Paddy Water Environ (2014) 12(Supp. 1):S29–S40
DOI 10.1007/s10333-014-0437-z

ARTICLE

Classifying plant species indicators of eutrophication in Korean lakes

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Received: 8 January 2014 / Revised: 4 April 2014 / Accepted: 6 April 2014 / Published online: 19 April 2014

Abstract The objectives of this study were to establish a method of classifying plants as indicator species of eutrophication, as a key metric for assessing lake ecosystem health, and to select sensitive and tolerant plant species among aquatic macrophytes and hygrophytes. Thus, 38 natural and artificial lakes throughout Korea were investigated. The distribution and abundance of plant species were investigated. As a measure of eutrophication, the modified trophic state index (TSI_{KO}), derived from total phosphorus and chlorophyll a, was used. Using TSI_{KO} criteria and the response curves of plants to TSI_{KO}, a selection method of classifying sensitive and tolerant species was developed. Overall, 15 sensitive and 11 tolerant species among 117 macrophytes and hygrophytes were classified. The applicability of the selected indicator species was verified by a comparison with the results of a multimetric analysis using eight variables. The results suggest that the selected indicator species is expected to be useful as a metric for assessing lake ecosystem health.

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Keywords Indicator · Aquatic macrophyte · Sensitive plant species · Tolerant plant species · Eutrophication · Trophic state index for Korea · Lake health assessment

Introduction

Biologists have been developing indicators of ecosystem integrity, seeking biological measures that show sensitive and consistent responses to specific stressors or degradation for over three decades (Albert and Minc 2004). These efforts had been initiated for fish and invertebrates, and have been widely applied as measures of stream health (Karr 1981; Karr and Chu 1997). Subsequently, a multimetric system using plants to assess aquatic ecosystem health had also been explored (e.g., Stewart 1995; Mack et al. 2000; Nichols et al. 2000; Simon et al. 2001; Miller et al. 2006).

Aquatic plants in the littoral zones of lakes react slowly and progressively to change in chemical and physical parameters; so they function as integrators of environmental conditions to which they are subjected. Therefore, they can be used as long-term indicators as their distribution and abundance reflect their habitat condition (Khedr 1997; Melzer 1999; Heegaard et al. 2001; Moss et al. 2003; Birk et al. 2006). Macrophytes are treated as important for assessing the ecological health of water regimes such as lakes and rivers in the European Water Framework Directive (EC 2000).

Rapid growth of the human population, industrialization, urbanization, and lack of proper regulations has caused eutrophication of lakes in Korea (Choi 2003; Lee 2004a; Heo et al. 2009). Lee (2004a) reported that only a few Korean lakes maintain oligotrophic conditions and that the majority of lakes show some degrees of eutrophication in terms of nutrient overload; 63 % of lakes fell into the categories of mesotrophic and eutrophic, and an additional 31 % were hypertrophic. Therefore, nutrient enrichment is currently the most important degradation factor from a Korean perspective.

Eutrophication leads to an increase of primary production and to modifications in species composition, that is, increasing plants indicative of eutrophic waters, while simultaneously decreasing plants typical of oligotrophic waters (Lachavanne et al. 1992). Although most plant species have a wide range of tolerance, some species live in more narrow environmental conditions. Therefore, they can consequently be used as more specific indicator species (Lacoul and Freedman 2006). Plants clearly respond to eutrophication through the presence or the absence and abundances such as biomass and coverage, and indicator species have been identified at regional, country, and continental scales such as Europe (e.g., Carbiener et al. 1990; Schneider 2007; Penning et al. 2008; Søndergaard et al. 2010).

Indicator species have been used as a single variable to evaluate the ecological status of lake ecosystems in Germany (Schaumburg et al. 2004; Stelzer et al. 2005), while as a metric among multiple variables in the US (Mack et al. 2000; Simon et al. 2001; Miller et al. 2006; Rothrock et al. 2008).

Lakes in Korea have been managed from the view of water supply and flood control. As a consequence, there is a pressing need for the lake management in Korea; however, the authority is changing to an ecosystem-based viewpoint for aquatic ecosystems and trying to develop a multimetric method to assess the health of lake ecosystems. Therefore, it is critical to identify indicator plant species to eutrophication.

The objectives of this study were to establish a method to classify plant indicator species to Lake eutrophication, and to select sensitive and tolerant macrophytes and hygrophytes based on the method developed. Thus, 38 diverse lakes in Korea were investigated for the distribution and abundance of the aquatic macrophytes and hygrophytes, as well as water-quality factors. Sensitive indicator species were defined as those mainly appearing on lakes that were oligotrophic or relatively less eutrophicated, and were not observed, or were in low abundance at eutrophicated lakes. Tolerant indicator species were defined as those mainly present at eutrophicated lakes with high abundance, and either not present or present in low abundance at oligotrophic lakes.

Materials and methods

Study lakes

We investigated lakes where aquatic vegetation had developed. However, natural lakes are very rare due to topography of the country. Thirty-eight lakes were investigated nationwide from 2010 to 2012, representing various eutrophic statuses and littoral vegetation types (Fig. 1). The survey included mostly reservoirs and dams and a few fluvial lakes and lagoons with a large diversity of sizes (all called 'lakes' henceforth). Water depth where plant grows was <1 m except for a few lakes.

Littoral vegetation survey

Vegetation was surveyed during May–August in 2010–2012. The spatial range of the littoral zone was determined as the area from the point of the highest water level to the limit of the vegetative zone within the lake. Vegetation often develops in patches at the littoral zone of lakes, and so only vegetation belts of >5 m were investigated. 1–10 transects per lake (total of 128 transects) were installed vertically within the littoral zone at each site, and vegetation was investigated using 5 m × 5 m plots. Plot size was regarded to be the minimum area (Kim 2010). The littoral zone was discontinuously surveyed with transects placed 5 or 10 m apart when identical vegetation distributions were continuous. The abundance of vascular plant species was surveyed using nine coverage classes: one—several; and several—1, 1–2, 2–5, 5–10, 10–25, 25–50, 50–75, and 75–100 %. Plants were scraped from 1-m of ground using double-headed rakes to evaluate the coverage of each species when submerged plants existed (Kim et al. 2012). The median value of each vegetation cover class was calculated. Plant species were identified using Lee (1996a, b, 2003, 2006), Oh (2000, 2006), Choi (2000), Korea National Arboretum (2004), Kadono (2008), and Park (2009). Species names followed Lee (1996b). Aquatic macrophytes and hygrophytes were distinguished based on Choung et al. (2012). Choung et al. (2012) categorized all vascular plant species occurring in the Korean Peninsula based on their frequency of occurrence and wetness in wetlands. A wetland was defined in a broad sense as in Ramsar's definition, which includes most rivers, streams, lakes, reservoirs, tidal flats, beaches, rice paddies, and fish farms. The protected species included the plants designated as endangered by the Ministry of Environment (2013), rare plants assigned by the Korea Forest Service (Korea National Arboretum 2009), and protected aquatic plants (Lim 2009).

Water-quality analysis and eutrophication indicators

Surface water was sampled from each transect at the same time when the vegetation was investigated for each lake. The sampled water was filtered through GF/C filters. The chlorophyll a (Chl.a) concentration was analyzed using the method of Moss (1967). Total phosphorus (TP) was measured using the persulfate digestion method. The digested sample was reacted with ascorbic acid method, and

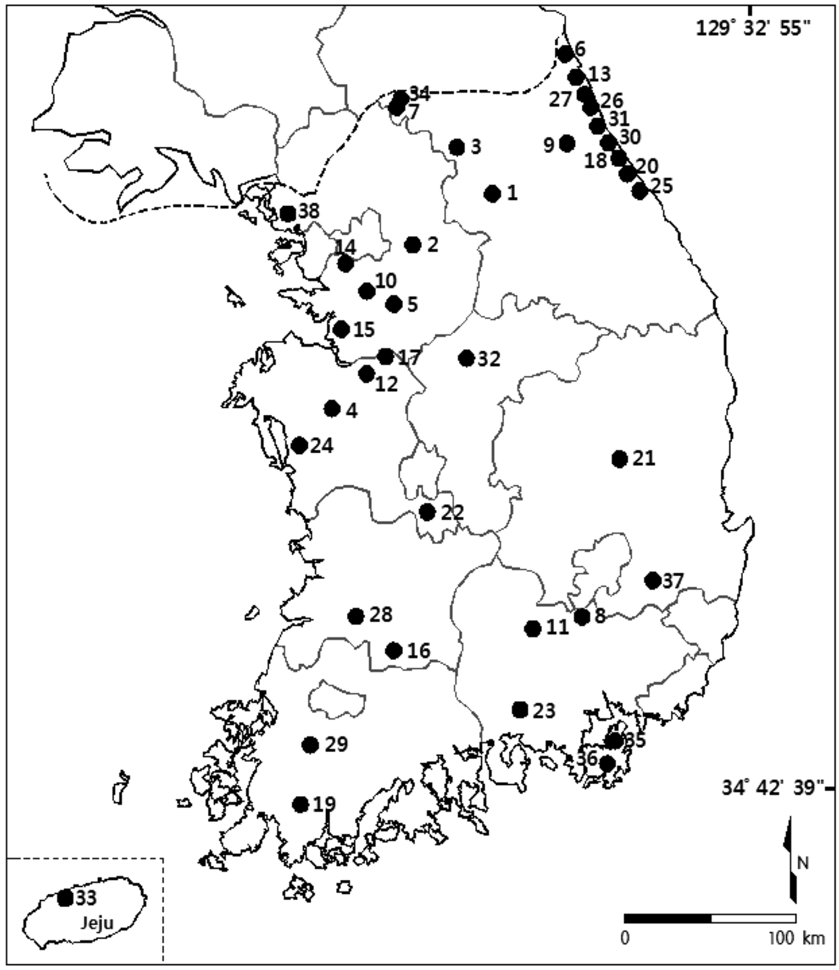

Fig. 1 Thirty-eight study lakes in South Korea. Jeju Island is relocated from the original geography. *1* Soyang, *2* Paldang, *3* Chuncheon, *4* Yedang, *5* Idong, *6* Hwajinpo, *7* Hak, *8* Upo, *9* Yeongdeok, *10* Wangsong, *11* Jeongyang, *12* Masan, *13* Songji, *14* Murwang, *15* Myeogu, *16* Geumpung, *17* Daehong, *18* Hyang, *19* Yeongu, *20* Mae, *21* Yongyeon, *22* Hwarim, *23* Geumseong, *24* Sinchon, *25* Sunpo, *26* Bongpo, *27* Cheonjin, *28* Illy, *29* Siksan, *30* Ssang, *31* Gapyeongri. *32* Yonggye, *33* Susan, *34* Togyo, *35* Yeoncho, *36* Gucheon, *37* Unmun, *38* Giljeong

absorption was measured at 880 nm using a spectrophotometer (UV-1700, Shimadzu) (APHA 1998). Surface water-quality data of Kim (2010) were used for the Lakes Soyang and Yonggye, and those of Kim (2013) for the Lakes Yeoncho, Gucheon, Unmun, and Giljeong. The trophic state index for Korea (TSI_{KO}) was used as an eutrophication indicator, following Lee (2014), which was calculated using Chl.a, TP, and chemical oxygen demand (COD); i.e., $TSI_{KO} = 0.25\ TSI_{KO}\ (Chl.a) + 0.25\ TSI_{KO}\ (TP) + 0.5\ TSI_{KO}\ (COD)$. These three variables were derived from the equations: $TSI_{KO}\ (Chl.a) = 12.2 + 38.6 \log (Chl.a\ mg/m^3)$; $TSI_{KO}\ (TP) = 114.6 + 43.6 \log (TP\ mg/L)$; and $TSI_{KO}\ (COD) = 5.8 + 64.4 \log (COD\ mg/L)$. We modified this equation by adopting two variables as an eutrophication measure, TSI_{KO} (Chl.a) and TSI_{KO} (TP), resulting in $TSI_{KO} = 0.5\ TSI_{KO}\ (Chl.a) + 0.5\ TSI_{KO}\ (TP)$ in this study. Lee (2014) evaluated water quality into four classes based on TSI_{KO}: oligotrophy (<30), mesotrophy (31–50), eutrophy (51–70), and hypereutrophy (>71).

Results

Trophic status of the lakes and plant species

No oligotrophic lakes ($TSI_{KO} < 30$) were encountered among the lakes studied (Table 1), although Yeongdeok, Togyo, Chuncheon, Soyang, and Gucheon Lakes were relatively close to oligotrophic. Sixteen lakes (42 %) were eutrophic, and 10 (26 %) were hypertrophic. The Lake Sunpo showed a TSI_{KO} of 113, which was the highest among the lakes.

A total of 373 vascular taxa were identified at the 38 lakes. Among them, 117 taxa were aquatic macrophytes and hygrophytes, of which aquatic macrophytes and hygrophyte were represented by 50 and 67 taxa, respectively. Among macrophytes, emergent plants were the most abundant with 28 taxa, followed by submerged plants (17 taxa), floating-leaved plants (16 taxa), and free floating plants (6 taxa).

Table 1 Lake size and trophic state index for Korea (TSI_{KO}) of the 38 study lakes

No.	Lake	Lake size (ha)	No. of samples	TP (μg/L)[a]	Chl.a (mg/m^3)[a]	TSI_{KO}
1	Soyang	7,000.0	4	11.1 ± 2.9	5.9 ± 4.5	36
2	Paldang	3,650.0	4	61.5 ± 31.8	16.0 ± 5.3	60
3	Chuncheon	1,700.0	5	11.2 ± 4.9	5.0 ± 1.3	35
4	Yedang	1,088.7	4	71.5 ± 6.5	78.2 ± 11.3	75
5	Idong	305.0	3	64.7 ± 14.7	41.4 ± 4.5	69
6	Hwajinpo	210.4	5	127.4 ± 22.6	25.2 ± 2.8	71
7	Hak	153.5	1	51.2	7.2	52
8	Upo	130.0	4	118.5 ± 15.5	16.9 ± 3.1	67
9	Yeongdeok	105.0	2	12.0 ± 3.0	3.9 ± 0.4	33
10	Wangsong	83.6	2	242.5 ± 78.5	185.2 ± 85.0	94
11	Jeongyang	76.0	2	58.0 ± 12.0	12.4 ± 8.2	58
12	Masan	75.0	3	424.3 ± 231.3	133.7 ± 36.0	96
13	Songji	54.7	6	21.5 ± 3.2	4.3 ± 0.7	40
14	Murwang	50.3	2	225.5 ± 77.5	151.2 ± 4.5	91
15	Myeogu	49.4	3	255.3 ± 143.5	70.8 ± 28.4	86
16	Geumpung	48.0	1	25.9	3.9	40
17	Daehong	39.6	2	82.0 ± 1.0	63.7 ± 46.7	75
18	Hyang	30.6	3	131.0 ± 55.4	16.7 ± 3.0	68
19	Yeongu	18.0	4	44.3 ± 3.9	17.5 ± 5.1	58
20	Mae	16.1	4	94.3 ± 31.3	7.3 ± 1.0	58
21	Yongyeon	14.8	3	63.7 ± 6.2	20.9 ± 3.0	63
22	Hwarim	10.0	1	62.0	43.1	69
23	Geumseong	8.0	2	89.0 ± 4.0	30.8 ± 2.5	69
24	Sinchon	7.2	2	32.0 ± 5.0	16.5 ± 1.5	55
25	Sunpo	2.7	1	889.3	437.3	113
26	Bongpo	2.6	5	58.4 ± 9.0	24.1 ± 2.2	63
27	Cheonjin	2.5	10	30.1 ± 15.1	5.6 ± 1.2	45
28	Illy	2.3	2	71.0 ± 11.0	26.0 ± 5.3	66
29	Siksan	0.5	1	102.8	64.9	77
30	Ssang	0.3	2	138.0 ± 90.0	35.0 ± 22.0	75
31	Gapyeongri	0.2	3	72.3 ± 11.9	6.6 ± 2.5	55
32	Yonggye	46.0	4	25.5 ± 3.1	9.0 ± 0.8	46
33	Susan	11.2	3	65.3 ± 13.5	5.8 ± 0.2	52
34	Togyo	335.0	3	39.7 ± 7.3	1.1 ± 0.2	34
35	Yeoncho	60.0	5	27.8 ± 8.7	8.9 ± 3.8	49
36	Gucheon	50.0	5	19.8 ± 7.4	3.8 ± 1.7	37
37	Unmun	783.0	5	24.2 ± 7.2	5.4 ± 2.7	42
38	Giljeong	56.0	5	21.8 ± 2.6	8.9 ± 3.5	45

[a] Values indicate mean ± standard error

TSI_{KO} criteria to classify indicator species: first step

As a first step to classify sensitive and tolerant species, the TSI_{KO} range was provided for 60 aquatic plant taxa, which occurred in more than three lakes (frequency ≥10 %). The TSI_{KO} of each species was calculated by averaging the TSI_{KO} values of the lakes where the species occurred. The median TSI_{KO} of lakes with each of their 53 species ranged from 33 to 86, showing high variation among species (Fig. 2). Among the species, *Viola verecunda* appeared at the lowest TSI_{KO} value, and *Persicaria pubescens* was observed at the highest TSI_{KO} value. If sensitive species are defined as those species only present in lakes with $TSI_{KO} < 30$, which is the standard for oligotrophic status (Kim 2010), then no species was included in this category. Because the objective of selecting indicator species was to assess the relative health of the lakes, it must include an appropriate number of sensitive and tolerant species. Therefore, the first standard was defined as ≤50 TSI_{KO} for sensitive species and ≥60 TSI_{KO} for tolerant species.

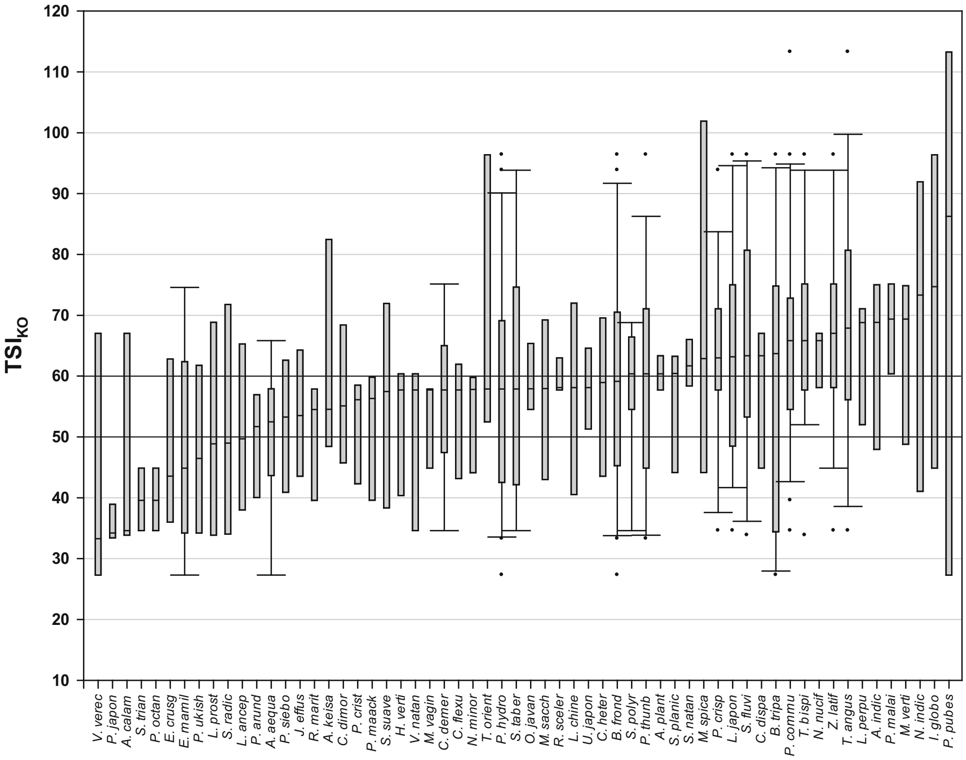

Fig. 2 Trophic state index (TSI$_{KO}$) range of the lakes for each plant species that occurred. The boundary of the box closest to zero indicates the 25th percentile, a line within the box marks the median, and the boundary of the box farthest from zero indicates the 75th percentile. Whiskers (*error bars*) above and below the box indicate the 90th and 10th percentiles, while *dots* indicate outliers. The first standards for sensitive species and tolerant species were defined as ≤50 TSI$_{KO}$ and ≥60 TSI$_{KO}$ respectively (*V. verec*, *Viola verecunda*; *P. japon*, *Phragmites japonica*; *A. calam*, *Acorus calamus* var. *angustatus*; *S. train*, *Scirpus triangulates*; *P. octan*, *Potamogeton octandrus*; *E. crusg*, *Echinochloa crus-galli*; *E. mamil*, *Eleocharis mamillata* var. *cyclocarpa*; *P. ukish*, *Pseudoraphis ukishiba*; *L. prost*, *Ludwigia prostrate*; *S. radic*, *Scirpus radicans*; *L. ancep*, *Lythrum anceps*; *P. arund*, *Phalaris arundinacea*; *A. aequa*, *Alopecurus aequalis*; *P. siebo*, *Persicaria sieboldii*; *J. effuse*, *Juncus effusus* var. *decipiens*; *R. marit*, *Ruppia maritime*; *A. keisa*, *Aneilema keisak*; *C. dimor*, *Carex dimorpholepis*; *P. crist*, *Potamogeton cristatus*; *P. maack*, *Potamogeton maackianus*; *S. suave*, *Sium suave*; *H. verti*, *Hydrilla verticillata*; *V. natan*, *Vallisneria natans*; *M. vagin*, *Monochoria vaginalis* var. *plantaginea*; *C. demer*, *Ceratophyllum demersum*; *C. flexu*, *Cardamine flexuosa*; *N. minor*, *Najas minor*; *T. orient*, *Typha orientalis*; *P. hydro*, *Persicaria hydropiper*; *S. taber*, *Scirpus tabernaemontanius*; *O. javan*, *Oenanthe javanica*; *M. sacch*, *Miscanthus sacchariflorus*; *R. sceler*, *Ranunculus sceleratus*; *L. chine; Lobelia chinensis*; *U. japon*, *Utricularia japonica*; *C. heter*, *Carex heterolepis*; *B. frond*, *Bidens frondosa*; *S. polyr*, *Spirodela polyrhiza*; *P. thumb*, *Persicaria thunbergii*; *A. plant*, *Alisma plantago-aquatica* var. *orientale*; *S. planic*, *Scirpus planiculmis*; *S. natan*, *Salvinia natans*; *M. spica*, *Myriophyllum spicatum*; *P. crisp*, *Potamogeton crispusv L. japon*, *Leersia japonica*; *S. fluvi*, *Scirpus fluviatilisv C. dispa*, *Carex dispalata*; *B. tripa*, *Bidens tripartite*; *P. commu*, *Phragmites communis*; *T. bispi*, *Trapa bispinosa* var. *inumai*; *N. nucif*, *Nelumbo nucifera*; *Z. latif*, *Zizania latifolia*; *T. angus*, *Typha angustifolia*; *L. perpu*, *Lemna perpusilla*; *A. indic*, *Aeschynomene indica*; *P. malai*, *Potamogeton malaianus*; *M. verti*, *Myriophyllum verticillatum*; *N. indic*, *Nymphoides indica*; *I. globo*, *Isachne globosa*; *P. pubes*, *Persicaria pubescens*)

Frequency and abundance criteria to classify indicator species: second step

The second step was to determine the selection standard for indicator species using abundance curves of 117 taxa in response to TSI$_{KO}$. Examples of six taxa are given in Fig. 3, and all raw data are given in Seo (2012). This curve represents the abundance of all lakes where a specific species occurred; thus, it shows the TSI$_{KO}$ range of occurrence for specific species. Some species such as *Juncus effusus var. decipiens* and *Ceratophyllum demersum* were distributed in a wide range of TSI$_{KO}$ conditions (Fig. 3). In contrast, other species such as *Scirpus triangulates* and *Potamogeton octandrus* mainly appeared at TSI$_{KO}$ ≤ 50, and other species such as *Trapa bispinosa* var. *inumai* and *Typha angustifolia* were mostly observed at TSI$_{KO}$ ≥ 60 with high cover. These response curves were used to analyze the frequency and abundance of each species and to identify sensitive and tolerant species.

Sensitive species were selected using the following criteria. Among the species that occurred at three lakes, >50 % of the observed lakes had TSI$_{KO}$ ≤ 50, where the average cover within this range was higher than that at TSI$_{KO}$ > 50. Species that occurred at only two lakes with a

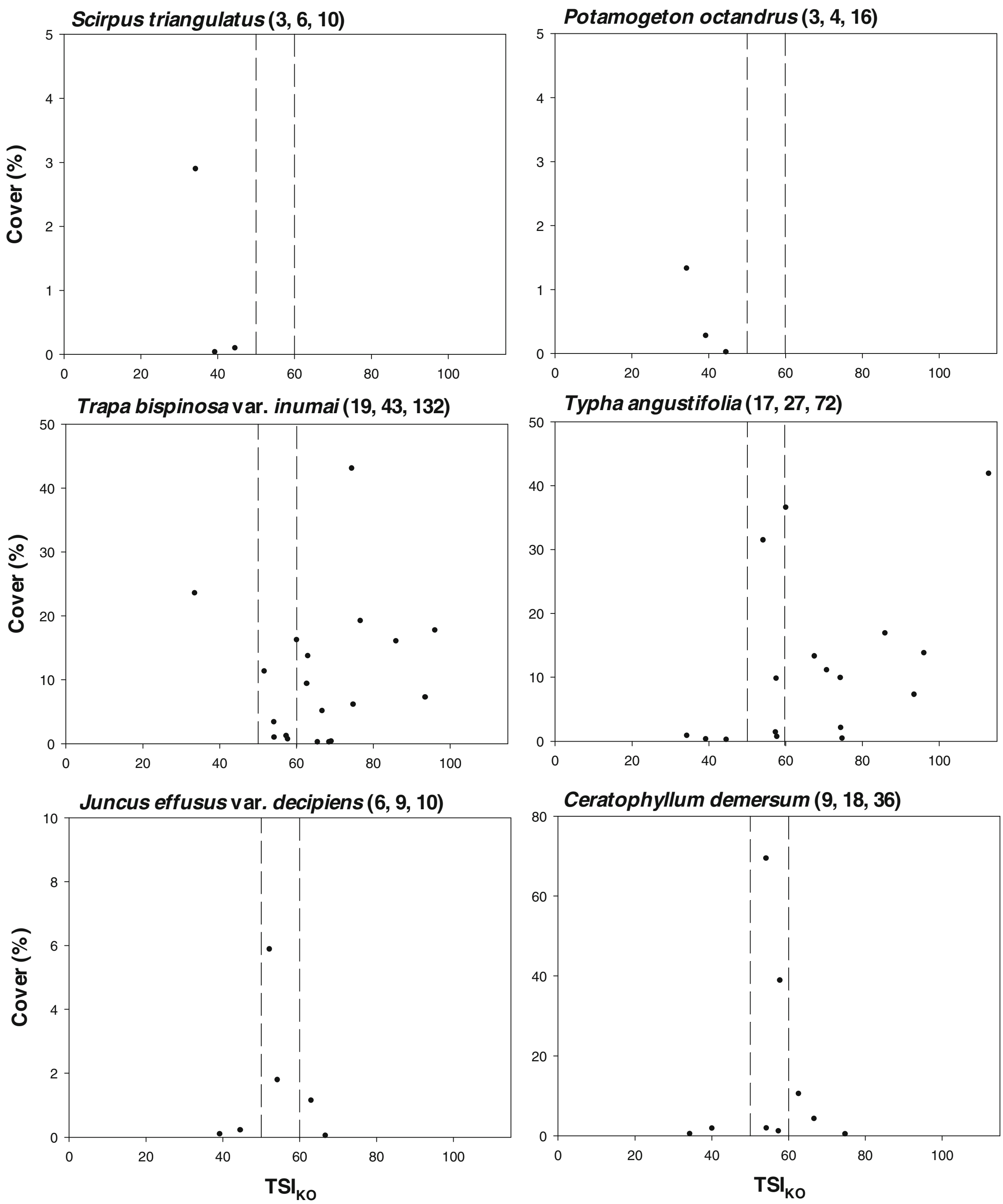

Fig. 3 Examples of abundance response curves of six plant species to eutrophication. Each *dot* represents the average coverage of the species at the lake. Numbers in parentheses indicate the number of lakes, transects and plots where the species occurred in order. *Left* and *right dashed lines* are trophic state index (TSI_{KO}) criteria for selecting sensitive species and tolerant species, respectively. Above the two species are examples of sensitive species. The two species in the middle are tolerant species, and the below two species are examples of indifferent species

$TSI_{KO} \leq 50$ were included. This is because extremely sensitive species might exist in just a few lakes and with low abundance, as Korea has so few oligotrophic lakes remaining. Even if a species was observed only at one lake, we checked whether eutrophication played a major threat to limit distribution.

The criterion for tolerant species classification was that they were in more than five lakes and considering far more eutrophic lakes. More than 50 % of the observed lakes should have $TSI_{KO} \geq 60$, with the average cover in this range higher than that where $TSI_{KO} < 60$.

Table 2 Classified sensitive species by the species abundance response curve

Species name	No. of lakes	No. of lakes ($\leq TSI_{KO}$ 50)[a]	% Frequency ($\leq TSI_{KO}$ 50)	% Cover ($\leq TSI_{KO}$ 50)	% Cover ($>TSI_{KO}$ 50)
Acorus calamus var. *angustatus*	3	4	67	6.3	0.2
Eleocharis mamillata var. *cyclocarpa*	9	3	67	3.3	1.2
Fimbristylis dichotoma	2	6	100	1.1	–[b]
Isoetes coreana	1	1	100	0.2	–
Lycopus ramosissimus var. *japonicus*	2	4	10	0.0	–
Lythrum anceps	6	2	50	0.9	0.2
Miscanthus sacchariflorus	8	4	50	4.9	4.8
Najas graminea	2	2	100	5.2	–
Phalaris arundinacea	4	3	50	40.7	5.3
Phragmites japonica	4	3	100	13.2	–
Potamogeton octandrus	3	2	100	0.5	–
Pseudoraphis ukishiba	5	2	80	15.0	3.0
Scirpus radicans	4	2	50	4.6	3.3
Scirpus triangulatus	3	2	100	1.0	–
Viola verecunda	3	2	67	5.7	0.0

[a] Trophic state index for Korea
[b] No presence of the species

Classification of sensitive and tolerant species

According to the criteria described, 16 taxa were selected as sensitive species (Table 2). *Isoetes coreana*, categorized as a rare plant by the Korea Forest Service and as a protected one by Lim (2009), was included even though it was observed at only one oligotrophic, Lake Chuncheon. Eutrophication was a major threat to this species. In the final list of sensitive species, hygrophytes (seven taxa; 47 %) were the most abundant, followed by emergent plants (four taxa; 27 %), submerged plants (two taxa; 13 %), and floating-leaf plants (two taxa; 13 %).

Eleven taxa were selected as tolerant species (Table 3). Among the tolerant species, emergent plants were the most abundant (four taxa; 36 %) and floating-leaf, floating, submerged, and marsh plants were one (9 %), two (18 %), two (18 %), and two (18 %) taxa, respectively.

Applying the indicator species to assess lake ecosystem health

We calculated the numbers of sensitive and tolerant species occurred, and average vegetated coverage occupied by sensitive and tolerant species at each lake. With the increase of TSI of the 38 study lakes, number and cover of the sensitive species clearly decreased (Fig. 4) While those of the tolerant species showed the opposite trend.

In addition, we evaluated whether the indicator species that we classified were useful for lake health assessments by analyzing the relationship between the lake scores calculated from the newly classified indicator species as a single metric and the lake scores estimated from the multimetric method. The latter lake score was developed based on the eight metrics; i.e., plant species richness, number of obligate wetland plant species, number of facultative wetland plant species, number of critically endangered plant species, number of endemic plant species, number of exotic plant species, vegetated area by emergent macrophytes, and vegetated area by submerged macrophytes (Kim 2013). According to the lake evaluation point endowing method, sensitive, indifferent, and tolerant species were given 5, 3, and 1 points, respectively, to calculate a “lake score” for each lake. A significant relationship was observed between the lake values from using only indicator species and the values from the multimetric method ($P < 0.001$; Fig. 5). Lake Chuncheon, which was nearly oligotrophic and had small water level variations, had the highest value from the single variable method, whereas Lake Murwang, which was eutrophic, with the most of the lake shore covered in stonework and with few plants, showed the lowest value.

Discussion

Classification method for sensitive and tolerant indicator species

Several methods have been developed to identify indicator species that respond to a narrow range of trophic environments. The first is a qualitative evaluation using an

Table 3 Classified tolerant species by the species abundance response curve

Species name	No. of lakes[a]	No. of lakes (≥TSI_{KO} 60)[b]	% Frequency (≥TSI_{KO} 60)	% Cover (≥TSI_{KO} 60)[c]	% Cover (<TSI_{KO} 60)
Carex heterolepis	6	3	50	1.7	1.4
Leersia japonica	16	10	63	4.5	2.2
Lemna perpusilla	7	4	57	0.9	0.1
Myriophyllum verticillatum	5	4	80	2.4	0.3
Persicaria thunbergii	19	10	53	2.8	0.4
Phragmites communis	25	15	60	17.5	14.1
Potamogeton crispus	15	9	60	10.7	5.2
Spirodela polyrhiza	9	5	56	0.9	0.1
Trapa bispinosa var. *inumai*	19	13	68	11.7	6.6
Typha angustifolia	17	10	59	15.1	6.2
Zizania latifolia	19	14	74	23.1	16.3

[a] Number of lakes occurred

[b] Trophic state index for Korea

[c] Average vegetated cover

expert group. The expert group qualitatively evaluated sensitive and tolerant species (Swink and Wilhelm 1994) and applied them for a lake evaluation in southern Florida, USA (Mack et al. 2000; Miller et al. 2006; Rothrock et al. 2008). The second is to classify the indicator species based on the frequency and abundance of plant species occurring in reference lakes, which are artificially disturbed with natural characteristics (Carbiener et al. 1990; Schneider 2007).

The third is to trace the species composition over time by lake succession and classify the indicator species succeeding during eutrophication (Toivonen and Baeck 1989; Rintanen 1996). The fourth is to investigate multiple lakes under various environmental conditions ranging from oligotrophic to eutrophic and classify indicator species by quantitatively analyzing the response of plants to environmental conditions (Seddon 1972; Toivonen and Huttunen 1995; Heegaard et al. 2001; Penning et al. 2008). It is difficult to apply the former three methods within Korea because Korea does not have sufficient expert groups or reference lakes with close to undisturbed conditions, and there is currently a dearth appropriate data.

Penning et al. (2008) selected indicator species based on the percentile method using an aquatic plant species database that surveyed 1,147 lakes in 12 European countries. This method provided highly reliable results, because it was based on the large database where species inhabited multiple lakes. In contrast, no such database is available in Korea. In addition, most of Korean lakes are artificially constructed with unsuitable beds to establish aquatic or hygrophyte plants. Therefore, to classify indicator species, we must investigate any lakes with various environmental conditions and quantitatively analyze the plant species.

Despite such limitations, we established an indicator species selection method according to the sensitivity and tolerance of indicator species that were selected among 117 taxa investigated at 38 lakes. We included as many lakes as where aquatic vegetation was found as possible. The data were analyzed as a single dataset without dividing it based on biogeographic region, alkalinity, salt tolerance, or lake type. Biogeographic regions for wetland plants have not been reported, unlike terrestrial plants in Korea. Wetland plants are capable of long-distance dispersion due to waterfowl and streams (Heegaard et al. 2001), resulting in rapid establishment (within a few years) within newly built reservoirs and sharing common plant species with other lakes (Odland 1997). Alkalinity is a matter of concern in Europe (Penning et al. 2008), but it is not a problem in Korea as the limestone region is very limited, and no lakes were investigated from the region.

It may not be ideal to include lagoons in the same pool as freshwater bodies. *Ruppia maritima* and *P. berchtoldii* inhabit lagoons and live in slightly saline conditions (Heo et al. 2009). The majority of aquatic plants (excluding halophytes) do not have tolerance to saline >10 ppm (Deegan et al. 2005). However, east shore lagoons in Korea are undergoing a process of desalination, except for Lake Hwajinpo, and particularly for Lakes Cheonjin, Bongpo, and Ssang, which have ∼0.1 ppm salinity. Moreover, *Myriophyllum spicatum* and *Zannichellia pedunculata* were only observed in east coastal lagoons, but they inhabit freshwater lagoons (Heo et al. 2009) and are known to be

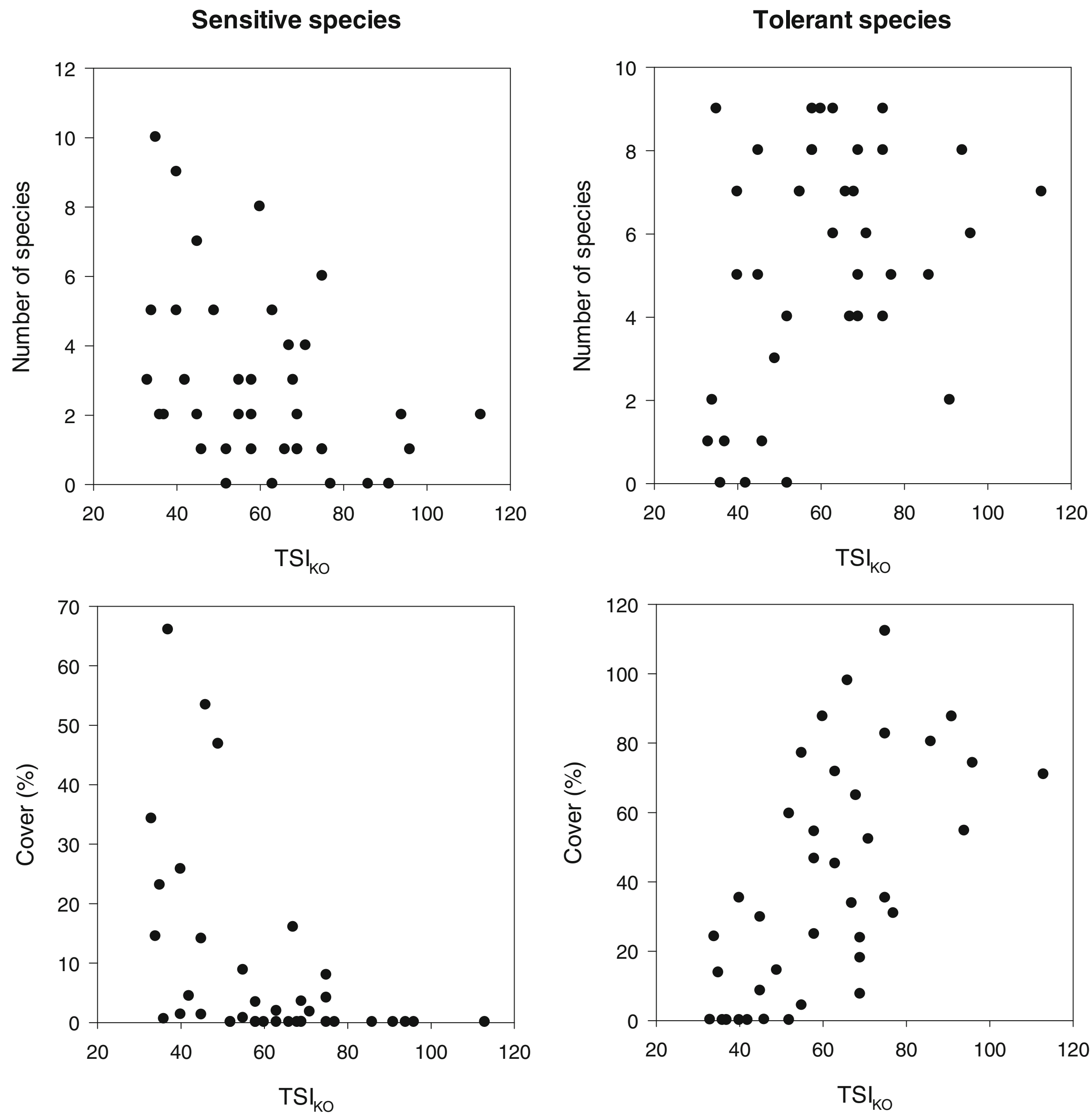

Fig. 4 Numbers of sensitive and tolerant species (*above*) and average vegetated coverage of sensitive and tolerant species (*below*) against trophic state index (TSI_{KO}) at 38 study lakes

distributed nationwide (Lim 2009). Therefore, lagoons on the east coast are freshwater-like natural lakes with minimum of water level changes and gentle slopes, although they experience artificial eutrophication due to various water pollution sources (Kim and Lee 2002). These lagoons have an ideal physical environment for plants to inhabit. In particular, Lake Songji is relatively desalinated and is protected from pollution sources. This has helped in preventing severe artificial eutrophication. This lake is considered to have the most suitable physical and chemical environment for plants among all Korean lakes. Plant distribution could be affected by lake type such as large dam, reservoir, or lake, mainly due to annual water fluctuations. However, this issue was not separately considered due to a limitation in the number of lakes.

Our selection method was mainly based on the spectrum of TSI_{KO} in the study lakes, the number of lakes, and the frequency and abundance of the species presented. Therefore, it is possible to change the selected indicator species if more lakes are added to the study. This approach may increase the nutrient spectrum, resulting in a modification of the TSI_{KO} range of sensitive and tolerant species. Considering that eutrophicated lakes rarely become oligotrophic, we do not believe that eutrophication range will increase in future lake surveys. However, if oligotrophic lakes are added, and plants species suitable to this nutrient

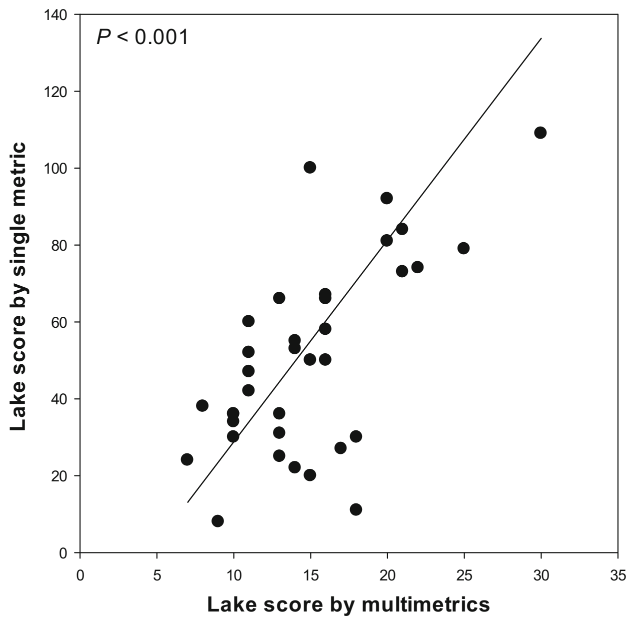

Fig. 5 The relationship between lake score assessed by single variable analysis of indicator species and lake scores driven by multivariate analysis in another study ($n = 38$ lakes)

condition are further categorized in terms of water chemistry data, but the TSI_{KO} standard for sensitive species can be lowered while still retaining an appropriate number of indicator species. Moreover, indicator species can be modified or increased if there are more lakes. It is highly possible that we may include rare species that had appeared in less than three lakes.

Classified sensitive and tolerant species

Submerged plants were the most abundant among the 15 plants classified as sensitive species. Submerged plants have an inundated sclerophyll, and their roots are poorly developed, and so they are more easily influenced by various environmental factors in the water. In particular, they are more sensitive to eutrophication, because photosynthetic rate is directly influenced by particulate matter in the water, including eutrophic algal blooms (Shin et al. 1997; Kim and Lee 2003; Kolada 2010). Among the relatively common submerged plants, *Myriophyllum verticillatum*, *C. demersum,* and *Potamogeton crispus* were not classified as sensitive species. This might be because *M. verticillatum* has aboveground leaves and *C. demersum* lives immediately beneath the water surface (Toivonen 1985). *P. crispus* grows long stems immediately under the water surface, and so, it is less influenced by decreased water transparency. However, *P. crispus* was selected as an indicator species for eutrophication in Poland (Kufel et al. 1996) and in the EU (Penning et al. 2008).

Floating-leaved plants and floating plants are tolerant to aquatic environments because their foliage is exposed on the water surface (Toivonen and Huttunen 1995; Vestergaard and Sand-Jensen 2000). About 27 % of tolerant species were floating-leaved and floating plants in this study. Lee (2004b) indicated that *T. bispinosa* var. *inumai* has a wide growth range in terms of nutrient condition, but it was a typical tolerant species appearing under eutrophic conditions and showing high abundance at $TSI_{KO} > 60$. *T. angustifolia* and *Leersia japonica* form dense stands where organic matter input is high (Lee 2004b, 2010).

Potamogeton perfoliatus and *N. pumilum* have also been classified as sensitive species in Europe (Penning et al. 2008), and *T. angustifolia* (Toivonen and Baeck 1989), *N. peltata*, *Salvinia natans*, and *S. polyrhiza* (Penning et al. 2008) were classified as tolerant species. However, *Z. pedunculata* (Melzer 1999), *C. demersum* (Kufel et al. 1996; Melzer 1999; Penning et al. 2008), *M. spicatum* (Kufel et al. 1996; Penning et al. 2008), *Najas marina,* and *T. incisa* (Penning et al. 2008) were classified as tolerant species, but were not included in the list of tolerant species in this study.

The use of indicators classified in other countries should be considered. However, there are not many common species, and plant ecological tolerance is assumed to be influenced by region. Plant indicator values are often expected to vary locally (Lachavanne et al. 1992).

Applying indicator species to assess lake ecosystem health

Richness and abundance of the selected indicator species at studying lakes showed a good relationship with the TSI, suggesting the meaning of the selection method. We verified the applicability of the indicator species that we classified for assessing lake ecosystem health. The lake scores calculated with the indicator species showed a significant correlation with those calculated by the developing multimetric method using eight metrics. Therefore, indicator species could be added as a key metric among multimetrics.

Some macrophytes and hygrophytes were not found in this study. It will be ideal that those plants are investigated and tested for the possibility of indicator species using the selection method we suggested here, before initiation of the periodic lake assessments by the Ministry of Environment. Then, this indicator system could be used for longer-term and wide use in this country.

Acknowledgments This study was supported by the Center for Aquatic Ecosystem Restoration (CAER) of Eco-STAR project (EW42-08-10) from the Ministry of Environment (MOE, Republic of Korea). The authors are grateful to Yonghak Lee, Changwan Woo, Kiyong Hwang, Inyong Hwang, and Jihye Heo for their field assistance. Also, special thanks to guest editors.

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