

Application of ecosystem stability and regime shift theories in ecosystem assessment-calculation variable and practical performance

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ABSTRACT

Assessing ecosystem states quantitatively or qualitatively is important for ecosystem management. Currently, Traditional Comprehensive Assessment (TCA), including ecosystem health, risk, and service assessment is used most often. Ecosystem stability theory (EST) and ecosystem regime shift theory (RST) from mathematical ecology have not been widely used. In this paper, we compare TCA and EST and RST result using two lakes, Onondaga Lake and Poyang Lake, as case studies. We find that biological oxygen demand (BOD) could be a suitable variable to calculate temporal stability and variance indexes in EST and RST, and trend in general. The result could replace TCA when the key lake driver is not too extreme. This recommendation is preliminary, needing validated with data.

1. Introduction

Effective ecosystem management requires an ability to assess ecosystem state. However, there is little consensus on the approach to that assessment because of ecosystem complexity (DeFries and Nagendra, 2017). The most widely used approaches are based on traditional comprehensive assessment (TCA), which includes ecosystem health and risk and service assessment. TCA uses various numerical methods to combine indexes defined for different parts of the ecosystem. While it usually addresses biological, physical, and chemical components of food webs and habitats. (Xu et al., 2001; Palmer and Febria, 2012; O'Brien et al., 2016), some approaches include social and economic effects (Pan et al., 2019; Qi et al., 2018a,b). Physical and chemical indexes are used widely because of their ease in use. While biological indexes are used less often because they are more difficult to apply, some mature efforts include diversity indexes (i.e. Shannon-Wiener index) and biological integrity indexes (i.e. Benthos biological integrity index). Biological indexes generally include structural and functional components. Structural features typically include biomass, composition, etc., whereas functional features include processes such as nutrient turnover time, specific respiration rates, etc. (Xu et al., 2001). Structural features are most often used because their data are easier to obtain. TCA focuses on the status at a certain point in time. TCA's advantage is its ability to be comprehensive and assess ecosystem state from various perspectives.

It's a widely accepted methodology.

At the same time, efforts to apply ecosystem stability theory (EST) and regime shift theory (RST), which come from mathematical ecology, in ecosystem assessment, are becoming more common. EST and RST focus on the ecosystem dynamics over a period of time and have solid theoretical foundations in ecology (Isbell et al., 2015; Tilman et al., 2006; Ives and Carpenter, 2007). In the first half of 20th century, Clements pointed out that stability was the common trend of all ecosystems. In Ecosystem Stability Theory (EST), it is thought that ecosystems tend to fluctuate near one equilibrium state, but may move from one equilibrium state to another when sufficiently disturbed. As such, EST focuses on the dynamics of ecosystems with disturbances and uses several indicators of the ecosystem's variables over time. Ecosystem stability is typically defined as temporal stability, resistance, resilience, and persistence (Pimm, 1984; Grimm and Wissel, 1997; Radchuk et al., 2019) (Fig. 1, Table S1). Temporal stability is the inverse of variability of the time series. Resistance is a measure of the degree that variable changes after perturbation. Persistence is the length of time a variable maintains its original value after perturbations. Resilience is the speed at which a variable returns to the original value after perturbations. Regime Shift Theory (RST) focuses on the existence of potential regime shifts and the indicators leading to it. As in EST, ecosystem state might change suddenly from one equilibrium state to another under certain conditions (Scheffer et al., 2001; Scheffer and Carpenter, 2003;

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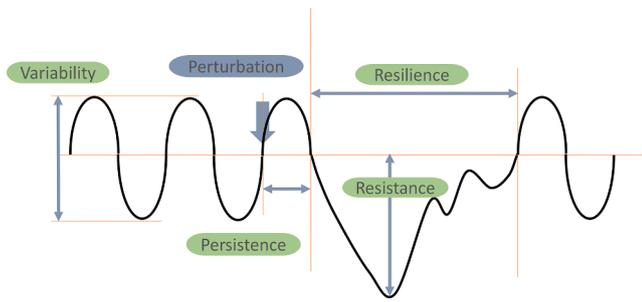


Fig. 1. Ecosystem stability theory. Variability is variance of time series. Resistance is a measure of the degree that variable changes after perturbation. Persistence is the time a variable maintains its original value after perturbations. Resilience is the speed at which a variable returns to the original value after perturbations.

Andersen et al., 2009) causing a regime shift (Fig. 2, Scheffer et al., 2001). Leading indicators for regime shifts have included variance (Carpenter and Brock, 2006; Carpenter et al., 2007), skewness (Guttal and Jayaprakash, 2008), and first order autocorrelation (AR1) (Scheffer et al., 2009) derived from ecosystem variables' time series. As confirmed in some field tests (Carpenter et al., 2011; Beck et al., 2018), when variance, skewness, and first order autocorrelation increase, ecosystems tend to shift to a new regime.

TCA, EST and RST have their own disadvantages and problems. TCA requires large amount of data to establish, and some data are hard to measure, such as fish biomass and gross primary production. EST and RST has little practice and confirmation, and the calculation variable, which should be used to calculate EST and RST indexes, is vague. Usually, calculation variable could be gross primary production or certain species. However, the reason of choosing these calculation variable has not been clearly addressed and discussed in literature. It seems that everyone tacitly approves that using system level variable, such as gross primary production, as calculation variable could reflect ecosystem stability in the system level. And using certain species, such as fish and diatom, as calculation variable could reflect stability of that species. Or if data is not enough, using certain species as calculation variable could also reflect ecosystem stability in the system level. There is no discussion to verify if these tacit consents are right. Also, some calculation variables, especially system level variables, are hard to measure.

In this paper, we compare TCA and EST and RST result using two lakes, Onondaga Lake and Poyang Lake, as case studies. Through comparison, we want to discuss and find a single suitable calculation variable for EST and RST indexes. That single suitable calculation variable could make EST and RST result similar to TCA result (TCA result is widely accepted in practice) and also easy to measure. This discussion could make up and solve both TCA and EST and RST's disadvantages and problems. One single suitable variable does not need plenty of resources to measure compared with TCA. Meanwhile, this research gives a clearly discussion about calculation variable from the angle of real ecosystem

assessment practice, which make up for the missing discussion. Finally, EST and RST with suitable variable could be a possible powerful assessment methodology with further confirmation.

2. Materials and methods

2.1. Case study sites, variables, and models

We choose two lakes, Onondaga Lake and Poyang Lake, as case studies in this paper. We choose these two lakes mainly due to the following reasons: 1) There are plenty of basic researches about them which provide necessary information to model their ecosystem. 2) The two lakes have different topography characteristics and key issues, and locate in totally different areas. The differences help us avoid special results and find general conclusions.

Onondaga Lake is a large urban lake located in North America (43°05'34.6"N 76°12'34.9"W), with a surface area of 12 km². It is 8 km long and 1.5 km wide, with mean depth of 10.9 m and maximum depth between 20.4 m and 22.6 m (Effler, 1996). It has significant water quality problems associated with high concentrations of ammonia, nitrate, and phosphorus (Taner et al., 2011).

Poyang Lake is a freshwater lake connecting with Yangtze River in China (29°10'17.2"N 116°17'43.0"E). Its surface area has declined from 5200 km² (1949) to 3287 km² during the 21st century. It is 173 km long and 74 km wide. Its mean and maximum depths are 8.4 m and 25.1 m. Nowadays, Poyang Lake's annual average water level is 12.55 m (Zhou et al., 2018). After the Three Gorges Dam was built, sediment load to the Yangtze River decreased significantly, creating substantial downstream scour resulting in lower water levels. Because the lake is connected to the river, its water level also decreased. As a result, the Poyang Lake's dry season has become longer resulting in loss of wetlands and declining habitats for migrant birds. Also, the number of days which water level is under the lowest ecological water level (12.03 m for Xingzi Station) increased, threatening aquatic organisms (Zhou et al., 2018). In order to solve this water level decreasing problem, government proposed to build a sluice to control Poyang Lake's water level. This propose other problems that Poyang Lake's water level may be too high after sluice building and the ecosystem may change to another state which we don't expect. Poyang Lake is large and deep, so nutrient loading would not be a control element when considering ecosystem pressure. Considering the real situation, water level is key issue for the ecosystem of Poyang Lake.

For our case studies, we created long time series with output from AQUATOX models of Onondaga Lake NY (Taner et al., 2011; AQUATOX Q&A url) and Poyang Lake. Onondaga Lake model's calibration is described in Taner's paper. The AQUATOX model is slightly modified from the Taner et al. (2011) model. The Taner's calibration results indicated that the simulated distributions of ammonia, nitrate, dissolved oxygen, diatom, green algae and daphnia were very similar to the observed distributions (i.e. within the 95% isopleth) while blue-green algae and cryptomonad were in the 80% isopleth. The only exception was chlorophyll, whose simulated distribution had a higher difference in

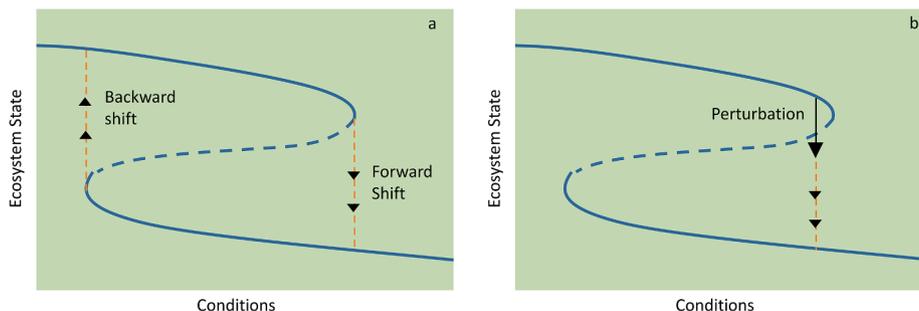


Fig. 2. Ecosystem Regime Shift (a) Ecosystem state will change suddenly when ecosystem conditions change fluently past a shift point; b) Ecosystem state will change suddenly with certain perturbation near a shift point.

Table 1
Calibration result of Poyang Lake model.

Output variable	Ammonia nitrogen mg/L	Nitrate nitrogen mg/L	Carbon dioxide mg/L	Solute oxygen mg/L	Diatomm g/L	Green algae mg/L	Chlorophyll mg/L	Total phosphorus mg/L	Biological oxygen demand mg/L
Relative bias	1.42	7.11	0.94	-0.51	-1.04	-1.61	-0.45	25.82	-1.19
Variance bias	0.48	0.13	2.16	2.03	0.01	0.02	3.11	0.64	0.01
Output variable	Copepod mg/L	Cladoceran mg/L	Tubifex g/m2	Chiron id g/m2	Gstropod g/m2				
Relative mean bias (Meansim/ Meanobs)	0.43	0.76	0.29	0.75	0.14				

variances (<8% isopleth).

Poyang Lake’s physical conditions and nutrient loadings were on the available data. Water inflow and water volume were set as mean values from 2008 to 2016. The model includes diatom, green algae, tubifex, chironomid, copepod, cladoceran, gastropod, minnow, carp and catfish, as well as nutrient cycles. Based on available data, the model was calibrated using relative bias and variance tests (Taner et al., 2011), as well as the relative mean bias test. Some data for calibration, ammonia, nitrate, carbon dioxide, dissolved oxygen, total phosphorus, biochemical oxygen demand, were provided by Nanjing Institute of Geography and Limnology, and other data, diatom, green algae, Chlorophyll, tubifex, chironomid, copepod, cladoceran, gastropod, were collected from literatures (Wang, 2014; Wang et al., 2018). For relative bias and variance tests, data for calibration is monthly data in one year. For relative mean bias test, data for calibration is annual average data. The sampling site for ammonia, nitrate, carbon dioxide, dissolved oxygen, total phosphorus is Hukou station. The sampling site for biochemical oxygen demand is Qingshanzha station. Diatom, green algae, Chlorophyll are lake average biomass. The sampling site for Copepod and Cladoceran is Junshanhu station. Tubifex, chironomid and gastropod are lake average biomass. All simulation results match observation well (Table 1). TP’s relative bias is large because that variance of observation is too small, but the simulation results match the observation well visually (Fig. S1). Carp, catfish and minnow were not calibrated because of inadequate data.

In this manuscript, these calibrations are sufficient, because we only require relative property sizes. For our purposes, and in the context of key system drivers, we use key subsets of variables (Tables S3 and S4).

Different ecosystem conditions are needed to compare TCA, EST and RST performance in ecosystem assessment, so we select several key driver’s values for each lake. For Poyang Lake, we used 18 water levels between 4 and 21 m at 1 m intervals. 4 m is the lowest and 21 m is the highest water level of Poyang Lake. This scenery designation is extreme, but can reflect ecosystem’s trend clearly under different water levels. If we use water level will appear recently, the trend may not clear and not able to discuss the issues about using EST and RST indexes. Because AQUATOX uses water volume as an input, we used the lake’s water volume-water level relationship (Fig. S2). For Onondaga Lake, we used 10 sets of ammonia, nitrate and phosphorus load estimates ranging between 10% and 100% of 10 mg/L, 10 mg/L and 1 mg/L, respectively, at 10% intervals. In 1989 ~ 1990, Onondaga Lake’s annual mean ammonia, nitrate and phosphorus are about 4 mg/L, 3 mg/L and 0.5 mg/L (Effer, 1996). This is a eutrophication condition. After that, artificial action solves the eutrophication condition and decrease the nutrient loadings. We use this scenery designation, which covers both eutrophication scenery and mesotrophic scenery, to show ecosystem’s clear trend under different nutrient loadings.

For each value of the key driver (nutrient load or water level), the models were run for multiple years until output stabilized, and the final year was used as the time series at daily resolution. We use the final year because that final year’s output is stabilized which can represent the real situation under each key driver’s value. The perturbation is changing water temperature during one year when calculating stability indexes.

Table 2
TCA framework.

Class1	Class2	Index for Onondaga Lake NY	Index for Poyang Lake	Better state	
Biological	Structural	Phytoplankton		-	
		Zooplankton		+	
		BZBP.ratio		+	
		Macrozooplankton		+	
		Microzooplankton		-	
			Perch	Carp	+
			Catfish	Catfish	+
			LMBassY		+
			LMBassL		+
		Functional	BP.ratio		+
		PR.ratio		=1	
		Exergy		+	
Chemical		Water quality (diatom.ratio)		+	
		TLL.TP		-	
		TLL.TN		-	
		TLL.BOD		-	
		TLL.Chl		-	
Physical			Lake area	+	

*Where a positive sign represents an increase in the index value and a negative sign represents a decrease, and each of these are associated with movement toward a “better state”. For example, an increase in Macrozooplankton leads to a better state, whereas an increase in Microzooplankton leads to a worse state.

Also, using the full year provides full seasonal dynamics, better reflecting the ecosystem dynamics.

2.2. EST and RST indexes

EST and RST index values are calculated according to Table S1 for each of the variables (Tables S3 and S4) based on the time series output.

While EST can be used to assess an ecosystem’s dynamic features, some indicators (e.g., resilience and persistence) are difficult to determine. As a result, most efforts analyze only temporal stability and resistance (Donohue et al., 2013; MacDougall et al., 2013; Pennekamp et al., 2018). However, resistance can vary substantially with different kinds of disturbances and individual indexes of EST can be contradictory (Donohue et al., 2016). For example, an ecosystem may have high temporal stability but low resilience. For these reasons, we choose to use only temporal stability (TS), the most widely used among EST indexes. For RST indexes, we choose to use only skewness and variance because AR1 has been shown unclear (Wang et al., 2012).

The relationships between ecosystem state and the directions of change for temporal stability, skewness, and variance are: higher temporal stability, lower variance, and lower skewness indicate a better state.

2.3. TCA indexes for comparison

In addressing issues associated with applying the EST and RST indexes, we compare them to widely used TCA indexes, where the relationships between the direction of change for each index and

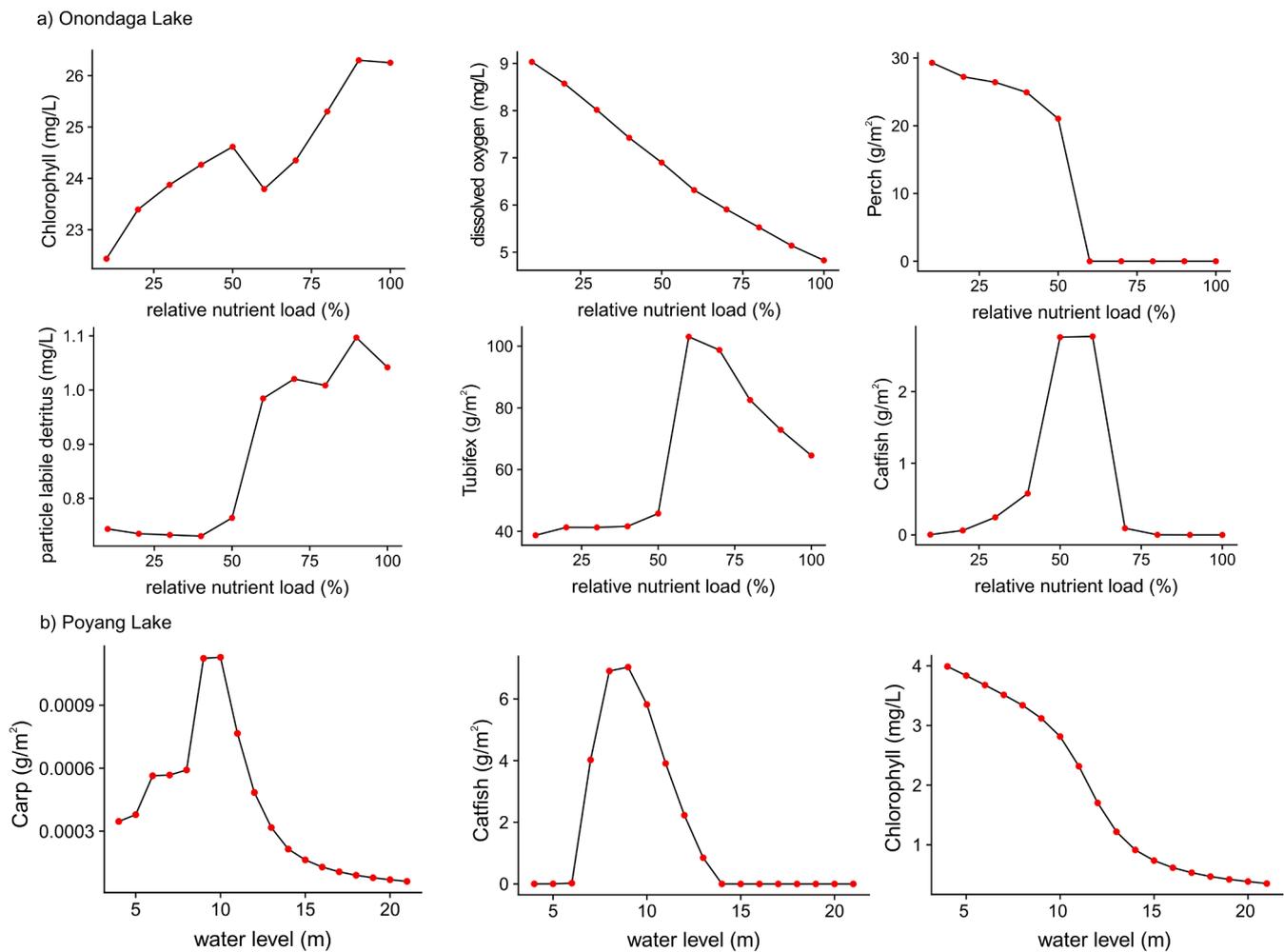


Fig. 3. Response of key model variables as a function of nutrient loading (Onondaga Lake) and water level (Poyang Lake). Label of y axis represent variable in model output. The value of them is annual mean value.

ecosystem state (Table 2) are based on Xu et al. (2001), Odum (2014), Odum (1985), Qi et al. (2018a), Qi et al. (2018b), and Davies and Jackson (2006). TCA index calculation ways are shown in Table S2. These TCA indexes can reflect the ecosystem status from different aspects. Exergy represent the chemical energy stored in the community. A mature ecosystem has higher biomass, stronger ecosystem network and more information than stressed one, and exergy reflects the ecosystem's information storage. Mature ecosystem has higher exergy. Phytoplankton has been widely used to assess the water body's eutrophication degree. Higher phytoplankton biomass represents eutrophication trend. Decrease of zooplankton biomass will decrease the information stored in it and decrease the ecosystem exergy. Zooplankton has higher gene information density than phytoplankton (about 10 times higher), so the ratio of zooplankton to phytoplankton (BZBP.ratio) affect the exergy density. Decrease of BZBP.ratio will decrease the exergy density. Macrozooplankton is more sensitive to external stress than microzooplankton, so the increase of macrozooplankton represent a better state and microzooplankton conversely. BP.ratio is the ratio of biomass to gross primary production. Biomass can be seen as energy stored in the ecosystem. Energy transport efficiency from primary production to ecosystem storage decreases in stressed ecosystem, so BP.ratio decreases. PR.ratio is the ratio of gross primary production to community respiration. When one ecosystem is stressed, community respiration will increase firstly to transfer more energy from production to repair and keep original state. One ecosystem could be seen as a thermodynamic system, and this PR.ratio change is a process of entropy reduction. In

stable state, PR.ratio trends to 1. Diatom.ratio is the ratio of diatom biomass to other phytoplankton biomass. Diatom.ratio is widely used as water quality index especially in aquaculture water body. Diatom is one of the most important food source for many fishes and other organism. Trophic level index (TLI) is widely used to estimate water trophic level. TLI can be calculated using phosphorous (TP), nitrogen (TN), chlorophyll (Chl), biochemical oxygen demand (BOD). Lake area represent the live space for water organism. Perch, Catfish, Largemouth Bass YOY (LMBassY), Largemouth Bass Ig (LMBassL), Carp are important fish species in Onondaga Lake and Poyang Lake.

2.4. Comparison methods

We use the Pearson correlation coefficient to compare EST, RST, and TCA indexes. For each key driver value (water level or nutrient loading), we used the variables' time series to calculate the temporal stability, skewness, variance, and TCA indexes (X_{ij}) and scores (S_{ij}) using Eq. (1) or Eq. (2) depending on whether a higher or lower indicator values represent a better ecosystem state. When calculating the temporal stability, skewness, and variance indexes we ignored difference smaller than 10% of mean value of all nutrient load condition or water level condition because such differences would not be detectible in field measurements.

TCA integral (T_j) and normalized (N_j) scores (Eqs. (3) and (4)) were calculated for comparison. Also, TCA second-normalized (SN_j) scores (Eq. (5)) were calculated to show the trend of TCA integral scores more

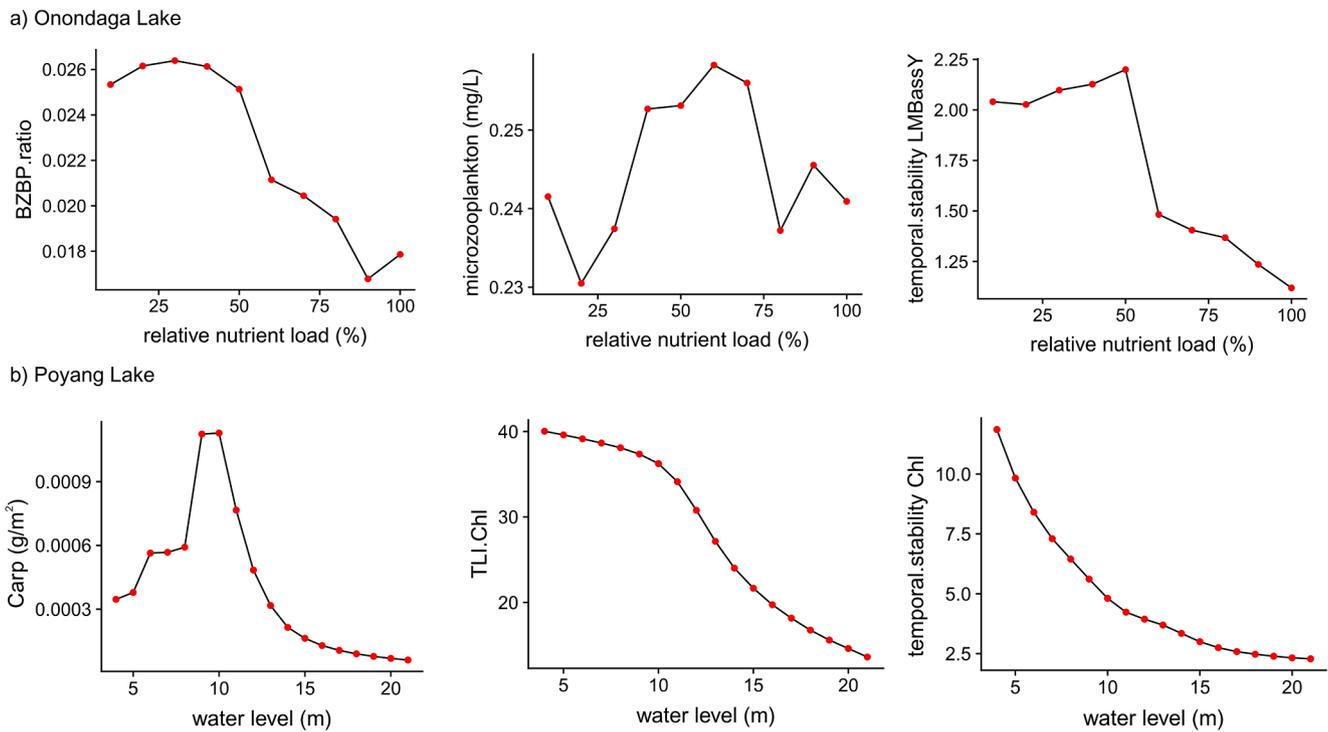


Fig. 4. Graphs about some TCA indexes and temporal stability changing with nutrient loading (Onondaga Lake) or water level (Poyang Lake). Label of y axis is index among TCA and temporal stability. Temporal stability chl means temporal stability calculated using chlorophyll variable in model output. Temporal stability tubifex means temporal stability calculated using tubifex variable in model output. Temporal stability LMBassY means temporal stability calculated using largemouth bass yoy variable in model output.

clearly.

$$S_{ij} = \frac{X_{ij} - \min(X_i)}{\max(X_i) - \min(X_i)} \tag{1}$$

$$S_{ij} = \frac{\max(X_i) - X_{ij}}{\max(X_i) - \min(X_i)} \tag{2}$$

$$T_j = \sum_i w_i S_{ij} \tag{3}$$

$$N_j = \frac{100T_j}{\max(T_j)} \tag{4}$$

$$SN_j = 100 \frac{N_j - \min(N_j)}{\max(N_j) - \min(N_j)} \tag{5}$$

Where i represents i^{th} index, j represents the j^{th} water level or nutrient load, w_i represents weight for i^{th} index. In this paper, each index has same weight.

Onondaga Lake has 17 TCA indexes and 3 EST and RST indexes (temporal stability, variance and skewness). Poyang Lake has 16 TCA indexes and 3 EST and RST indexes. Onondaga Lake has 10 value of key driver with 10 different nutrient loadings. Poyang Lake has 18 value of key driver with 18 water levels. Onondaga Lake has 30 calculation variables (Table S3). Poyang Lake has 30 calculation variables (Table S4). For each EST and RST index, each key driver value and each calculation variable, there is one index score. For each TCA index and each key driver value, there is one index score. For each key driver value, there is one TCA integral score or TCA normalized score or TCA second-normalized score. For each EST and RST index and each calculation variable, there is one vector composed by index scores under different key driver values. For each TCA index, there is one vector composed by index scores under different key driver values. There is one TCA integral result vector composed by TCA integral scores under

different key driver values. These vectors are used to conduct the Pearson correlation analysis. If these vectors are similar, Pearson correlation rate will be positive and high, otherwise, Pearson correlation rate will be negative and low. Similar vectors represent that corresponding indexes perform similarly when assessing the ecosystem under different key driver value. Dissimilar vectors represent that corresponding indexes may contradict each other when assessing the ecosystem under different key driver value.

We first analyze correlations among TCA indexes. Then, we analyzed the correlations among EST and RST indexes. Finally, we analyzed the correlations between EST and RST indexes and TCA second-normalized result.

3. Results

3.1. Model responses to varying key drivers

We give some graphs (Fig. 3) about variables changing with nutrient loading (Onondaga Lake) or water level (Poyang Lake). This graphs show mean value of variables. We focus on the trends of them and ignore single point deviation caused by program oscillation.

For Onondaga Lake (Fig. 3a), chlorophyll increases with increasing nutrient loading because nitrogen and phosphorus are key drivers for phytoplankton growth. Dissolved oxygen concentration also decreases with nutrient loading, and when decreases to a level corresponding to a 50% nutrient loading, perch decrease to near zero. The death of fish increases particle labile detritus and sediment labile detritus, which is the entire food source of tubifex. So, tubifex increases sharply when nutrient loading increases to near 50%. Because tubifex is the main food for catfish, and the other fishes have declined, catfish show a sharp increase when nutrient loading increases to near 50%. Catfish decreases when nutrient loading continues to increase after 50% because dissolved oxygen decreases further.

For Poyang Lake (Fig. 3b), Chlorophyll decreases with increasing

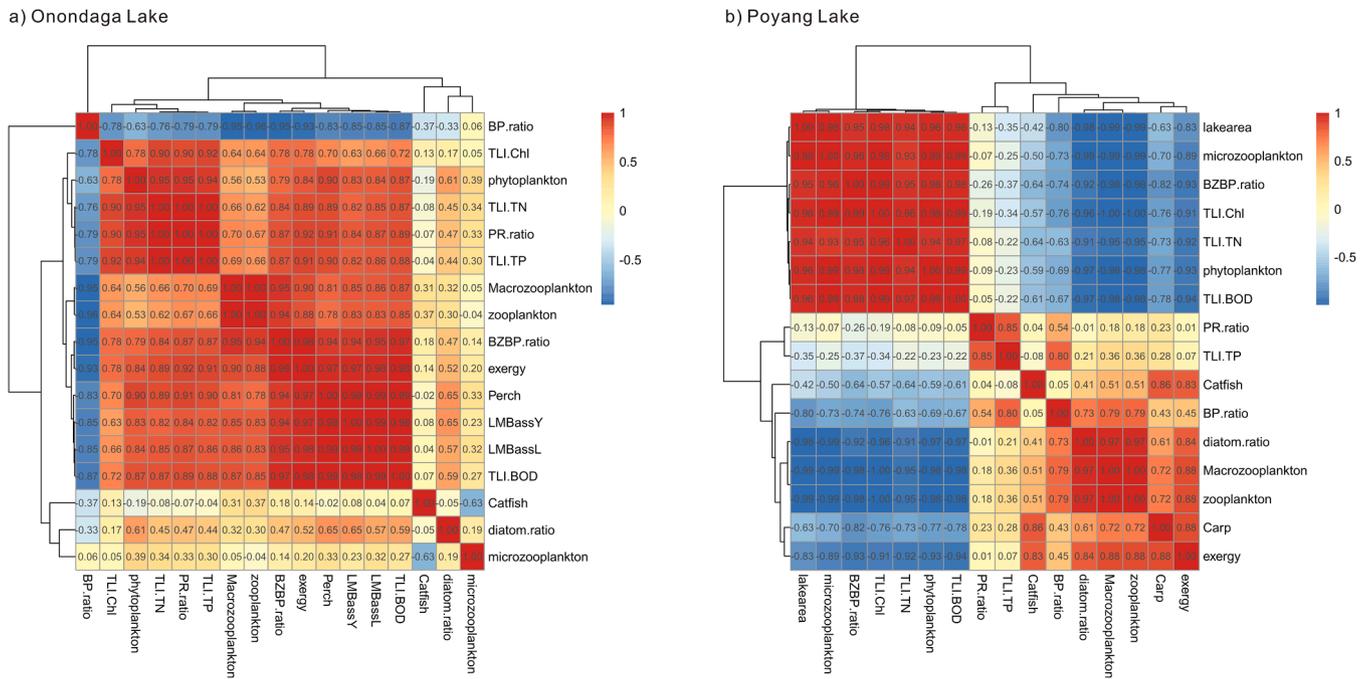


Fig. 5. Correlation among TCA indexes. Where the number in boxes is correlation rate between two indexes. Thicker red means higher correlation rate. The horizontal and vertical axis are both TCA indexes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

water level because nutrient density decreases. Fishes such as carp and catfish’s biomass increase with increasing water level at first because the live space for them increases, then decrease with increasing water level after 10 m because food density for them decreases.

3.2. Indexes value

We also give some graphs (Fig. 4) about TCA indexes and temporal stability changing with nutrient loading (Onondaga Lake) or water level (Poyang Lake).

For Onondaga Lake (Fig. 4a), we can see that most of indexes have clear trends. However, the trends may contradict each other. For example, indicated by BZBP.ratio, ecosystem state’s general trend is decrease with increasing nutrient loading. Indicated by temporal stability calculated by largemouth bass YoY (LMBassY), ecosystem state’s general trend is increase first and then decrease with increasing nutrient loading. Indicated by microzooplankton, ecosystem state’s general trend is decrease first and then increase with increasing nutrient loading.

For Poyang Lake (Fig. 4b), same circumstance occurs. Indicated by Carp, ecosystem state’s general trend is increase first and then decrease with increasing water level. Indicated by trophic level index (TLI.Chl), ecosystem state’s general trend is increase with increasing water level. Indicated by temporal stability calculated by chlorophyll (Chl), ecosystem state’s general trend is decrease with increasing water level.

3.3. Correlation among TCA frame

We analyzed correlation among TCA indexes to see connections and contradictions within TCA frame. (Fig. 5). For Onondaga Lake (Fig. 5a), most of indexes have positive and high correlation rate with each other, and about half of correlation significance is high (p-value < 0.05, Table S5). The three indexes, Catfish, microzooplankton and diatom.ratio, have slightly lower correlation with other indexes. However, their general trends are consistent with other indexes (correlation rate is positive or slightly negative). For Poyang Lake (Fig. 5b), about half of indexes have negative and low correlation rate with another half. Their trends contradict each other. Most of correlation significance is high (p-

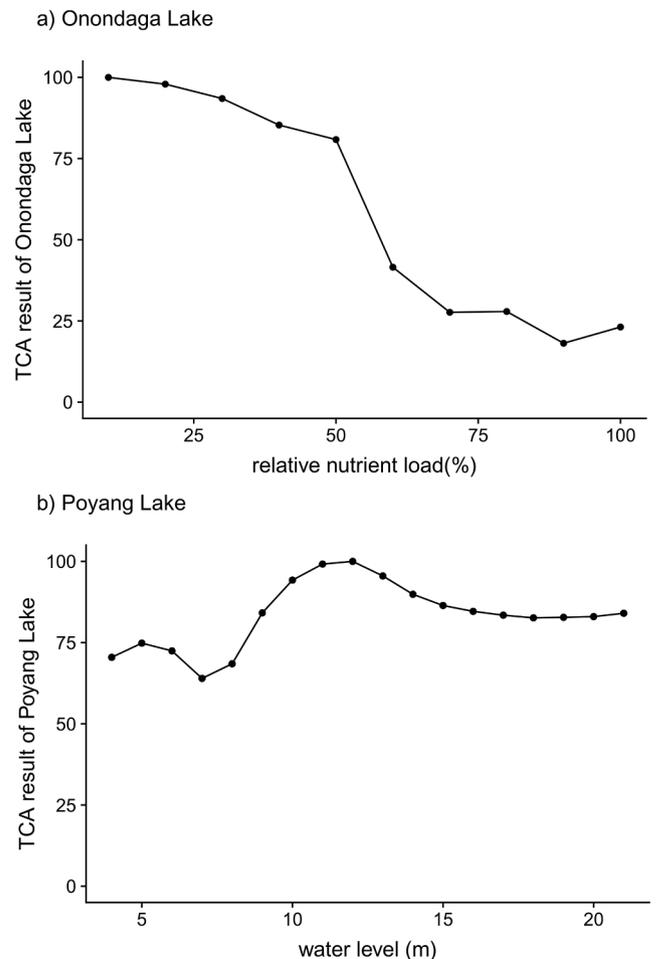


Fig. 6. TCA results.

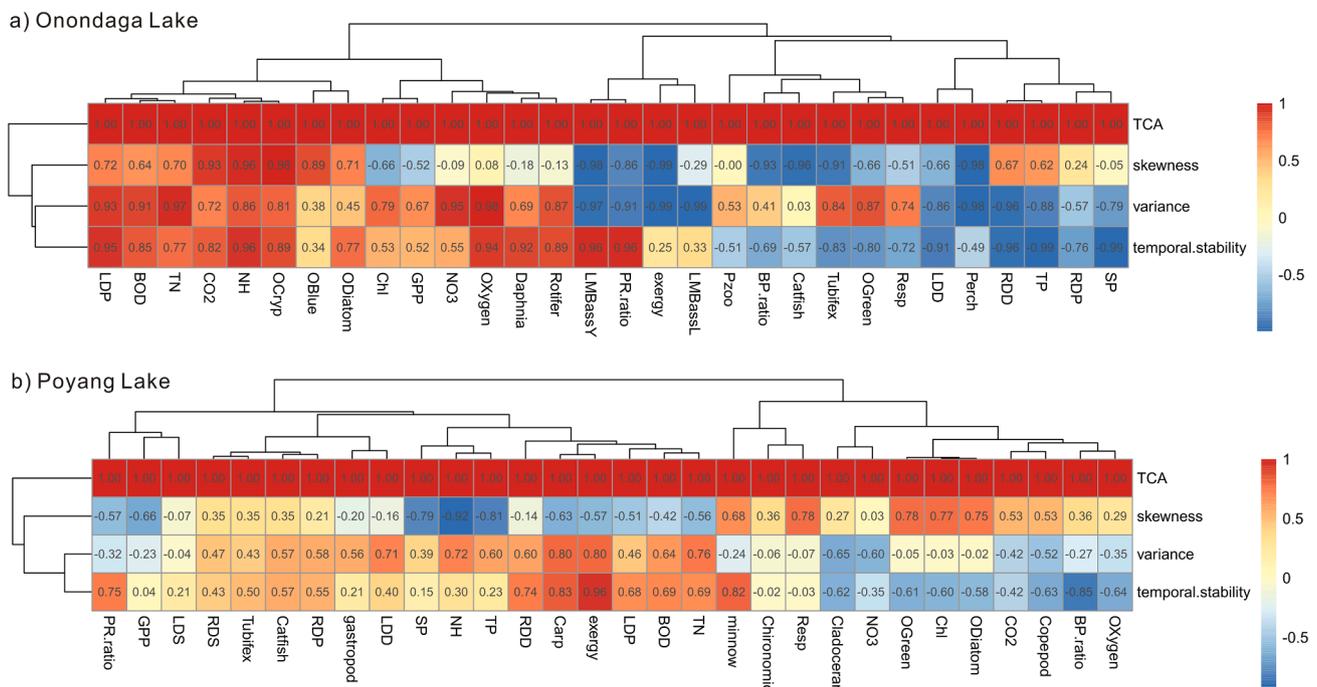


Fig. 8. Correlation between temporal stability, skewness, variance and TCA integral result. Where the number in boxes is correlation rate between two indexes. Thicker red means higher correlation rate. The horizontal axis is variables used to calculate temporal stability, skewness and variance index. The vertical axis is temporal stability, skewness, variance and TCA. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

phosphorus (SP), carbon dioxide (CO₂), dissolved oxygen (Oxygen), dissolved refractory detritus (RDD), dissolved labile detritus (LDD), particle refractory detritus (RDP), particle labile detritus (LDP), diatom (ODiatom), green algae (OGreen), blue-green algae (OBlue), Cryptomonad (OCryp), Predatory zooplankton (PZoo), Largemouth Bass, YOY (LMBassY), Largemouth Bass, Lg (LMBassL), gross primary productivity (GPP), respiration of the community (Resp), The ratio of gross primary production to total respiration (PR.ratio), The ratio of total biomass to gross primary production (BP.ratio), Chlorophyll (Chl), total nitrogen (TN), total phosphorus (TP), biochemical oxygen demand (BOD), sediment refractory detritus (RDS), sediment labile detritus (LDS).

The correlation among temporal stability, skewness and variance varies with the variables using to calculate them (Fig. 7).

Onondaga Lake – Using most of calculation variables, variance and temporal stability are correlated. Skewness is not correlated with variance or temporal stability for about half of calculation variables.

Poyang Lake – The correlation among indexes is lower than that for Onondaga Lake. The correlation between skewness and other two indexes is very low for most of variables.

3.6. Correlation among temporal stability, variance, skewness indexes and TCA indexes

Correlation among temporal stability, variance, skewness indexes and separate TCA indexes- For Onondaga Lake, correlation among temporal stability, variance, skewness indexes and separate TCA indexes are high for most of them and most of calculation variable (Fig. S3). Due to the high consistency within TCA index frame, some calculation variables lead to high correlation between temporal stability, variance, skewness and most of TCA indexes, while the rest lead to low correlation for most of TCA indexes. However, for Poyang Lake, due to the low consistency within TCA index frame, one calculation variable leads to high correlation between temporal stability, skewness, variance and about half of TCA indexes, and leads to low correlation for another half.

Correlation among temporal stability, variance, skewness indexes and

integral TCA result- For Onondaga Lake, carbon dioxide (CO₂), ammonia nitrogen (NH), cryptomonas (OCryp), total nitrogen (TN), biochemical oxygen demand (BOD), particle labile detritus (LDP) as calculation variables lead to high correlation between temporal stability, variance, skewness and integral TCA result (Fig. 8a). For Poyang Lake, dissolved refractory detritus (RDD), Carp, exergy, biochemical oxygen demand (BOD), total nitrogen (TN) as calculation variables lead to high correlation between temporal stability, variance and integral TCA result, while green algae (OGreen), diatom (ODiatom), Chlorophyll (Chl) as calculation variables lead to high correlation between skewness and integral TCA result (Fig. 8b).

4. Discussion

4.1. EST and RST indexes' practical performance

Variance and temporal stability has better performance than skewness. Using most of calculation variables, skewness does not perform well. So, we judge that skewness is not practical in ecosystem assessment under most situations, though there may be some unique situations skewness could perform well. Temporal stability is the most practical index. In the following discussion, we show skewness result but focus on discussion about variance and temporal stability result.

4.2. Suitable calculation variable

Contradictory to classical opinion, using system variable such as exergy and gross primary production (GPP) as calculation variables don't perform very well in both two case studies. Different ecosystems and key drivers lead to different suitable variables.

Considering general trend, ammonia nitrogen (NH) and exergy are most suitable calculation variable for Onondaga Lake and Poyang Lake separately (Fig. 8). For Onondaga Lake, same as TCA result, temporal stability and variance results decrease when relative nutrient load increases, while the skewness's general trend doesn't match TCA's general

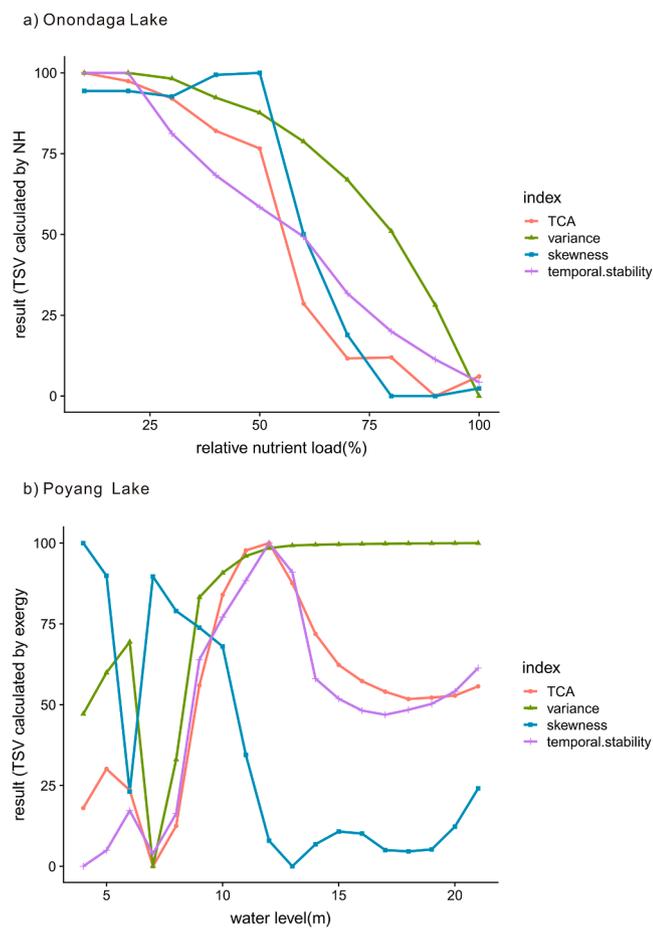


Fig. 9. Temporal stability, skewness, variance and TCA result using most recommended variable to calculate. ‘TSV’ in y axis represent ‘temporal stability, skewness and variance’.

trend (Fig. 9a). For Poyang Lake, temporal stability result’s general trend match TCA result when water level increases. However, variance result match TCA result only when water level changes between 4 m and 12 m. Also, skewness result does not match TCA result (Fig. 9b).

Considering both Onondaga Lake and Poyang Lake, we could find some calculation variables perform well in both Lakes (Fig. 8). These calculation variables are biochemical oxygen demand (BOD), labile detritus particle (LDP) and total nitrogen (TN). As labile particle detritus (LDP) is hard to measure in practice, and total nitrogen (TN) is highly sensitive to accident, so we recommend biochemical oxygen demand (BOD) as suitable calculation variable. For Onondaga Lake, temporal stability and variance result show same trend as TCA result when relative nutrient load changes between 50% and 80% (Fig. 10a). For Poyang Lake, temporal stability result shows similar trend with TCA result when water level changes between 7 m and 21 m, while variance result shows similar trend with TCA result when water level changes between 7 m and 12 m (Fig. 10b).

4.3. Possibility of using temporal stability and variance to replace TCA

BOD is a routine monitoring variable in practice which is easy to access. In the above, we find that temporal stability and variance using BOD as calculation variable show similar trend with TCA result when the key drivers are not too extreme. So, we judge that, considering general trend, the temporal stability and variance result could replace TCA result when the key driver’s condition of lake is not too extreme. In order to preliminary validate this possibility, we use BOD measurement data of Poyang Lake (Qingyezha station) from 1996 ~ 2008 to calculate

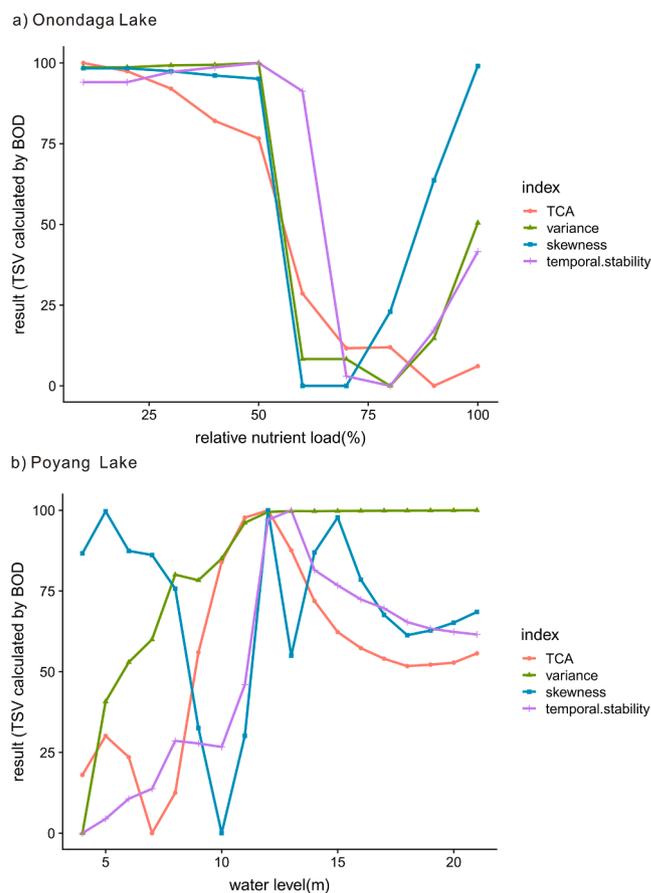


Fig. 10. Temporal stability, skewness, variance and TCA result using BOD to calculate. ‘TSV’ in y axis represent ‘temporal stability, skewness and variance’.

temporal stability and variance (Fig. 11). Temporal stability show a slow decrease general trend and variance show a slow increase trend which represent that Poyang Lake’s ecosystem equality show a slow decrease trend. This result fit Poyang Lake’s water level trend as Poyang Lake’s water level shows a decrease trend, and decreasing water level will pose great threat to the ecosystem (Zhou et al., 2018).

4.4. Practices guidance in other lakes

According to the results and discussions above, we give possible practices guidance in lakes about using EST and RST indexes.

Firstly, skewness is not practical while temporal stability and variance is practical in ecosystem assessment. Other EST and RST indexes are not researched in this manuscript.

Secondly, Biochemical oxygen demand (BOD) is recommended as calculation variable to calculate temporal stability and variance, which is easy to acquire and can make the result similar to TCA’s result.

Thirdly, Using BOD to calculate temporal stability and variance can replace TCA when the situation is not extreme. This replacement will make ecosystem monitoring more easy and take low cost.

Fourthly, temporal stability and variance is good at assessing ecosystem status trend. They may be incorrect when comparing several individual statuses. So, if there are only several individual data points without continues trends, temporal stability and variance should be used with caution and TCA is necessary.

Lastly, this manuscript uses lakes with nutrient loading and water level key issues to do the research. These two issues are most widely seen issues in lakes. Lakes with other key issues may not suitable to this manuscript’s conclusion and need further research.

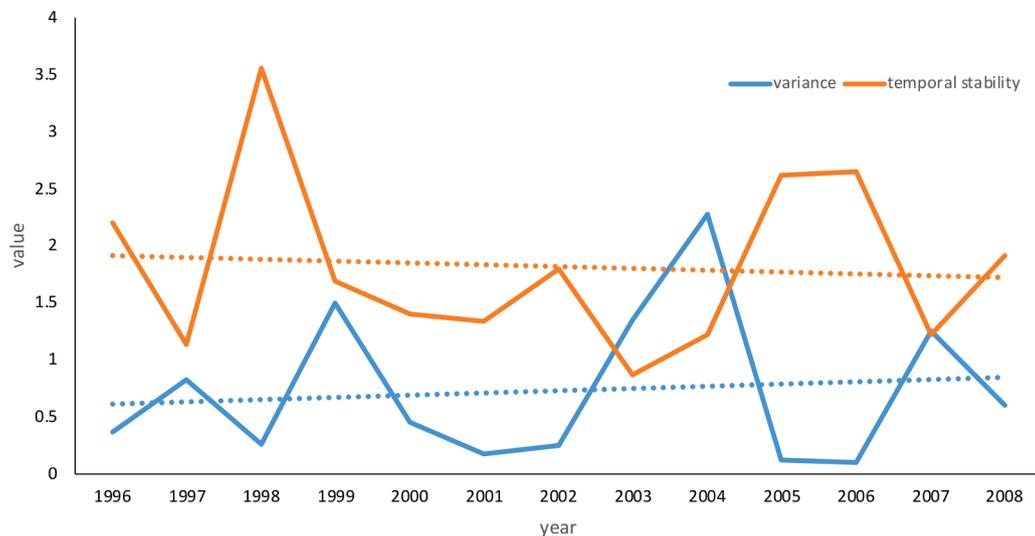


Fig. 11. Temporal stability and variance calculated by biochemical oxygen demand (BOD) of Poyang Lake from 1996 ~ 2008.

5. Conclusion

This paper discuss calculation variable when using ecosystem stability theory (EST) and regime shift theory (RST) indexes in ecosystem assessment. For clarity, we only choose temporal stability, skewness and variance among EST and RST indexes. We use result of traditional comprehensive assessment (TCA) as baseline. We use two lakes with different key issue, Onondaga Lake with nutrient load and Poyang Lake with water level, as case studies. The data used in assessment is provided by calibrated AQUATOX model. By comparing result of temporal stability, skewness, variance indexes and result of TCA of the two lakes (more similar to TCA, better performance of temporal stability, skewness and variance), we try to find suitable calculation variable to calculate EST and RST indexes.

TCA results show that for Onondaga Lake, keeping ammonia, nitrate and phosphorus loading smaller than 5 mg/L, 5 mg/L, 0.5 mg/L will be a good choice to make the water body ecosystem in a good state. For Poyang Lake, the optimum year-round maintenance of water level (keep this water level during the whole year) for Poyang Lake is 8 m–15 m.

After comparison among TCA, temporal stability, variance and skewness result, we find that skewness is less practical in ecosystem assessment. Considering general trend, ammonia nitrogen and exergy are most suitable calculation variable for Onondaga Lake and Poyang Lake separately. BOD could be suitable calculation variable when the key drivers condition is not too extreme for both two lakes. We recommend using BOD as calculation variable to calculate temporal stability and variance, and the result could replace TCA result when the key drivers are not too extreme. This replacement will make ecosystem monitoring more easy and take low cost. This recommendation is preliminary validated using measurement data. However, it's important to emphasize that temporal stability and variance is good at analyzing trend, rather than analyzing two separate situations. Using temporal stability and variance to analyze and compare two separate situations is questionable. Further validation is welcomed to see the detailed effective range of application.

CRedit authorship contribution statement

Jia-Nan Meng: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Hongwei Fang:** Conceptualization, Supervision, Project administration, Funding acquisition. **Donald Scavia:** Methodology, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecolind.2021.107529>.

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