusus,* and an annual forb, *Persicaria,* which probably provide suitable environments for the inhabitation. However, the succession of the habitats could lead to the change of dominant plant community. Therefore, the management of water level at 3–7 cm might be needed to maintain earlier successional plants.
3. The soil and water characteristics of the present habitats are in a more oligotrophic state than the *N. pygmaea*–disappearing habitats. The change to more trophic state in the environments with the succession of the habitats could cause higher biodiversity and influence the suitability for *N. pygmaea.* Thus, the newly constructed habitats need to be maintained in relatively oligotrophic state to keep the favorable environmental habitats for *N. pygmaea.*

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