Bot. Bull. Acad. Sin. (2001) **42:** 17-22

Characteristics of the acidic environment of the Yuanyang Lake (Taiwan)

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(Received May 15, 2000; Accepted July 14, 2000)

Abstract. Yuanyang Lake is an acidic alpine lake located in northern Taiwan. The lake's acidity displays both spatial and temporal variations and is correlated with concentrations of organic and inorganic carbon, and with some cations in the lake water. The factors relating to such characteristics were studied, with particular focus on acid precipitation and the role of biological communities in the watershed. Twelve species of mosses and liverworts were collected from the watershed and used in an elution experiment. The results indicated that the pH of natural rainwater was significantly reduced following contact with these epiphytes. The acidity of Yuanyang Lake may largely be a result of natural acid leaching from the vegetation, rather than acidic precipitation.

Keywords: Acidity; Epiphyte; Lake acidification; Limnology; Terrestrial vegetation; Yuanyang Lake.

Abbreviations: Ca, calcium; **Cl,** chloride; **Cond,** conductivity; **Fe,** iron; **K,** potassium; **Mg,** magnesium; **Na,** sodium; $\mathbf{NH_4^+}$, ammonium-N; $\mathbf{NO_3^-}$, nitrate-N; $\mathbf{NO_2^-}$, nitrite-N; PO_4^{3-}, phosphate; $\mathbf{SO_4^{2-}}$, sulphate; $\mathbf{SiO_2}$, silicate; **TIC,** total inorganic carbon; **TN,** total organic nitrogen; **TOC,** total organic carbon; **TP,** total phosphorus.

Introduction

In many regions of the world, the deposition of acids from the atmosphere has resulted in the acidification of lakes, ponds, rivers and streams (Abrahamsen, 1983; Henrikson, 1989; Johnson and Lindberg, 1992). However, regions with such lakes often contain water bodies that are naturally acidic, due to inputs of organic acid from vegetation and soils, or from natural processes operating in the lake (Reiner and Olsen, 1984; Coxson, 1991; Emmett et al., 1994). To accurately assess the degree of environmental impact, it is important to differentiate between natural sources of acidity and man-made sources. In this study we address this issue by presenting a case study of a subtropical alpine lake in Taiwan.

Yuanyang Lake is located in northern Taiwan in a 370 ha watershed that is forested mainly by cypress trees (*Chamaecyparis formosensis* Matsum and *C. obtusa* var. *formosana* [Hay.] Rehder) (Liu and Hsu, 1973; Chou et al., 2000). The watershed is characterized by a thin layer of soil overlying granitic bedrock (Chen and Chiu, 2000). Both the lake and watershed have been the subject of long-term ecological studies since 1993.

Although the area of the lake is small it has a pronounced pH gradient between the inlet and outlet (Wu and Chang, 1996). This gradient has been observed on all sampling occasions. In Taiwan, acid precipitation is commonly observed, and it is well documented in a great part of the island. In the Yuanyang Lake area, the rainwater typically is ca. pH 5.0. The pH of lake water is much lower than this value. It is therefore of interest to elucidate the causal factors of the lake's acidity.

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Materials and Methods

Study Site

Yuanyang Lake is located in a nature preserve in northern Taiwan (24°35'N, 121°24'E) at an altitude of 1,670 m (Figure 1). It has a maximum depth of 4 m, an area of 3.6 ha and a volume of 54,000 m^3. In addition to cypress trees the watershed has an understory of *Rhododendron formosanum* Heiml and a rich array of epiphytes, mainly mosses (Liu and Hsu, 1973). In the lake there are three emergent aquatic macrophytes: *Potamogeton octandra* Poir., *Schoenoplectus mucronatus* (L.) Pall. ssp. *robustus* (Miq.) T. Koyama and *Sparganium fallax* Graebn. (Hwang et al., 1996). In an adjacent marsh area there is a dense growth of the filamentous green alga, *Spirogyra* sp.

The region around the lake has high relative humidity (>80%) and annual precipitation between 250-450 cm. During this study the pH of rainfall varied from 3.8 to 6.2. Water temperatures in the lake varied from 4 to 21°C.

The soils of the investigated system are either partially podzolized soils or nearly pure peats with a highly organic surface layer. The forest soils are generally very shallow

(< 60 cm) with granite bedrock underground. The soils are strongly acidic. The pH values of the surface horizon, measured in water, range from 3.3 to 4.1. The forest soils can be divided into three groups (Chiu et al., 1999): histosol (Lithic Medihemist), inceptisol (Clayey mixed mesic Typic Dystrochrept) and ultisol (Clayey mixed mesic Typic Hapludult). Histosol stretches from lakeshore to toeslope. The thick organic layer, probably derived from peat, directly covers the primarily weathered bedrock. Inceptisol covers most of the forest. Poor drainage, originating from the clay or silty clay mineral layer beneath the organic layer, limits the downward movement of the minerals and, consequently, retards the development of the soil profile. Ultisol, a relatively well-drained soil, is distributed on the shoulder of the mountain.

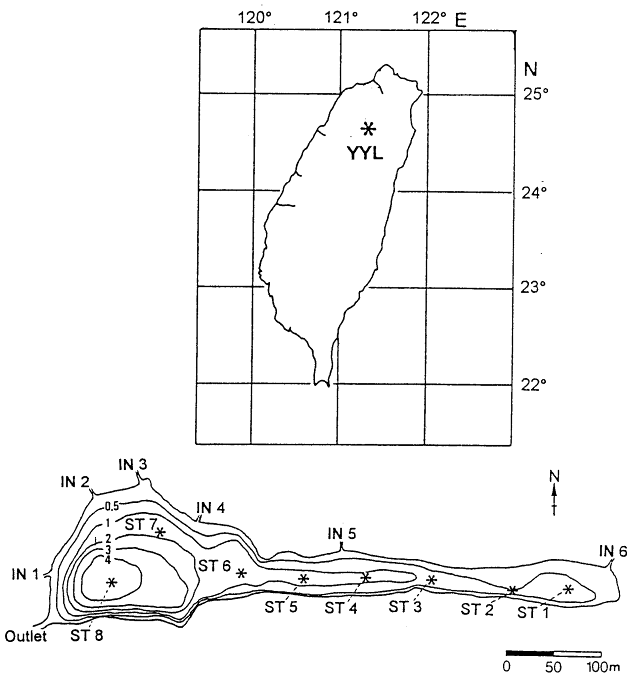

Figure 1. Map of Taiwan, showing the locations of the Yuanyang Lake (YYL) and the sampling sites in the lake (ST 1-8) and inlets (IN 1-6) of lake water.

Sampling and Analysis of Water Quality

Lake water was sampled from August 1993 to July 1997, on a seasonal basis at 15 locations: eight in the lake, six at inlets, and one at the single outlet (Figure 1). Concentrations of ammonium, chloride, nitrate, nitrite, phosphate, silicate, sulfate, total organic nitrogen (TON) and total phosphorus (TP) were analyzed according to standard methods (APHA, 1992). The pH and conductivity of water were measured with a Sentron pH System (Roden, The Netherlands) and a Hanna conductivity meter (Singapore), respectively. The concentrations of total organic carbon (TOC) and total inorganic carbon (TIC) in water were determined by a TOC analyzer (OI Analytical, Texas, USA), while cations, including calcium, iron, magnesium, manganese, potassium, and sodium were assayed with an atom absorption spectrophotometer (Perkin Elmer 2380, Norwalk, Connecticut). Data were analyzed using the software package Statistica (Microsoft Co., Oklahoma). Unweighted pair-group average (UPGMA) (Sneath and Sokal, 1973) and multiple r-square methods were used for cluster analysis and principal component analysis, respectively. The aim was to identify statistically significant relationships in time and/or space between the water quality attributes.

Elution Experiment

Elution experiments also were performed, using 12 species of epiphytes, including mosses and liverworts (shown in Table 1) collected from the stems of cypress and *R. formosanum*. Epiphytes were cleaned of detritus and contamination of other species prior to the experiments. A biomass of 30 ± 1 g (fresh weight) of each species was loaded into a funnel and sprayed with 100 ml of either freshly prepared distilled water (pH 6.82) or natural rainwater (pH 4.88, collected in an area close to Yuanyang Lake in December 1994). The eluted solutions were then collected for determination of pH.

Table 1. Variation in pH value of eluents from 12 epiphytes collected from the watershed of Yuanyang Lake after elution with distilled water (pH 6.82) or rainwater (pH 4.88), and the lowered pH units per gram of fresh plant materials.

Species of epiphyte	Eluted with distilled water	Eluted with rainwater	ΔpH•g^{-1} wet weight
Bazzania fauriana (Steph.) Hatt.	4.54 ± 0.10	3.91 ± 0.32	0.021 ± 0.002
Dicranodontium uncinatum (Harv.) Jaeg.	4.29 ± 0.12	3.85 ± 0.33	0.015 ± 0.002
Dicranoloma blumii (Nees) Par.	4.54 ± 0.11	4.02 ± 0.44	0.017 ± 0.002
Herbertus aduncus (Dicks.) Gray	4.69 ± 0.10	4.40 ± 0.21	0.010 ± 0.001
Hypnum oldhamii (Mitt.) Jaeg.	4.94 ± 0.31	4.24 ± 0.11	0.023 ± 0.002
Mastigophora diclados (Brid.) Nees	4.58 ± 0.20	4.43 ± 0.05	0.005 ± 0.001
Pseudospiridentopsis horrida (Card.) Fleisch.	4.90 ± 0.09	4.75 ± 0.24	0.005 ± 0.001
Pyrrhobryum latifolium (Bosch et Lac.) Mitt.	4.12 ± 0.21	3.81 ± 0.39	0.010 ± 0.002
Scapania ornithopodioides (With.) Waddel	4.57 ± 0.06	4.35 ± 0.20	0.007 ± 0.001
Schistochila acuminata Steph.	4.50 ± 0.12	4.21 ± 0.27	0.010 ± 0.001
Sphagnum palustre L. subsp. *pseudocymbifolium* (C. Müll.) Eddy	5.13 ± 0.19	4.82 ± 0.30	0.010 ± 0.001
Sphagnum sericeum C. Müll.	4.84 ± 0.09	4.57 ± 0.05	0.009 ± 0.001

Results

Seasonal Variation in Acidity of Lake Water

The acidity of lakewater varied from year to year during the study, and also among seasons within years. The pH measured towards the center of the lake was lowest in the spring and highest in summer to winter (Figure 2). This pH variation did not correspond with seasonal variations in precipitation, which displayed a maximum in the summer. Thus variation in acidity of lakewater was independent of the amount of precipitation entering the lake.

Variation in Acidity of Inlet Water

The runoff from the watershed of Yuanyang Lake was quite acidic. The pH measured at six inlets ranged from 4.2 to 6.8. Acidity varied among inlet locations; the lowest values occurred at station IN 2 and IN 6 and highest values at IN 4 (Figure 3). As was the case for lakewater, water at the inlets displayed a seasonal variation in acidity, with the lowest pH in spring (the dry season) and the highest pH in summer to winter. This suggests that lake acidity may be determined by the acidity of inlet water.

Relationship Between Lakewater Acidity and Physico-Chemical Variables

The lakewater was most acidic at Station 1, and increased towards Station 8 (Figure 4). Associated with this acidity gradient were other attributes of the water including conductivity, concentrations of sulphate, TIC, TOC, ammonium, nitrate, phosphate, and chlorophyll *a*. When principal factor analysis was employed to analyze the correlation among water quality attributes and acidity, the strongest association was with TIC, nitrite, and total organic nitrogen (Figure 5). Cations, such as Mg, Ca, Fe, Na and K, and anions, such as sulphate, chloride, phosphate and nitrate, were not well correlated with the variations in acidity.

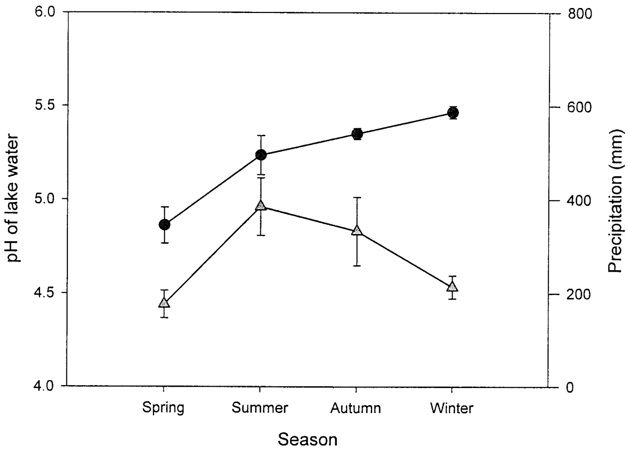

Figure 2. Seasonal variation in acidity (circle) of lakewater and monthly average of precipitation (triangle) in the Yuanyang Lake. Error bars indicate standard error.

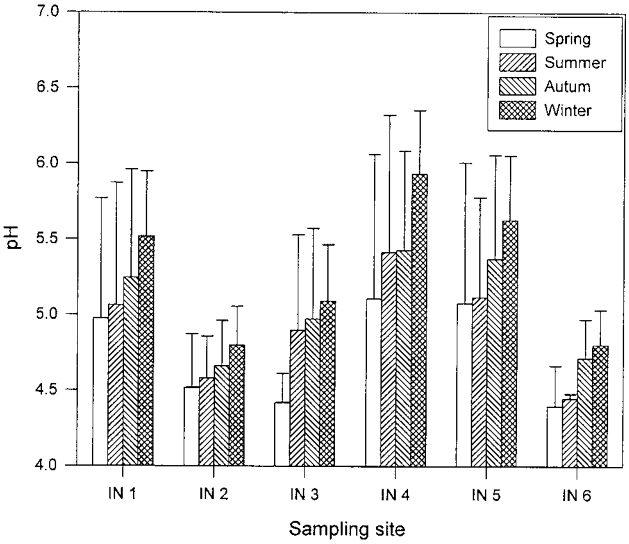

Figure 3. Seasonal variation in pH values of water at six inlets (IN 1-6) of the Yuanyang Lake. Error bars indicate standard error.

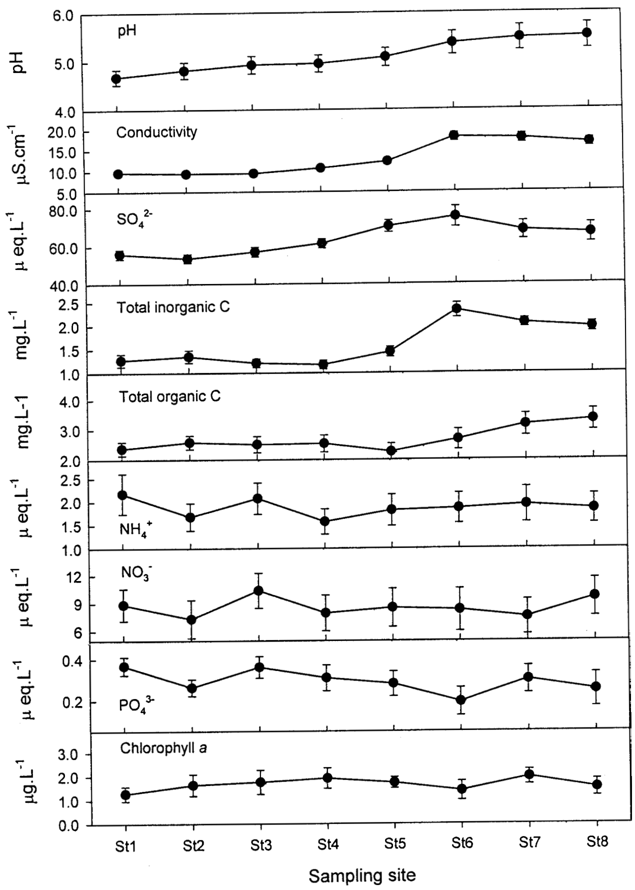

Figure 4. Variation in pH, conductivity, concentrations of sulphate, total inorganic carbon, total organic carbon, ammonium-N, nitrate-N, phosphate, and chlorophyll *a* in lake water at sampling sites St1~St8 during the time of this study. Error bars indicate standard error.

Relationship Between Inlet Water Acidity and Physico-Chemical Variables

Compared with lakewater, variables related to the variation in acidity of inlet water were somewhat different. Results of cluster analysis indicated that TOC was more closely correlated than other variables with changes in acidity. Figure 6 shows that both the pH and TOC are in a cluster while other variables have a greater distance from pH. This suggests that TOC may play the greatest role in determining the acidity of inlet water among the variables studied.

Effect of Epiphytes on Acidity of the Environment

In the Yuanyang Lake ecosystem, stemflow from arboreal plants had different acidity when epiphytes were growing on them. Measurement on *Chamaecyparis formosensis* plants showed that the stemflow from stems with various species of liverworts had lower pH values (pH 3.9-4.8) than throughflow (pH 4.2-5.8).

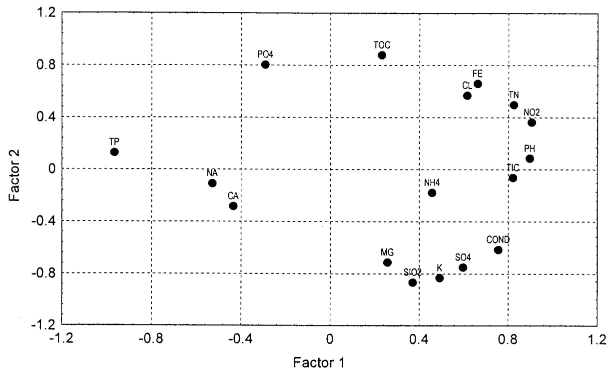

Figure 5. Principal factor analysis of the variables related to spatial variation in acidity of water in the Yuanyang Lake. COND: conductivity; TP: total phosphorus; SO4: sulphate; SIO2: silicate; TIC: total inorganic carbon; MG: magnesium; CA: calcium; NH4: ammonium-N; NO3: nitrate-N; NO2: nitrite-N; PO4: phosphate; FE: iron; TN: total organic nitrogen; NA: sodium; K: potassium; CL: chloride; TOC: total organic carbon; PH: pH.

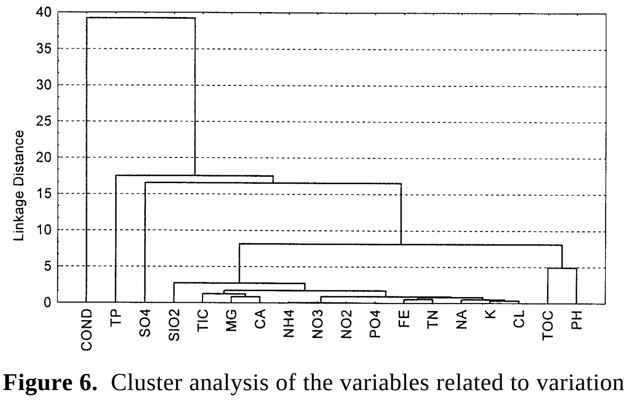

Figure 6. Cluster analysis of the variables related to variation in acidity (PH) at the inlets of the Yuanyang Lake. Abbreviations are the same as in Figure 5.

In the elution experiments, the solutions eluting from epiphyte samples were acidic (Table 1), with pH between 4.1 and 5.1 when distilled water (pH 6.8) was used for elution. The pH of the eluted solutions was reduced by just 0.2-0.7 units when acid rainwater was used in place of distilled water. The pH of eluted water was dependent of plant species tested.

Discussion

The water in the Yuanyang Lake and its inlets was brown-colored and rich in dissolved organic acids, in particular fulvic and humic acids. The lake water and inlet water exhibited a similar seasonal variation in pH. This finding, and the results of elution experiments, indicates that the acidity of lake water may be primarily determined by the runoff from terrestrial parts. This hypothesis is further supported by results of the cluster analysis, which indicated that the acidity of inlet water was more closely correlated with TOC than with other variables such as sulfate.

Based on pollen analysis of the lake sediments, it previously was suggested that the composition of vegetation in the watershed has changed little in the last 4,000 years (Chen and Wu, 1999). Furthermore, the acidity inferred by the diatom assemblages has been very constant during that time. As long as the vegetation type has not significantly changed, the sources contributing to the acidity of the lake should be principally the same, and so, not surprisingly, lakewater pH has not changed markedly. It is noteworthy that the diatom-inferred pH near the surface sediments dipped slightly (Chen and Wu, 1999), indicating some recent, and minor, effects of acid precipitation.

Acidification due to acid precipitation is a worldwide phenomenon (Dickson, 1975; Tamm, 1976; ECE, 1981; Schmidt and Simola, 1991), and it occurs in the area surrounding the Yuanyang Lake. In elution experiments with epiphytes, acid rainwater was revealed to be able to enhance the acidity of an eluted solution, while distilled water would not. Certainly, it is more reasonable to use non-polluted rainwater as a control for the elution experiment. However, air pollution is so widespread in Taiwan that it is nearly impossible to get non-polluted rainwater. Nevertheless, the elution experiment indicates that acid deposition from anthropogenic sources might have contributed to the recent acidification of this lake.

The acidity of lake water exhibited spatial and temporal variations. The spatial variation might be a result of non-uniform distribution of algae or the different acidity of run-off from certain areas of the watershed. The photosynthetic activity of algae can affect the acidity of water (Geider and Osborne, 1992). However, there was not a strong correlation between pH and chlorophyll *a*. It is therefore unlikely that spatial variation in the acidity can be attributed to a non-uniform distribution of algae in the lake.

The vegetation in the watershed was characterized by a rich array of epiphytes that grew on arboreal plants, their understory, and the soil surface. The epiphytes are one of the main sources of TOC in the runoff from the terrestrial communities, particularly during heavy rains. The majority of TOC is comprised of humic and fulvic acids derived from plant degradation products. However, some of the TOC also may be derived from acid solute leaching from epiphytes due to rewetting. It has been documented that after a period of desiccation, lichens and bryophytes tend to release nutrients or organic solutes during rewetting (Gupta, 1976; Coxson, 1991). This alters precipitation chemistry (Reiner and Olson, 1984; Lovett et al., 1985). Solute losses also are more pronounced in the dry season; the solute loss on rewetting is acidic and largely in the form of organically bound N. The results of the present study showed that waters in the inlets as well as in the lake were more acidic in the dry season (i.e. spring) and the acidity had a close correlation with total organic N. This agrees well with the facts mentioned by previous authors. Certainly, it is also possible that some dry depositions from anthropogenic sources sticking to plant surfaces are flushed out during rewetting in dry season and contribute to a certain degree to the acidity of the ecosystem. However, this should play only a smaller role compared to the loss of internally held ions in epiphytes, because the dry season is very short.

In the lake's watershed, thin soils overlie granite bedrock. As pointed out by Henrikson (1989), such a soil/bedrock system is most sensitive to acidification due to acid precipitation. Under acidification, more calcium and magnesium are leached from the soil and the amount of enhanced cation loss is negatively correlated with the pH of precipitation (Abrahamsen, 1983). In the present study, the concentrations of calcium and magnesium in the inlets correlated well with each other. They also closely correlated with total inorganic carbon, other cations, and inorganic N, showing a result typical of acid precipitation-related elution.

In conclusion, the present study indicates that the acidity of Yuanyang Lake is related to several factors: leachates from vegetation, solute loss from epiphytes during rewetting, and perhaps acid precipitation. The former two seem to play the greatest role, i.e., the acidification of this lake is largely due to natural causes.

Acknowledgement. The authors highly appreciate the Department of Forest Management, Veterans Affairs Commission, Executive Yuan, Taiwan for the assistance in the course of this study.

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鴛鴦湖酸性環境之特性研究

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鴛鴦湖位於北台灣中高海拔（1,670 m）之自然保護區內，是個酸性湖，本研究從湖水之水質理化因子、入流支流之水質特性及以附生苔蘚進行淋洗試驗，探討湖水呈酸性之成因。此湖泊之酸鹼度不僅有季節差異，湖水在不同地點其酸度值也有不同，成為梯度現象。隨此梯度現象，水中營養鹽類、總有機碳、導電度等也有起伏變化。入流於鴛鴦湖之六條支流間，其酸鹼值及水中所含營養鹽類及導電度等各有不同。從相關分析顯示，水域之酸度主要與水中之有機物含量有關，此有機物係源自湖周森林。當以森林中附生之苔蘚進行淋洗試驗時，所測得之淋洗液均為酸性，其酸度隨不同種類而異，而與湖水酸鹼度相近，證明湖周森林中之附生植物，應是造成湖水酸性化的主要成因。此外，有苔蘚著生也會造成土壤之淋釋液成為酸性。不過，在此區域所收集之雨水均為酸雨，以此酸雨淋洗苔蘚時，會降低淋洗液之酸度值，顯示酸雨也對湖水酸化扮演若干角色，但是其貢獻不若附生植物為大。

關鍵詞：鴛鴦湖；酸性；湖沼學；附生植物；陸域植生；湖泊酸化。