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論　文　*ORIGINAL ARTICLE*

The effect of water level fluctuation due to decreased precipitation on the non-submerged aquatic vegetation in Nong Bong Khai Non-hunting Area, Northern Thailand

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Abstract: The hydrology of a wetland largely influences its vegetation, which affects the value of the wetland to human and animal life. Water level fluctuation is one of many factors impacting wetland ecosystem diversity, and precipitation variability is one of the most influential drivers of plant species composition in wetlands. This study describes the effects of water level fluctuation caused by decreased precipitation on the non-submerged aquatic vegetation community in the Nong Bong Khai Lake, Nong Bong Khai Non-hunting Area, Chiang Rai, Thailand. We applied non-submerged aquatic vegetation distribution maps based on images from unmanned aerial vehicle (UAV) at two altitudes (30 m and 90 m). Rapid decreases (from 1.0 m to 0.2 m) in the water level from 2018 to 2020 were influenced by lower than average precipitation during 2019 and 2020. Increased terrestrial area (dry land) caused by low water levels offered favorable conditions for terrestrial plant species productivity. The vegetation map generated from a 30-m orthophoto showed a decrease in native plant species and an increase in invasive plant species, most notably a rapid expansion of *Mimosa pigra* in low water level areas. The distribution map generated by applying a 90-m UAV orthophoto showed *Eichhornia crassipes* continuously increased during the period of low water level. Mapping revealed that the species declined in the area in March 2020 due to the destruction caused by a heavy hailstorm. Extensive water coverage by *Eichhornia crassipes* mats might result in low dissolved oxygen values, indicating an increase in pollution in the lake.
Key words: water level fluctuation, Nong Bong Khai Non-hunting Area, vegetation distribution map, *Mimosa pigra*, *Eichhornia crassipes*

摘要：湿地の水文は，その植生に大きく影響し，ひいては人間や野生動植物の生息に影響する。降水量の変動によって生じる水位変動は，湿地生態系の多様性に影響を与え，湿地における植物種の絶滅や変化の大きな要因の1つである。本研究は，タイ・チェンライ県ノン・ボン・カイ禁猟区において，2つの高度（30 m・90 m）の無人航空機（UAV）からの画像に基づいて水域の植生に対する水位変動の影響を明らかにすることを目的とした。研究の結果，2019年～2020年の少雨の影響によって，2018年から2020年の間に，水深が1 mから0.2 mに低下していた。この低水位による陸域の拡大は，陸上植物種に好適な生息条件を提供することとなった。UAVによって高度30 mから撮影された正射投影画像から生成された植生分布図は，自生植物の減少と侵略的外来植物の増加，とくに低水位期間におけるミモザ・ピグラ（*Mimosa pigra*）の急速な拡大を示した。高度90 mからの画像により作成されたホテイアオイ（*Eichhornia crassipes*）の分布図は，低水位期間における同種の広い被覆を示した。しかし，ホテイアオイは2019年末に起きた雹害により，2020年3月には減少していた。ホテイアオイによる広範囲の被覆は，湖水の低酸素化をもたらしたことが示唆された。
キーワード：水位変動，ノン・ボン・カイ禁猟区，植生分布図，ミモザ・ピグラ，ホテイアオイ

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1. Introduction

Hydrology is the most influential variable of wetland ecosystems. It can determine plant species composition, distribution, productivity, and nutrient uptake capacity (Fennessy et al., 2004). Along lake borders, the distribution of plant species is influenced by the hydrological gradient from permanently dry areas on land to permanently wet areas in the water (Nicol and Ganf, 2000). Water level fluctuation is one of the major factors affecting vegetation biomass, diversity, composition, and structure by influencing variables that impact plant growth, such as light, oxygen, air temperature, and nutrient availability (Nõges and Nõges, 1999; Geest et al., 2005; Yang et al., 2014).

Seasonal fluctuations are commonly used as the primary factor for understanding wetland biotic processes (Hofmann et al., 2008; Jabłońska et al., 2011). Water level fluctuation is a complex variable, and its range, frequency, and regularity of change should be considered as they may affect the vegetation in different ways and present major disturbances that influence the wetland ecosystem (Keddy and Reznicek, 1986; Raulings et al., 2010; McGowan et al., 2011; Nielsen et al., 2013). Water-depth ranges have affinities and influence to physiological adaptations of individual plant species and communities of species, and also their life forms (Sculthorpe, 1967; Spence, 1982; Kozlowski, 1984; Wooten, 1986; Hejny and Hroudova, 1987; Keddy 2000).

Shallow-rooted aquatic plants in wetland areas, in particular, are extremely vulnerable to water level fluctuation in the dry season (Li et al., 2013; El-Vilaly et al., 2018). These plants cannot tolerate extreme drought and may be lost from the ecosystem, dramatically changing wetland vegetation composition (Liu et al., 2012). The hydrological interactions between the water body and the surrounding areas may be altered by more frequent water level fluctuation, increasing the area affected (Wright et al., 2017; Garssen et al., 2015; Striker et al., 2017).

Many wetlands in Thailand suffer from drought caused by low precipitation, which results in water level fluctuation, altering vegetation (Office of Natural Resources and Environmental Policy and Planning, 2013). In 2017, the Thailand Institute of Scientific and Technological Research reported that the Nong Bong Khai wetland is also affected by low precipitation, impacting native and alien plant species. The most notable effect of these drier conditions is increased *Eichhornia crassipes*. This crisis increases the risk of extinction of rare and native species and overall species variation in wetland ecosystems.

Aquatic wetland plant populations may be successfully evaluated using unmanned aerial vehicles (UAVs), which can provide data for vegetation mapping surveys (Wongsupathai et al., 2021). The physiological and ecological characteristics of plant communities, such as texture and color, can be represented in high-resolution orthophotos obtained by low-altitude UAV photogrammetry (Li et al., 2010). Furthermore, UAVs are excellent in discriminating and mapping various vegetation classes and species (Klemas, 2015).

The purpose of this research is to study the effects of water level fluctuation caused by decreased precipitation on the non-submerged aquatic vegetation community and the expansion of *Eichhornia crassipes* in the Nong Bong Khai Lake in the Nong Bong Khai Non-hunting Area, Chiang Rai, Thailand. Non-submerged aquatic vegetation distribution maps based on images from UAV were used. This research will inform further conservation measures and management strategies in this natural area.

2. Materials and Methods

2.1 Study area

Nong Bong Khai Lake is a wetland under the supervision of the Nong Bong Khai Non-hunting Area office, Department of National Parks, Wildlife and Plant Conservation. It is located in the Yonok and Pa Sak sub-districts in the Chiang Saen District, Chiang Rai Province, northern Thailand, between 20° 14′ 33″ and 20° 15′ 59″ N and 100° 0′ 44″ and 100° 3′ 7″ E (Fig. 1). The lake covers an area of approximately 434 ha, with an average depth of 2 m. The lake is a closed water body with no canals connected to the Mekong River or other water bodies. Thus, rainfall is the only source of water inflow. The water in the lake is reserved for agricultural purposes, obtained at the south end of the lake and dispersed

into a ditch created. Land use and land cover in the Nong Bong Khai watershed in 2018 shows that the 3,133.75-ha watershed consists of field crops (36.44%), natural water bodies (15.93%), deciduous forest (8.38%), paddy field (7.36%), rangeland (6.64%), and other types (25.24%) (Wongsupathai et al., 2021). Most (80%) of the area around the lake is a flat

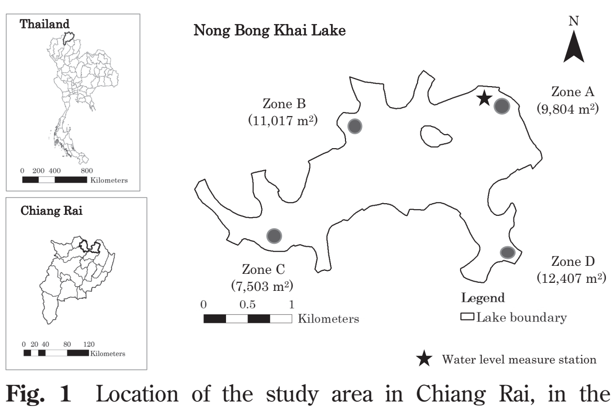


Fig. 1 Location of the study area in Chiang Rai, in the northern region of Thailand

plain with a slope of less than 2% (The Department of National Parks, 2019). A soil map from the Land Development Department (2020) shows that soils in the Nong Bong Khai area are mostly composed of a well-drained, dark brown clay loam with moderate to low nutrient concentrations and moderate permeability. An erosion risk exists in steep areas. The climate is tropical and is influenced by northeast and southwest monsoons. The area has an annual rainfall of 1,705.4 mm/year. The highest average rainfall occurs between July and October (the highest single-month rainfall is 367.4 mm in July). The average temperature is 25.0℃, highest in April (35.3℃) and lowest in January (12.5℃). The average annual relative humidity is 72.1%, and annual accumulative evaporation is 1,396.3 mm (Thai Meteorological Department, 2021).

2.2 Rainfall data

Monthly Chiang Rai Province rainfall data from 2018 to 2020 were obtained from the Northern Meteorological Center, Thailand (2020). The weather can be clearly delineated into two season types (dry season and rainy season), in which the dry season occurs in summer and winter. Thus, there are three separate seasons.

2.3 Water level

The monthly water levels of Nong Bong Khai Lake during the study period (September 2018 to December 2020) were obtained from measurements collected by Nong Bong Khai Non-hunting Area personnel using a level measurement staff at the lake pier.

2.4 Data collection

2.4.1 Study zone designation

The study spanned four periods: rainy season (September 2018), dry season (March 2019), rainy season (September 2019), and dry season (March 2020). The distribution data of the non-submerged aquatic plants (marginal, emerged, and floating plants) were needed to designate the study zones. An aerial survey and a ground truth survey were implemented to obtain vegetation distribution data over the entire lake. An aerial survey of the entire lake was carried out by the automatic flight of a DJI Mavic Pro UAV with a built-in Mavic Pro 12.35 M effective pixel RGB camera (FOV = 78.8°, focal length equivalent to 26 mm of a 35-mm format, F-stop = $f/2.2$) and a DJI GS Pro application (www.dji.com, Japan). To obtain a continuous multi-shot aerial photo with a 28-mm pixel size captured at 2-s intervals, the initial flight parameters were set at 80% and 60% for the front and side overlap ratios, respectively, with a flight speed of 8.5 m/s and an altitude of 90 m (the maximum flight height permitted by Thailand law). An orthophoto of the entire lake was created using Agisoft Metashape software version 1.5 (Agisoft, Russia). A ground survey was conducted by boat and on foot to observe the non-submerged aquatic plants. Background information for Nong Bong Khai Non-hunting Area was obtained via officer interviews. Four study zones in different areas of the lake were designated by analysis of the information obtained from the two survey methods: zone A was in the eastern part of the lake (approximate area, 9,804 m^2), zone B was in the northern part of the lake (≈11,017 m^2), zone C was in the western part of the lake (≈7,503 m^2), and zone D was in the southern part of the lake (≈12,407 m^2).

2.4.2 Data collection in the study zones

Four procedures were used to collect data：

1) Aerial RGB photos were taken at an altitude of 2–10 m in the four study zones. The UAV was manually controlled to capture a single-shot photo of the individual species at very close range with less than 3-mm pixel size.

2) Aerial RGB photos were taken at an altitude of 30 m in four study zones in March 2019, September 2019, and March 2020. The UAV was controlled by an automatic flight program, the DJI GS Pro application, to record a continuous multi-shot photo with a 9-mm pixel size captured at equal 2-s time intervals with an 80%/60% front/side overlap. The flight speed was 2.8 m/s. Over the entire lake, aerial RGB photos at an altitude of 90 m were taken in September 2018, March 2019, September 2019, and March 2020.

3) Random vegetation sampling plots were selected, of which 82 were sampled in March 2019, 95 in September 2019, and 165 in March 2020, randomized in the four study zones with a 1 × 1 m quadrat. In each zone, the dominant species was visually distinguished. For each dominant species, several sampling plots were randomized. The Braun-Blanquet cover-abundance scale was applied to record vegetation data (Mueller and Ellenberg, 1974). A photograph of each sample plot was captured by a GoPro 12-MP digital camera. The coordinates were recorded by a GPS-60 CSx. The water depth was also recorded at every sample plot.

4) For water quality sampling, six parameters were measured for 12 samples from four study zones (three samples in each zone) by two methods. A HORIBA U 53 G series was used in the field test to measure four parameters (water temperature, pH, dissolved oxygen [DO], and conductivity). Two parameters (total phosphorus and total nitrogen) were measured in the laboratory.

2.5 Data analysis

2.5.1 Plant species identification

According to the data obtained from the sampling quadrats in the four study zones, the scientific name and family of each aquatic plant were identified by a taxonomist at the Herbarium Department of the National Parks, Wildlife and Plant Conservation, Bangkok, Thailand.

2.5.2 UAV data analysis

The analysis involved two procedures, generating orthophotos and generating vegetation maps. An orthophoto of each study zone was generated by Agisoft Metashape Professional software version 1.5 (Agisoft, Russia), which combined the UAV multi-shot photos by the following seven processes: photo alignment, build the dense, mesh creation, texture building, tile model building, DEM building, and creation of an orthophoto that is a high-resolution perpendicular photo with a high level of coordinate accuracy. Vegetation maps were manually processed by ArcMap software (version 10.5). A UAV orthophoto was directly visually interpreted with a maximum patch size of 3 × 3 m at two altitude levels (30 m and 90 m). At 30 m altitude with a resolution of 7.64 mm/pixel, the UAV orthophoto was used to construct a vegetation map that could describe the coverage and type of all plant communities in the area. Although the 90-m orthophoto with a resolution of 27.02 mm/pixel did not provide sufficient resolution to aid in constructing a vegetation map, it could be referred to for a vegetation distribution map to provide the coverage of some distinct color and texture species in the area. The maps constructed from the 30-m orthophoto are representative of the vegetation in the four study zones. Moreover, the map interpreted from the 90-m orthophoto represented the distribution of *Eichhornia crassipes* over the entire lake.

After direct interpretation of the 30-m orthophotos to create vegetation maps of the four study zones, the boundaries of the dominant plant species in the 30-m vegetation map were designated with reference to the color and texture differences in the orthophotos and supported by the single-shot RGB photos captured at an altitude of 2–10 m. Furthermore, the ground truth survey data were co-analyzed for more accuracy.

The distribution map of the entire lake was interpreted using the 90-m orthophoto. The boundaries of the 90-m map were determined using the 90-m orthophoto as the color and texture of *Eichhornia crassipes* could be distinguished.

2.5.3 Water quality analysis

The results of water quality analyses of samples collected in each zone were averaged and compared with the Standard Quality of Surface Water, Thailand (Class 3), and the Standard Methods for the Examination of Water and Wastewater. All the parameters were compared in the samples collected in September 2018, March 2019, September 2019, and March 2020 and analyzed with vegetation distribution.

3. Results

3.1 Species identification

A total of 90 plant species in 38 aquatic plant families were identified within the 4 study zones. The highest number of species (71) was found in March 2020. The next highest number (55) was found in September 2019. A total of 54 species was found in March 2019. Poaceae was the most prevalent family found in the three surveys. Regarding general life forms, there were 35 species of herbs, 20 grasses, nine climbers, eight aquatics, six shrubs, four undershrubs, three trees, two terrestrial ferns, two epiphytes, and one bamboo. These species had different habitats: terrestrial (47), marginal (34), floating (5), and emerged (4) (Appendix 1). In addition, *Sparganium erectum,* a plant species native to the United Kingdom (Newman, 2005), was identified three times in the survey results.

3.2 Vegetation maps

The vegetation maps generated by the 30-m orthophotos showed the coverage area of the dominant plant species in zones A, B, C, and D in March 2019, September 2019, and March 2020 (Figs. 2–5). The details and coverage areas of each dominant species found in the four study zones are summarized in Appendix 2. The distribution map based on the 90-m orthophoto concentrated on the entire lake. The map showed the distribution of *Eichhornia crassipes* in September 2018, March 2019, September 2019, and March 2020 (Fig. 6). The coverage area of *Eichhornia crassipes* was approximately 359,832 m^2 in September 2018, 592,888 m^2 in March 2019, 892,420 m^2 in September 2019, and 678,365 m^2 in March 2020.

3.3 Relationship between non-submerged vegetation and rainfall.

Comparing coverage area of vegetation and actual rainfall data in three survey periods (March 2019, September 2019, and March 2020) (Fig. 7) shows that the highest vegetation coverage areas in zones A and D (11,202 m^2 and 13,184 m^2) occurred in September 2019 with 70.7 mm actual rainfall. The greatest coverage in zones B and C (12,955 m^2 and 8,490 m^2) occurred in March 2020 with 0.8 mm actual rainfall. The lowest vegetation coverage area of all study zones occurred in March 2019 with zero actual rainfall. Considering the actual rainfall data over the entire lake in the four survey periods (September 2018, March 2019, September 2019, and March 2020), the highest *Eichhornia crassipes* coverage area occurred in September 2019 (892,420 m^2). The lowest coverage area occurred in September 2018 (359,832 m^2) (Fig. 8).

3.4 Relationship between non-submerged vegetation and water level

A comparison of the coverage area classified by vegetation habitat and water depth in all study zones (Fig. 9) shows vegetation changed as the water depth declined in the four study zones. In zone A, marginal plants and floating plants increased from March 2019 to September 2019 by 2,280 m^2 and 1,012 m^2, respectively, while in March 2020, they de-

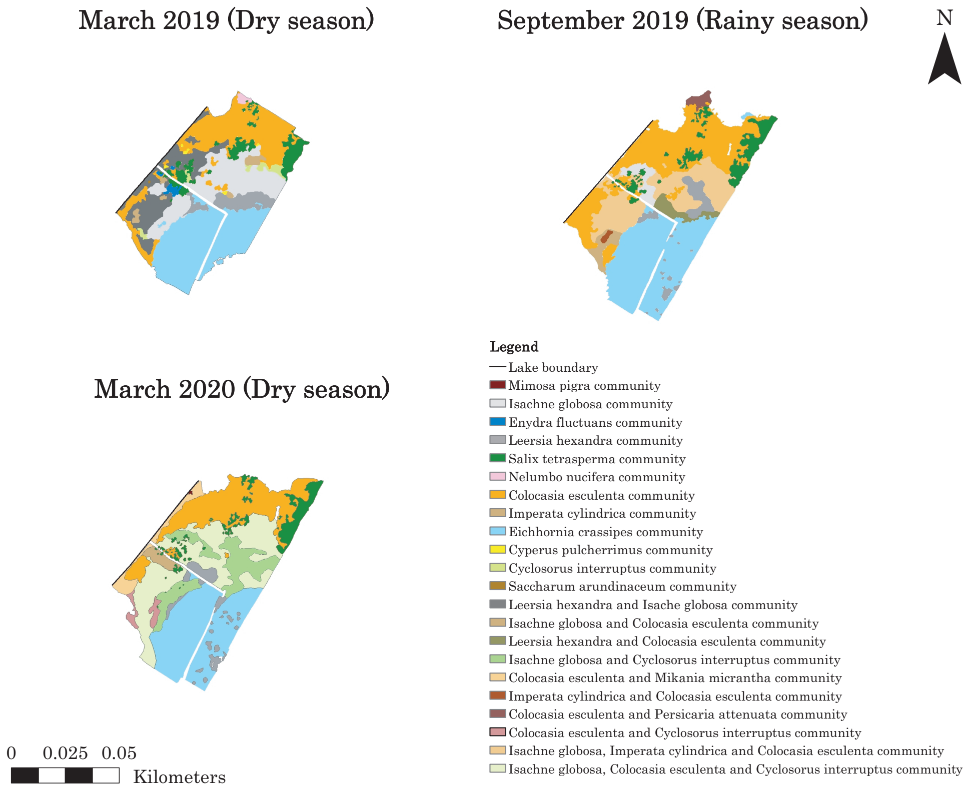


Fig. 2 Manual mapping by direct visual interpretation of Zone A in March 2019 (dry season), September 2019 (rainy season), and March 2020 (dry season)

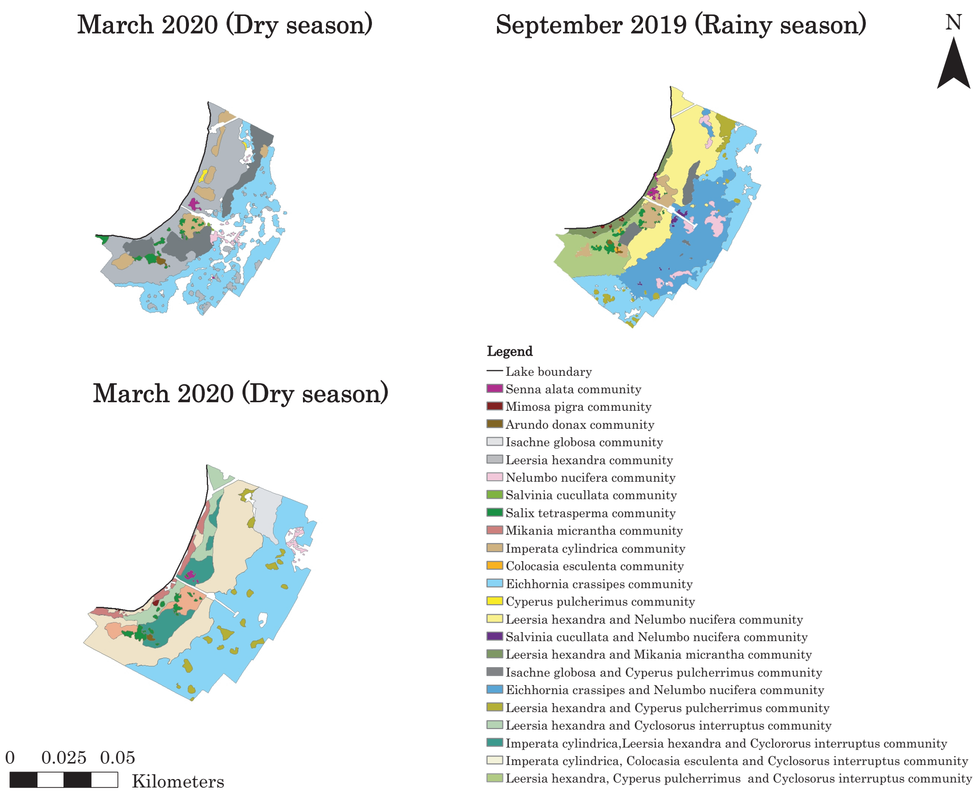


Fig. 3 Manual mapping by direct visual interpretation of Zone B in March 2019 (dry season), September 2019 (rainy season), and March 2020 (dry season)

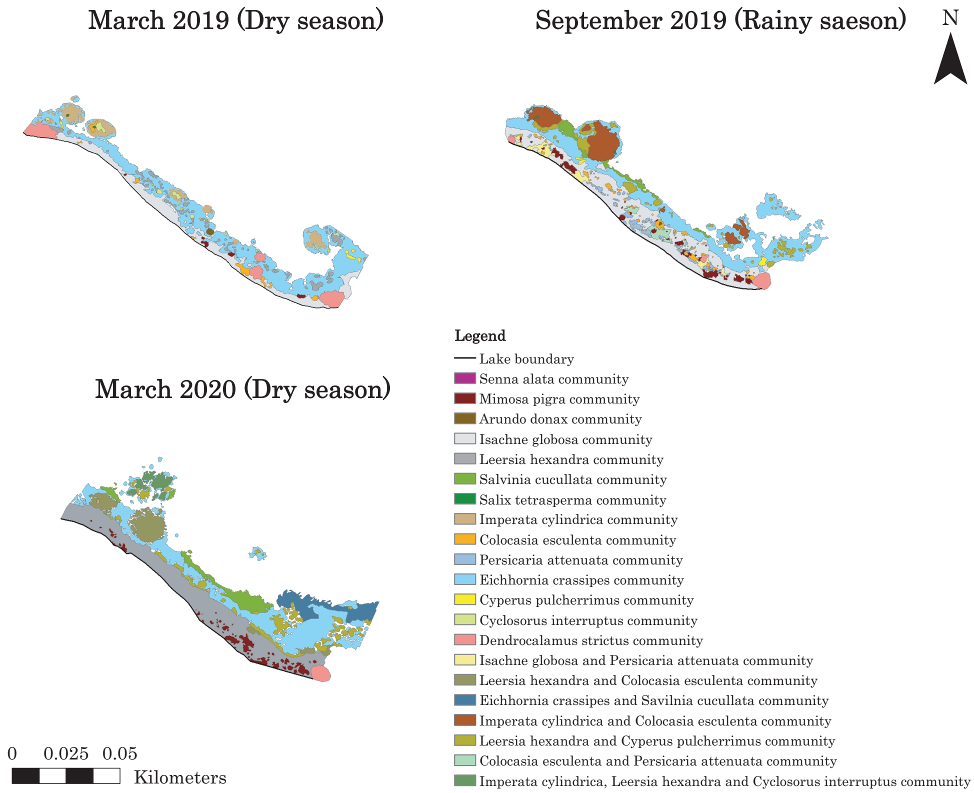


Fig. 4 Manual mapping by direct visual interpretation of Zone C in March 2019 (dry season), September 2019 (rainy season), and March 2020 (dry season)

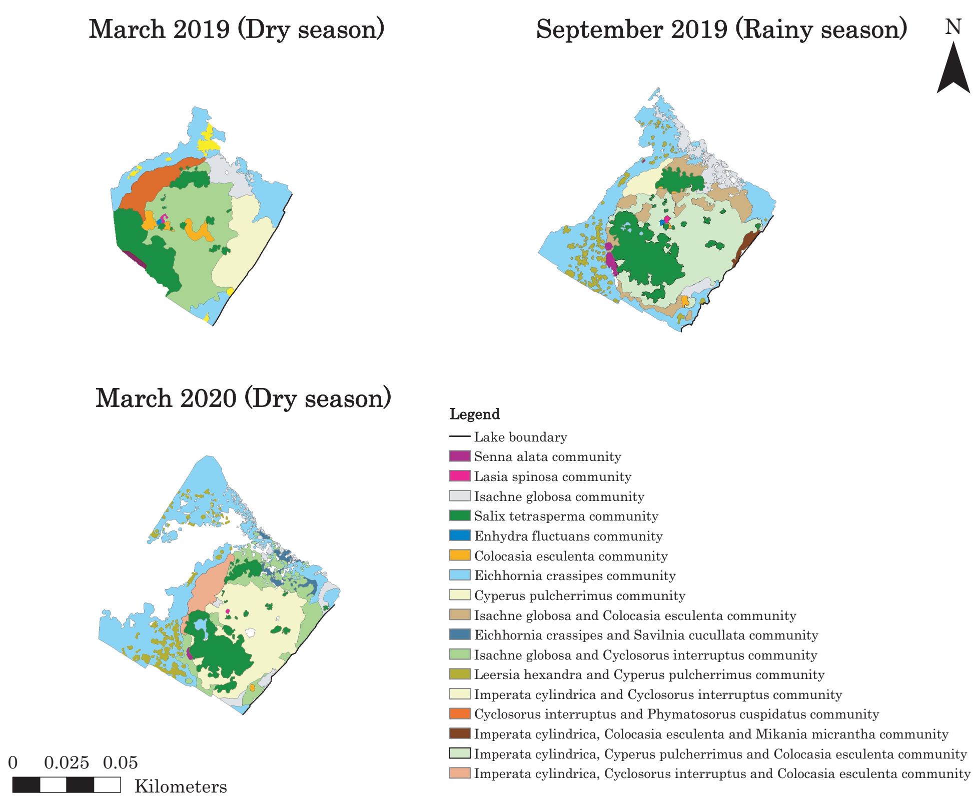


Fig. 5 Manual mapping by direct visual interpretation of Zone D in March 2019 (dry season), September 2019 (rainy season), and March 2020 (dry season)

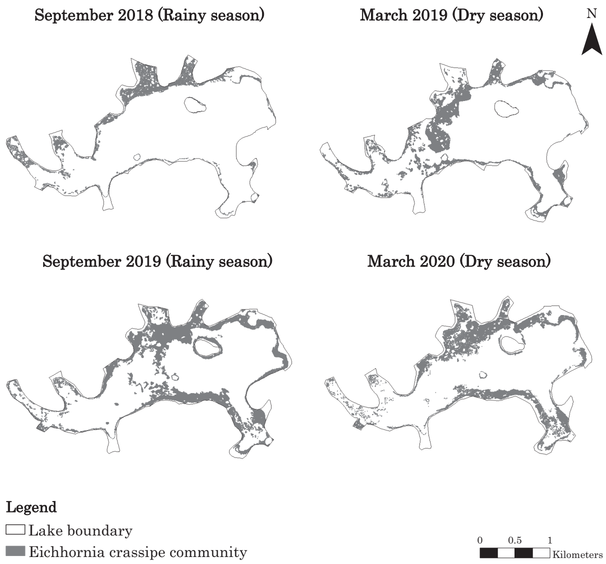


Fig. 6 Distribution map of the *Eichhornia crassipes* community by direct visual interpretation in September 2018 (rainy season), March 2019 (dry season), September 2019 (rainy season), and March 2020 (dry season)

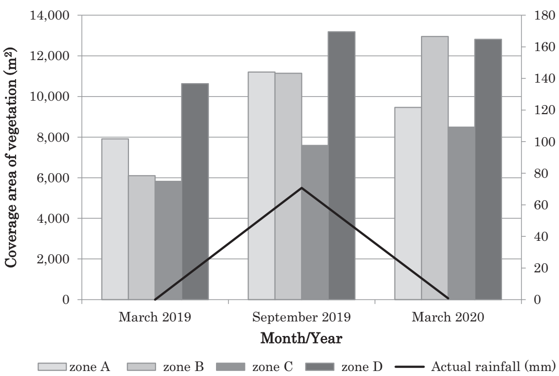


Fig. 7 Coverage area of vegetation and actual rainfall in March 2019 (dry season), September 2019 (rainy season), and March 2020 (dry season).

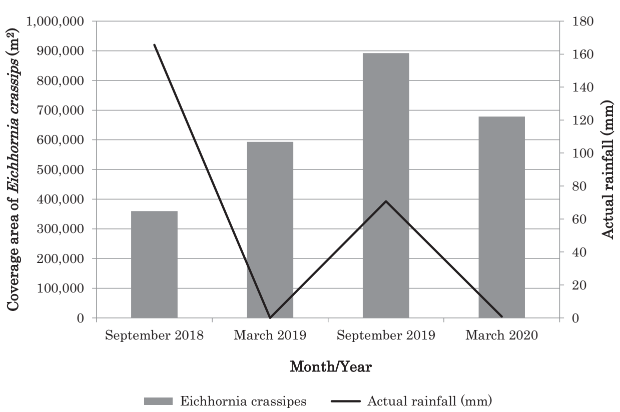


Fig. 8 Coverage area of *Eichhornia crassipes* and actual rainfall in September 2018 (rainy season), March 2019 (dry season), September 2019 (rainy season), and March 2020 (dry season)

creased by 1,174 m^2 and 877 m^2, respectively. In zone B, the floating plant area increased from March 2019 to September 2019 by 3,4154 m^2, then decreased by 132 m^2 in March 2020. One example, *Nelumbo nucifera*, increased from March 2019 to September 2019 by 275 m^2, then by March 2020, had decreased by 267 m^2. Marginal plants decreased from March 2019 to September 2019 by 1,256 m^2 then increased by 4,489 m^2 in March 2020. In zone C, marginal plants and floating plants increased from March 2019 to March 2020 by 2,253 m^2 and 736 m^2, respectively. For example, the area covered by *Mimosa priga* increased continuously from March 2019 to March 2020 by 293 m^2. In zone D, marginal plants increased from March 2019 to September 2019 by 1,524 m^2, and then decreased by March 2020 by 817 m^2. Floating plants increased from March 2019 to March 2020 by 2,263 m^2.

As the water level declined between September 2018 (1 m) and March 2020 (0.2 m), the coverage area of *Eichhornia crassipes* increased by 532,588 m^2 between September 2018 and September 2019, and then decreased by 214,055 m^2 in March 2020 (Fig. 10).

3.5 Relationship between non-submerged vegetation and water quality

Results of the water quality measurements in the four study zones (Table 1) were compared to the accepted values of the Standard Quality of Surface Water, Thailand (Class 3). The pH was between 6.07 and 8.10, within the accepted values (pH 5–9). The DO values in March 2019, September 2019, and March 2020 were lower than the standard value (4 mg/L). The results of the total phosphorus and total nitrogen were compared to the accepted values of the Standard Methods for the Examination of Water and Wastewater. Total phosphorus measured in samples collected in March 2019 (1.12 mg/L) and March 2020 (1.14 mg/L) in zone A and March 2020 (0.80 mg/L) in zone B were higher than the standard (0.5 mg/L). Moreover, total nitrogen measured in samples collected from zone B in March 2019 (4.98 mg/L) and March 2020 (5.32 mg/L), as well as those in zone D in March 2019 (4.08 mg/L) and March 2020 (4.53 mg/L), also exceeded the standard (4 mg/L). The conductivity values in the four study zones were between 30.22 μS/cm and 82.39 μS/cm, and they rapidly increased from September 2019 to March 2020 in all zones.

The coverage area of floating plants in the four study zones continuously increased after March 2019. Furthermore, the coverage area of *Eichhornia crassipes* over the entire lake increased after September 2018. These results are consistent with the decline of observed DO values after September 2018 and increased TP, TN, and conductivity, especially in March 2020.

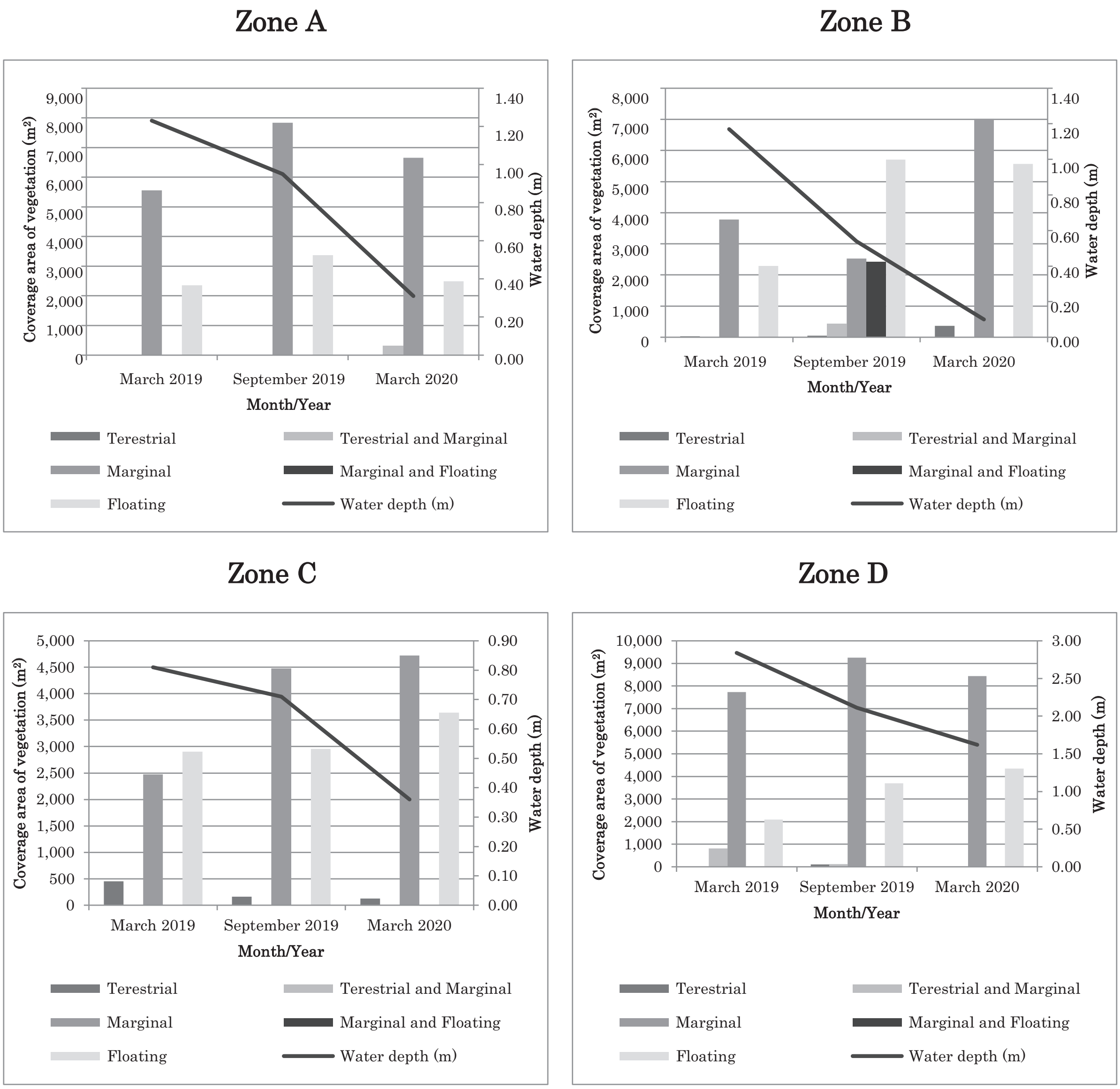


Fig. 9 Coverage area of vegetation and water depth in March 2019 (dry season), September 2019 (rainy season), and March 2020 (dry season)

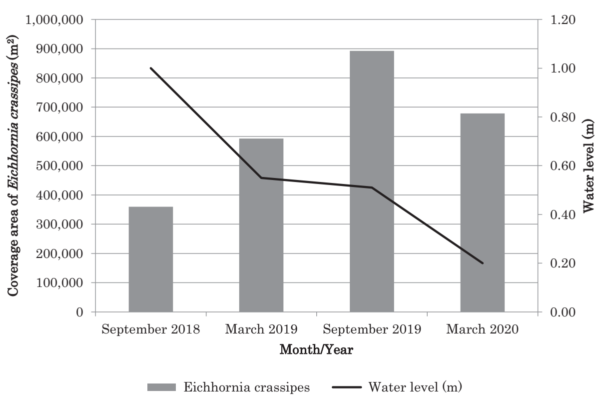


Fig. 10 Coverage area of *Eichhornia crassipes* and water level in September 2018 (rainy season), March 2019 (dry season), September 2019 (rainy season), and March 2020 (dry season)

4. Discussion

4.1 UAV and vegetation mapping

In a previous study, UAV was found to be effective in aquatic plant surveys and vegetation mapping via the direct visual interpretation technique in Nong Bong Khai Lake because UAV can collect close-range vegetation photos (Wongsupathai et al., 2021). Valta-Hulkkonen et al. (2003 b) found that mapping from visual interpretation gave more detailed species information than automated classification. A 90-m UAV orthophoto is clear enough to permit the identification of *Eichhornia crassipes*. In a 30-m UAV orthophoto, species and the boundary between vegetation communities can be identified clearly. However, to avoid neglecting some small species (with a stem diameter or leaf width not exceeding 10

Table 1 Water quality comparison of the Nong Bong Khai Lake in September 2018, March 2019, September 2019, and March 2020

Zone	Month	Year	Water Temp (°C)	pH	DO (mg/l)	Conductivity (μs/cm)	TP (mg/l)	TN (mg/l)
A	September	2018	29.22	7.63	8.60	31.20	—	—
	March	2019	22.57	6.50	3.07	30.22	1.12	3.48
	September	2019	29.20	6.62	3.08	30.86	0.00	0.56
	March	2020	23.05	6.79	3.24	82.39	1.14	3.86
B	September	2018	29.10	6.63	4.21	37.10	—	—
	March	2019	23.83	6.33	3.33	35.15	0.40	4.98
	September	2019	26.90	6.24	3.40	39.46	0.04	0.59
	March	2020	25.30	6.07	3.25	60.35	0.80	5.32
C	September	2018	30.50	8.10	9.72	37.50	—	—
	March	2019	25.17	6.77	3.53	37.62	0.08	0.13
	September	2019	29.82	6.95	3.36	38.06	0.00	0.13
	March	2020	26.68	6.39	3.54	50.80	0.04	1.79
D	September	2018	29.78	6.71	7.12	31.12	—	—
	March	2019	25.67	7.03	3.08	30.83	0.22	4.08
	September	2019	30.58	6.94	3.09	31.17	0.05	0.29
	March	2020	26.82	7.98	3.48	45.75	0.28	4.53

Remark: Index: DO = Dissolved Oxygen, TP = Total Phosphorus, TN = Total Nitrogen

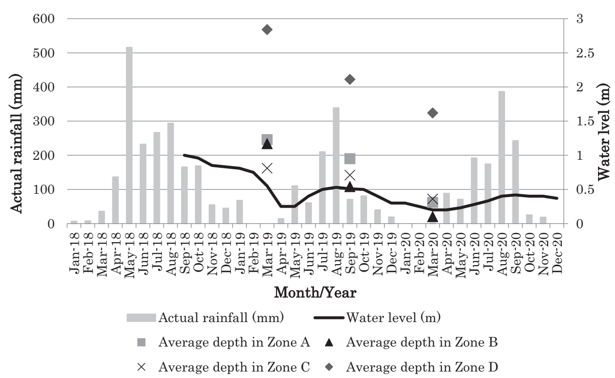


Fig. 11 Actual rainfall, water level (measured at office's pier), and average depth (measured at sampling plots) in Nong Bong Khai Lake from September 2018 to December 2020

cm, such as *Enhydra fluctuans* and *Eleocharis dulcis*), low coverage area species and similar color species, a photo at 2–10 m altitude is needed. The success of UAV notwithstanding, field surveys are always necessary to assess map accuracy.

4.2 Relationship between non-submerged vegetation and rainfall

The vegetation coverage area in the four study zones and the rainfall data in three of the surveys (March 2019, September 2019, and March 2020) indicate that the vegetation in zones A and D was highest during the highest rainfall of 70.7 mm in September 2019. In zones B and C, the vegetation coverage area was highest in March 2020 when rainfall was scant (0.8 mm). When there was zero rainfall in March 2019, the vegetation coverage area in all study zones was lowest. These data show that the amount of rainfall affects vegetation coverage. Coverage of a plant found in wet, humid environments (rainfall > 2000 mm/year), *Colocasia esculenta*, clearly increased in zones A and D during the high amount of rainfall (Hunter et al., 2000). Various meteorological factors such as the size, frequency, and timing of precipitation pulses, may affect plant eco-physiological responses (Ogle and Reynolds, 2004), but plant responses may differ depending upon the species (Hayden et al., 2010; Ensslin and Fischer, 2015; Gao et al., 2015). The precipitation patterns are widely known as governing functional and species diversity (Dodd et al., 1998; Schwinning et al., 2003). On a daily basis, the intensity of precipitation profoundly affects plant photosynthesis, transpiration, or stomatal conductance (Zhao and Liu, 2010; Yang et al., 2014). So, the impact of precipitation changes on the different life-history stages of plants is important to ecological research (Bai et al., 2008; Franks and Weis, 2008; Gornish et al., 2015).

The report from the Northern Meteorological Center showed that the level of rainfall (2020) (Fig. 11) was continuously lower than normal from the beginning of 2019 to the middle of 2020 (normal values of the actual rainfall are referred to as the average rainfall over the 30-year period 1981–2010). The Thai Meteorological Department (2021) reported that the occurrence of El Niño in the first half of 2019 caused the low actual rainfall. Although the El Niño phenomena did not occur in the second half of 2019, the actual rainfall was still low due to the Positive Indian Ocean Dipole. In addition, the precipitation decreases directly resulted in the decline of water level because the lake's water originates only from precipitation.

4.3 Relationship between non-submerged vegetation and water level

The water level in the study area during the entire study period (September 2018-December 2020) (Fig. 12) shows that the amount of actual rainfall was a major determinant of the water level in the lake. Comparing the vegetation coverage area and the water depth in all study zones shows the relationship between the decrease in water depth and decline in the native plant species. This is evident in the vegetation map of zone B for *Nelumbo nucifera*. In September 2019, it covered 351 m^2 at 0.51 m water depth and declined to 84 m^2 at 0.20 m in March 2020. Normally, this species survives in habitats with water depths between 0.30 m and 1.50 m (Nohara and Tsuchiya, 1990; Sou and Fujishige, 1995). The vegetation map shows that terrestrial plants and marginal plants increased during the low water depth in March

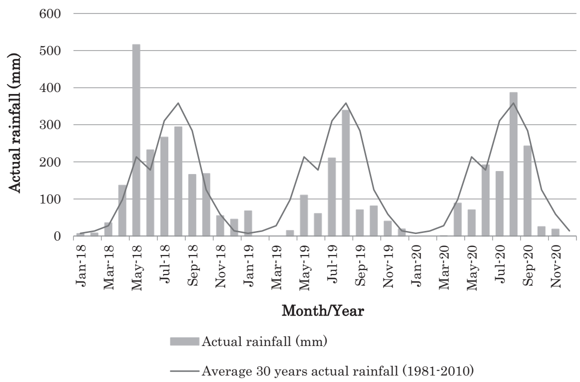


Fig. 12 Actual rainfall and normal value in Chiang Rai, Thailand, from January 2018 to December 2020

2020 (the lowest in three survey periods), especially *Mimosa pigra,* a marginal plant. The vegetation maps reveal that this species coverage increased enormously by 316 m^2 since the 2019 dry season. Yongyut (2006) found few *Mimosa pigra* in the study area in 2006 because the water in the lake was maintained at a high level, and the plant could not invade into the lake area. High water levels have a strong negative effect on *Mimosa pigra* (Asyraf and Micheal, 2011). One of the main causes of increased coverage by *Mimosa pigra* is a decrease in water level. The low water level in March 2020 also resulted in an increase in other terrestrial plant species, especially grasses (*Isachne globosa* and *Leersia hexandra*). The results from 2020 dry season vegetation survey show the appearance of alien species, such as *Bidens pilosa*, *Chromolaena odorata*, and *Mimosa pudica*. These results are consistent with Barros and Albernaz (2014), who observed that a reduction in precipitation could result in low water levels in rivers and extended drought in the Amazon floodplain (Marengo and Nobre, 2001). Under these conditions, the flooded areas might be reduced or replaced with drylands (Burkett and Kusler, 2000). An inadequate flooding period might result in the decline of many species that require an adequate flooding period to complete their life cycle. Moreover, a short flooding period might offer a window of opportunity for invasive species (Poff, 2002; Döll and Zhang, 2010).

The water level of the lake and the coverage area of *Eichhornia crassipes* between September 2018, March 2019, September 2019, and March 2020 were compared (Fig. 10). This comparison showed that the coverage area of *Eichhornia crassipes* continuously increased while the water level decreased. Excluding March 2020, the overall coverage area of *Eichhornia crassipes* decreased by 214,055 m^2 while the lake's water level continuously decreased. This abnormal event occurred due to an unusually heavy 30-minute hailstorm in December 2019 (The Meteorological Department, 2021). The officer of Nong Bong Khai Non-hunting Area reported that many plants in the lake were destroyed by the impact (and likely cold) of the heavy hail. An increase of *Eichhornia crassipes* during decreasing water levels shows how well this species adapts to the unfavorable environment. *Eichhornia crassipes* is an aquatic plant that can survive for several months with no water and in moist sediments (Center et al., 2002). In shallow water, *Eichhornia crassipes* can grow roots into sediment or mud (Hasan et al., 1989; Adrian, 2006). Furthermore, the species can be propagated by its seeds or stolon (Pieterse, 1978). *Eichhornia crassipes* is commonly spread by vegetative propagation, but it can also be propagated by seeds that can remain viable for 20 years (Matthews et al. 1977; Pieterse 1978).

4.4 Relationship between non-submerged vegetation and water quality

The results of water quality analyses in September 2018, March 2019, September 2019, and March 2020 (Table 1) showed below acceptable DO values during March 2019 to March 2020, an indicator of potential water pollution. In March 2020, during the lowest water level of all survey periods, the highest concentrations of nutrients (phosphorous and nitrogen) were detected (Sale et al., 1985; Gopal, 1987; Santamaría, 2002; Xie and Yu, 2003; Xie et al., 2004). The increase in phosphorous and nitrogen also increased conductivity in March 2020 (Wiser and Blom, 2016).

Water quality test results are consistent with the increase in the floating plants, especially *Eichhornia crassipes*, the coverage of which increased beginning in September 2018. Kwanruen (2008) found that areas with dense floating islands and *Eichhornia crassipes* in Nong Bong Khai Lake had low DO, resulting in unsuitable living conditions for aquatic animals. The large *Eichhornia crassipes* mats cover the water, blocking the sunlight and obstructing oxygen exchange. Dense *Eichhornia crassipes* mats degrade water quality, potentially altering species composition and decreasing biodiversity (Masifwa, 2001; Center et al., 2002; Brendock, 2003; Meerhoff et al., 2003). Moreover, the average temperatures (22.57℃ to 30.58℃) and pH values (6.07 to 7.98) were suitable for the growth of *Eichhornia crassipes*. This species grows very well in warm water that is rich in macronutrients, especially waters that are still or slow-moving (Howard and Harley, 1998; Center et al., 2002).

4.5 Implications for management and conservation policies

Low precipitation causes the water depth to decline in the lake, which results in increased coverage by non-native invasive plant species. To mitigate this, it is necessary to maintain the water at an appropriate level. Because the inflow water of the lake is only from precipitation, it cannot be controlled. However, the water in the lake is utilized for only agricultural purposes—the cultivation of off-season paddy fields from January to March of each year. As the water flows out only via the weir in the southern area of the lake, it can be controlled. So, we propose maintaining at least 1 m of water in the lake to prevent the invasion of alien plant species, especially *Mimosa pigra*. Moreover, the increase in *Eichhornia crassipes* resulted of worsening water quality. So, to remove them from the lake, such as by applying a hydraulic mowing boat, is necessary to improve the water quality (Kathryn et al., 2013).

5. Conclusions

Water level fluctuations due to decreased precipitation affected the distribution of the non-submerged aquatic vegetation community and the expansion of *Eichhornia crassipes* in Nong Bong Khai wetland, Thailand. Although the periods of lower precipitation in 2019 and 2020 seem brief, they resulted in a substantial decrease in water level. A vegetation map from the 30-m orthophoto showed significantly increased coverage by non-native, invasive plant species, especially *Mimosa pigra*, during the low water level period. A distribution map of *Eichhornia crassipes* interpreted from a 90-m orthophoto shows its coverage also increased when the water level declined. The water quality testing results indicated that the water in Nong Bong Khai Lake becomes polluted at lower water levels. Maintaining the water at an appropriate depth and removing *Eichhornia crassipes* is necessary to improve the water quality and conserve the wetland ecosystem.

Appendix 1 Species lists of the aquatic plants in the Nong Bong Khai lake.

Family/Species	Life form	Habitat	Mar. 2019 (Dry season)	zone	Water Depth (m)	Sep. 2019 (Rainy season)	zone	Water Depth (m)	Mar. 2020 (Dry season)	zone	Water depth (m)
Acanthaceae											
Justicia sp.	S	Ter	—	—	—	✓	C	1.2	✓	D	0
Amaranthaceae											
Alternanthera philoxeroides	Aq	Eg	—	—	—	—	—	—	✓	C	0
Alternanthera sessilis (L.) DC.	H	Eg	—	—	—	✓	A, C	0–0.65	—	—	—
Ancistrocladaceae											
Ancistrocladus tectorius (Lour.) Merr.	C	Ter	✓	C	0	✓	C	0	✓	C	0
Apiaceae											
Oenanthe javanica (Blume) DC.	H	M	✓	A, B, C, D	0.60–2.95	✓	A, B, C, D	0.20–2.50	✓	A, B, C, D	0–1.90
Apocynaceae											
Marsdenia tinctoria R. Br.	C	Ter	✓	B, D	0.85–2.90	✓	B, D	0.20–2.50	✓	A, B, C, D	0–2.00
Alstonia scholaris (L.) R. Br.	T	Ter	—	—	—	—	—	—	✓	B	0
Araceae											
Colocasia esculenta (L.) Schott	H	M	✓	A, B, C, D	0–2.95	✓	A, B, C, D	0.5–2.5	✓	A, B, C, D	0–1.95
Lasia spinosa (L.) Thwaites	H	M	✓	C, D	1.30–2.90	✓	D	2.45	✓	D	1.90
Pistia stratiotes L.	Aq	F	✓	C, D	1.40–2.80	✓	B	0.65	✓	C	0.25
Asteraceae											
Ageratum conyzoides L.	H	Ter	✓	C	0	✓	B, C, D	0.55–2.15	✓	C	0
Crassocephalum crepidioides (Benth) S. Moore	H	Ter	✓	C	0	✓	C	0–1.00	✓	A, B, C, D	0–0.70
Enhydra fluctuans Lour	Aq	M	✓	A, C, D	0.83–2.90	✓	A, B, C, D	0–2.45	✓	A, B, C, D	0–2.00
Mikania micrantha Kunth	C	Ter	✓	A, B, C, D	0–2.95	✓	A, B, C, D	0.15–2.50	✓	A, B, C, D	0–1.90
Bidens pilosa L.	H	Ter	—	—	—	—	—	—	✓	B, C	0
Chromolaena odorata (L.) R.M.King & H. Rob.	H	Ter	—	—	—	—	—	—	✓	B, C	0–0.30
Athyriaceae											
Diplazium esculentum (Retz.) Sw	TerF	M	✓	D	2.90	—	—	—	—	—	—
Combretaceae											
Getonia floribunda Roxb.	C	Ter	✓	C	0.95	—	—	—	—	—	—

Family/Species	Life form	Habitat	Mar. 2019 (Dry season)	zone	Water Depth (m)	Sep. 2019 (Rainy season)	zone	Water Depth (m)	Mar. 2020 (Dry season)	zone	Water depth (m)
Commelinaceae											
Commelina benghalensis L.	H	Ter	—	—	—	—	—	—	✓	B, C	0–0.50
Commelina diffusa Burm. f.	H	Ter	—	—	—	✓	B	0.25–0.60	—	—	—
Convolvulaceae											
Aniseia martinicensis	C	Ter	—	—	—	✓	B	0.70	—	—	—
Ipomoea aquatica Forssk.	H	M	✓	B, C	0–2.10	✓	A, B, D	0.25–1.25	✓	B	0–0.25
Ipomoea sp.	H	M	—	—	—	✓	A	0.65	—	—	—
Merremia umbellata (L.) Hallier f.	C	Ter	—	—	—	—	—	—	✓	A	0–0.75
Cucurbitaceae											
Gymnopetalum integrifolium (Roxb.) Kurz.	C	Ter	—	—	—	—	—	—	✓	C	0
Cyperaceae											
Actinoscirpus grossus (L. f.) Goetgh. & D. A. Simpson	H	M	—	—	—	—	—	—	✓	A, B, C, D	0–1.05
Cyperus cephalotes Vahl	H	M	—	—	—	✓	C	1.20	✓	C, D	0.25–1.65
Cyperus compactus Retz.	H	M	—	—	—	✓	D	2.45	—	—	—
Cyperus procerus Rottb.	H	M	—	—	—	✓	B, C	0–0.65	—	—	—
Cyperus pulcherrimus Willd. ex Kunth	H	M	✓	A, B, C, D	0–2.70	✓	A, B, C, D	0.25–2.45	✓	A, B, D	0–1.95
Cyperus rotundus L.	H	M	—	—	—	✓	D	2.30	—	—	—
Eleocharis dulcis (Burm. f.) Trin. ex Hensch.	H	Eg	✓	A, B, C, D	0.63–2.90	✓	A, B, C, D	0.2–2.55	✓	A, B, C, D	0–2.00
Eriocaulaceae											
Eriocaulon cinereum R. Br.	H	M	✓	C	0	—	—	—	✓	C	0
Euphorbiaceae											
Phyllanthus urinaria L.	H	Ter	—	—	—	—	—	—	✓	C, D	0–0.40
Fabaceae											
Acacia auriculiformis A. Cunn. ex Benth.	T	Ter	—	—	—	—	—	—	✓	C	0
Mimosa invisa Mart.	H	M	—	—	—	—	—	—	✓	C	0
Mimosa pigra L.	S	M	✓	B, C	0–0.80	✓	B, C	0–1.20	✓	A, B, C	0
Mimosa pudica L.	H	M	—	—	—	—	—	—	✓	C	0
Mucuna pruriens (L.) DC.	C	Ter	✓	B	0.85–1.25	✓	B, D	0.50–2.30	✓	B, C	0
Senna alata (L.) Roxb.	S	Ter	✓	B, D	0.85–2.95	✓	B, C, D	0–0.25	✓	B, C, D	0–1.80
Senna tora (L.) Roxb.	US	Ter	—	—	—	✓	C	0	✓	C	0
Hydroleaceae											
Hydrolea zeylanica (L.) Vahl	H	M	—	—	—	—	—	—	✓	C	0–0.90
Linderniaceae											
Lindernia anagallis (Burm. f.) Pennell	H	M	✓	B, C, D	0–3.0	✓	A, B, C, D	0–2.55	✓	A, B, C	0–0.90
Lygodiaceae											
Lygodium microphyllum (Cav.) R. Br	C	Ter	✓	D	2.85	—	—	—	—	—	—
Lythraceae											
Rotala rotundifolia (Roxb.) Koehne	H	Eg	—	—	—	✓	C	1.20	✓	C, D	0.5–1.50

Family/Species	Life form	Habitat	Mar. 2019 (Dry season)	zone	Water Depth (m)	Sep. 2019 (Rainy season)	zone	Water Depth (m)	Mar. 2020 (Dry season)	zone	Water depth (m)
Malvaceae											
Sida acuta Burm. f.	US	Ter	✓	C	0	—	—	—	—	—	—
Urena lobata L.	US	Ter	—	—	—	—	—	—	✓	C	0
Waltheria indica L.	US	Ter	—	—	—	✓	C	0	—	—	—
Melastomataceae											
Osbeckia stellata Buch-Ham. ex Ker Gawl.	S	Ter	✓	C, D	1.65–2.95	✓	C	1.20	✓	C	0.70
Molluginaceae											
Glinus oppositifolius (L.) A.DC.	H	Ter	✓	C	0	—	—	—	✓	C	0
Nelumbonaceae											
Nelumbo nucifera Gaertn.	Aq	F	✓	A, B	1.10	✓	A, B	0.30–0.70	✓	B	0.30
Onagraceae											
Ludwigia adscendens (L.) H. Hara	Aq	M	✓	B, C, D	0.80–2.95	✓	A, B, C, D	0–1.55	✓	B, C, D	0–1.80
Ludwigia hyssopifolia (G. Don) Exell	H	M	✓	A	1.65	✓	C	0.65	—	—	—
Ludwigia octovalvis (Jacq.) P. H. Raven	H	M	✓	A	1.15	✓	A, B, C	0–2.00	✓	C	0
Orchidaceae											
Thrixspermum amplexicaule (Blume) Rchb. f	E	Ter	✓	C, D	1.85–2.95	✓	D	2.45	✓	D	1.45–1.90
Phyllanthaceae											
Glochidion sphaerogynum (Mull. Arg.) Kurz	S	Ter	✓	B, C	0.90–1.30	✓	B	0.25	✓	B, D	0
Phyllanthus amarus Schumach. & Thonn.	H	Ter	✓	C	1.50	—	—	—	✓	C	0
Plantaginaceae											
Scoparia dulcis L.	H	Ter	—	—	—	✓	B, C	0.50–1.35	✓	B	0.25
Poaceae											
Arundo donax L	G	M	✓	B, C	0.95–1.30	✓	A, B	0.50–0.70	✓	A, B, C, D	0–2.10
Axonopus compuuressus P.Beauv	G	Ter	—	—	—	—	—	—	✓	C	0
Brachiaria mutica	G	Ter	—	—	—	—	—	—	✓	D	0.65
Chrysopogon zizanioides (L.) Roberty	G	Ter	✓	C	0–0.40	—	—	—	—	—	—
Cynodon dactylon (L.) Pers	G	Ter	✓	C	0	✓	C	0	✓	B, C	0
Cyrtococcum oxyphyllum (Steud.) Stapf	G	Ter	—	—	—	—	—	—	✓	C	0
Dendrocalamus strictus (Roxb.) Nees	B	Ter	✓	C	0–1.30	—	—	—	—	—	—
Echinochloa colona (L.) Link	G	M	✓	B, C	0–1.30	✓	B, C, D	0.50–1.45	✓	B, C, D	0–0.50
Echinochloa crus-galli (L.) P. Beauv.	G	Ter	—	—	—	—	—	—	✓	B	0
Eragrostis unioloides (Retz.) Nees ex Steud	G	Ter	—	—	—	—	—	—	✓	C	0
Imperata cylindrica (L.) Raeusch	G	M	✓	A, B, C, D	0–2.95	✓	A, B, C, D	0.20–2.55	✓	A, B, C, D	0–1.95
Isachne globosa (Thunb.) Kuntze	G	M	✓	A, B, C, D	0–2.95	✓	A, B, C, D	0.20–2.55	✓	A, B, C, D	0–1.95
Ischaemum barbatum Retz	G	M	✓	C, D	0–2.95	✓	B, D	0.20–2.40	✓	C	0–0.90
Ischaemum rugosum Salisb.	G	Ter	—	—	—	✓	C	0	✓	A, B	0
Leersia hexandra Sw	G	M	✓	A, B, C, D	0–2.95	✓	A, B, C, D	0.20–2.55	✓	A, B, C, D	0–1.95

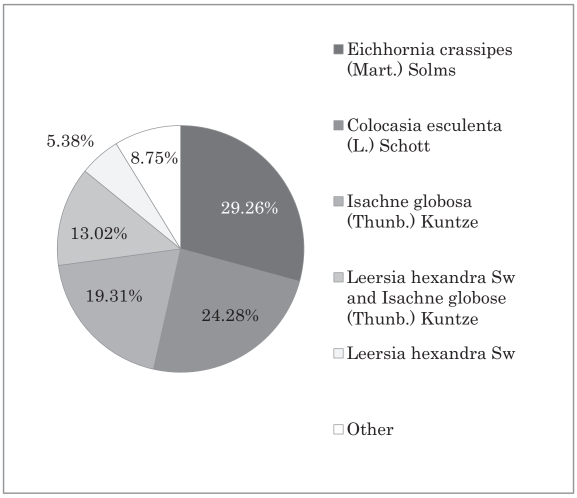
Family/Species	Life form	Habitat	Mar. 2019 (Dry season)	zone	Water Depth (m)	Sep. 2019 (Rainy season)	zone	Water Depth (m)	Mar. 2020 (Dry season)	zone	Water depth (m)
Leptochloa chinensis (L.) Nees	G	Ter	—	—	—	—	—	—	✓	A	0
Panicum repens L	G	Ter	✓	A, B, C	0–2.10	✓	C	0–1.20	✓	B, C, D	0–2.00
Pennisetum polystachion (L.) Schult.	G	Ter	—	—	—	—	—	—	✓	B	0
Saccharum arundinaceum Retz.	G	Ter	✓	A	1.10	—	—	—	—	—	—
Sacciolepis indica (L.) Chase	G	M	✓	C, D	0–3.00	✓	A, B, C, D	0–2.20	✓	B, C, D	0–1.80
Stenotaphrum helferi Munro ex Hook.f.	G	Ter	✓	C	1.70	—	—	—	—	—	—
Polygonaceae											
Persicaria attenuata (R. Br.) Soják var.	H	M	✓	C	0–1.30	✓	A, B, C	0–1.00	✓	A, B, C	0
Persicaria sp.	H	M	✓	A, B, C, D	0–2.95	✓	A, B, C, D	0.20–2.55	✓	A, B, C, D	0–1.95
Polypodiaceae											
Phymatosorus cuspidatus (D. Don) Pic. Serm.	E	Ter	✓	C, D	1.65–2.90	✓	C, D	0.50–2.50	✓	D	1.95
Pontederiaceae											
Eichhornia crassipes (Mart.) Solms	Aq	F	✓	A, B, C, D	0–2.95	✓	A, B, C, D	0.20–2.50	✓	A, B, C, D	0–1.80
Salicaceae											
Salix tetrasperma Roxb.	T	M	✓	A, B, C, D	0–2.85	✓	A, B, D	0.25–2.35	✓	A, B, D	0–1.85
Salviniaceae											
Azolla pinnata R. Br.	Aq	F	✓	C	1.20	—	—	—	—	—	—
Salviniaceae											
Salvinia cucullata Roxb. ex Bory	Aq	F	✓	A, B, C, D	0–2.85	✓	A, B, C, D	0.50–2.50	✓	B, C, D	0–1.95
Solanaceae											
Solanum torvum Swartz.	S	Ter	—	—	—	—	—	—	✓	C	0
Sparganiaceae											
Sparganium erectum L.	H	M	✓	D	2.90	✓	D	1.45–2.50	✓	A, D	0–2.10
Thelypteridaceae											
Cyclosorus interruptus (Willd.) H. Itô	TerF	M	✓	A, B, C, D	0–2.95	✓	A, B, C, D	0.20–2.50	✓	A, B, C, D	0–1.90
Zingiberaceae											
Alpinia sp.	H	Ter	✓	C	0	—	—	—	—	—	—

Remark: T = Tree, S = Shrub, US = Under Shrub, H = Herb, G = Grass, B = Bamboo, C = Climber, E = Epiphyte, TerF = Terrestrial Ferns, Aq = Aquatic, Ter = Terrestrial, M = Marginal, Eg = Emergent, F = Floating

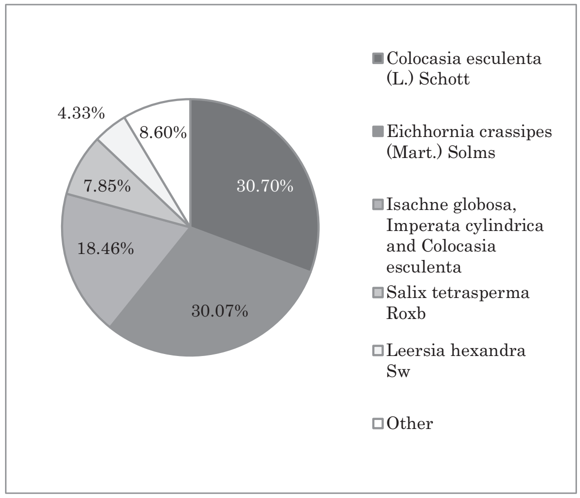
Appendix 2 Coverage area of each plant community in Zones A, B, C, and D in March 2019 (dry season), September 2019 (rainy season), and March 2020 (dry season).

Zone A

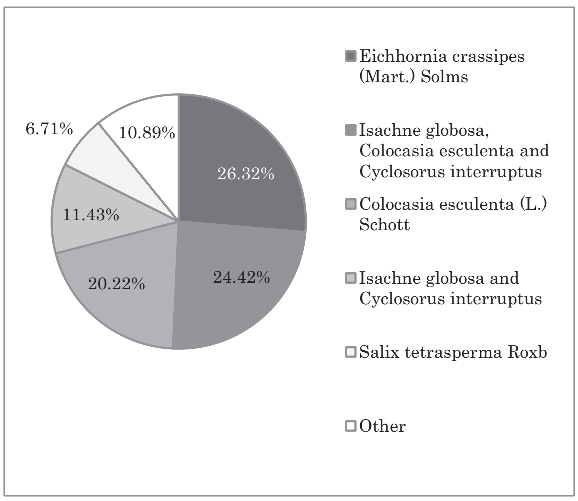
March 2019 (Dry season)



September 2019 (Rainy season)

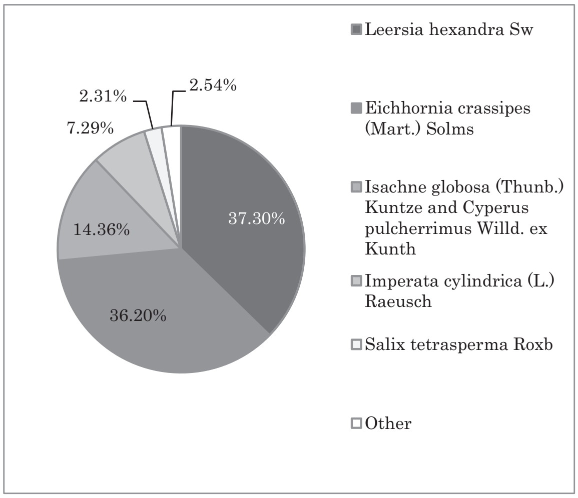


March 2020 (Dry season)

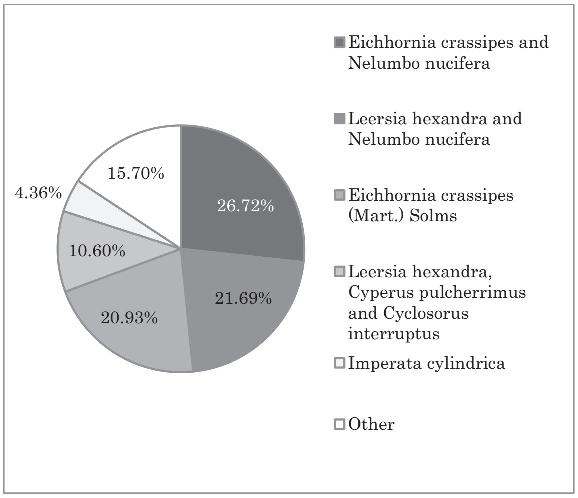


Zone B

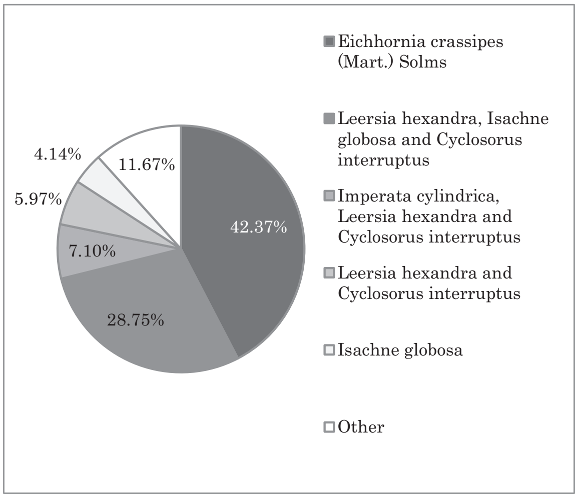
March 2019 (Dry season)



September 2019 (Rainy season)

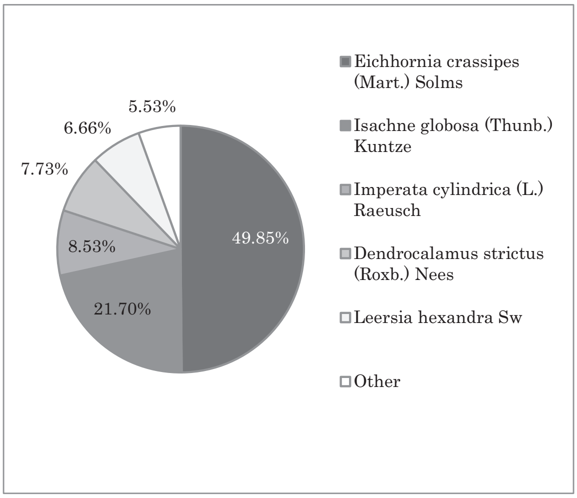


March 2020 (Dry season)

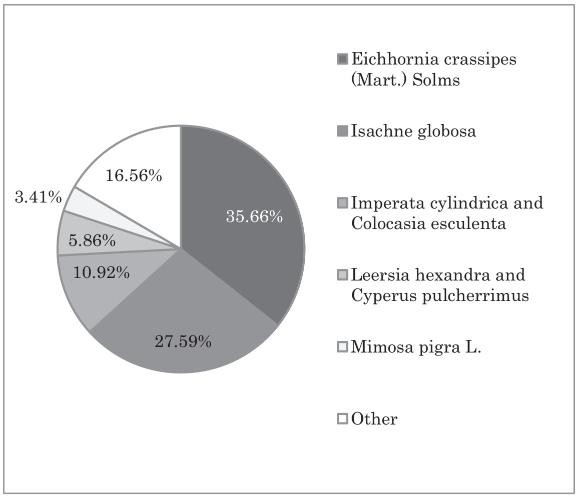


Zone C

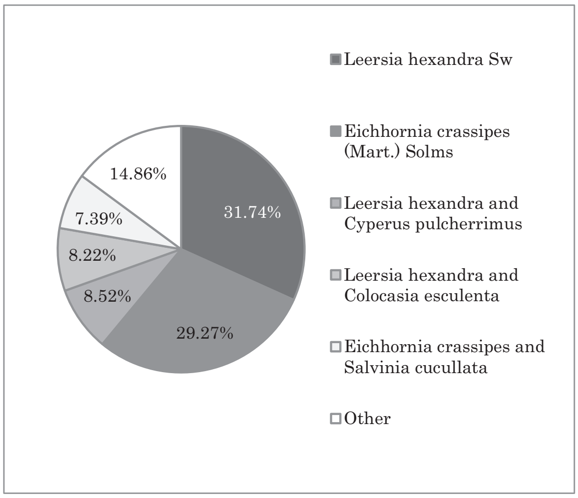
March 2019 (Dry season)



September 2019 (Rainy season)

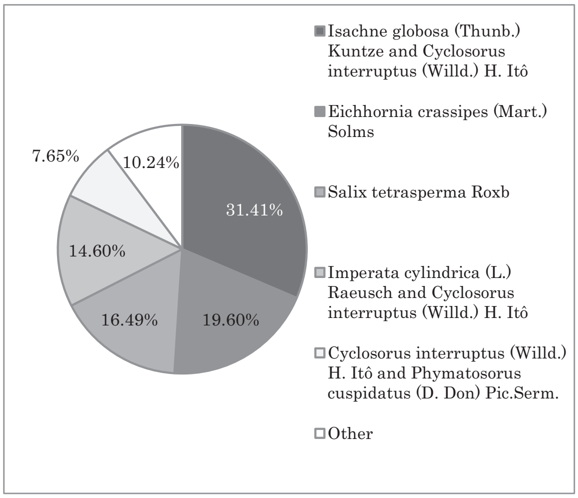


March 2020 (Dry season)

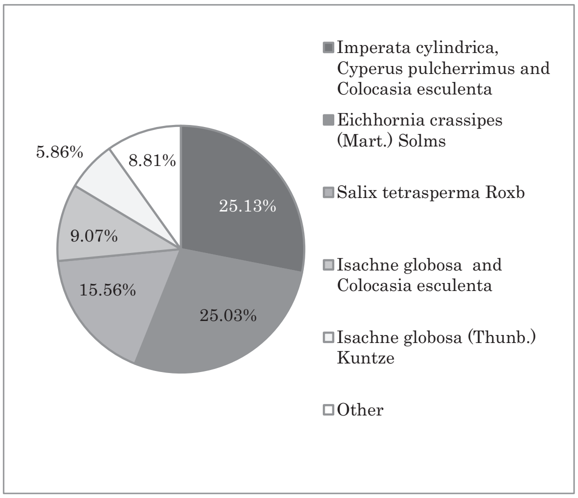


Zone D

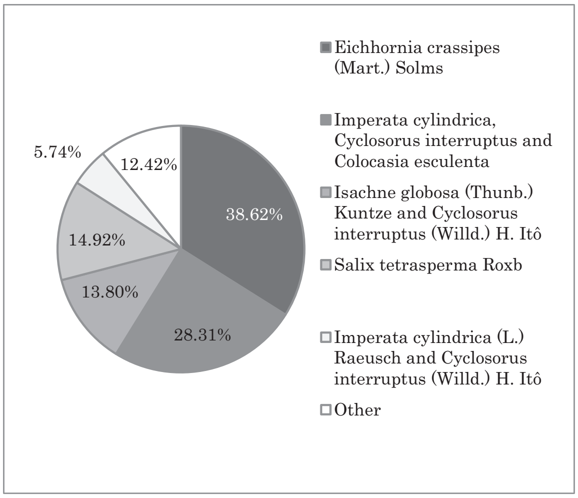
March 2019 (Dry season)



September 2019 (Rainy season)



March 2020 (Dry season)



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