

Emerging resilience metrics in an intensely managed ecological system

Nikolaos Toumasis^a, Daniel Simms^a, Will Rust^a, Jim Harris^a, John R. White^b,
Joanna Zawadzka^a, Ron Corstanje^{a,*}

^a Cranfield Environment Centre, Cranfield University, Bedford MK43 0AL, UK

^b Department of Oceanography & Coastal Sciences, Coast & Environment Building, LA, United States

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ABSTRACT

There is growing interest in understanding resilience of ecosystems because of the potential of abrupt and possibly irreversible shifts between alternative ecosystem states. Tipping points are observed in systems with strong positive feedback, providing early warning signals of potential instability. These points can be detected through metrics like critical slowing down (CSD), such as increased recovery time, variance, and autocorrelation. These indicators have been tested in laboratory experiments and field settings, ignoring trait changes. Here we present a long-term temporal analysis of several large, intensely monitored constructed wetlands, the Everglades Stormwater Treatment Areas (STAs), in which sudden changes in plant community composition have been observed. Using wavelet analysis, significant increases and decreases of variance properties (long-term flow data, water quality and nutrient TP loads) across these systems can indicate when and which STAs are less resilient to perturbations. In this study, continuous wavelet transform (CWT) was used to determine the periodicity of any cyclical activity in the data and to determine changes in autocorrelation and variance as measures of CSD. The change detection methods were used to find significant changes in variations and correlations across the time series. By employing these techniques, we were able to spot substantial shifts in model-observed wavelet correlation and model residual wavelet variance and thereby identify where these systems exhibit CSD. Although our analysis is limited to historical data, the proposed approach has practical value in that it identifies STAs that may be vulnerable to perturbation. The study also presents one of the few studies in which CSD is observed in practice rather than modelled in theory.

1. Introduction

Since its inception in 1973, resilience has been given heuristic, symbolic, and normative dimensions (e.g., [Holling, 2001](#); [Ott and Döring, 2004](#); [Pickett et al., 2004](#); [Hughes et al., 2005](#)) in addition to its initial significance as a description of ecological processes ([Holling, 1973](#)). Ecological and social systems may be studied using this method in a broad variety of scientific domains ([Anderies et al., 2006](#); [Folke, 2006](#)). However, the idea of resilience is often difficult to put into practice in ecological research. Because of this, the development and maturation of resilience theory is hindered ([Armstrong et al., 2023](#)).

The ecological literature defines system resilience in two ways, each reflecting a distinct feature of stability. [Holling \(1973\)](#) began by emphasizing these many dimensions of stability so to illustrate the distinctions between efficiency and persistence, constancy and change, and predictability and unpredictability. Holling defined stability as the

endurance of a system near or towards equilibrium. Resilience, on the other hand, was described as the behaviour of dynamic system in which resilience as the degree of disturbance that a system can tolerate without altering state, i.e. reorganizing itself through changes to the variables and processes that drive behaviour. Ecological resilience is predicated on the existence of many stability domains and the system's tolerance for shocks that enable transitions between stable states ([Henry and Ramirez-Marquez, 2012](#)). As a result, ecological resilience refers to the breadth or limit of a stability domain, which is determined by the amount of disturbance that a system can tolerate before changing stable states. When a system's regulating factors, including feedback, produce a qualitatively different set of structures and dynamics, this is known as a "regime shift." Over the past three decades, there has been disagreement about whether or not alternate regimes or states can be found in ecological systems. Alternative stable regimes emphasise threshold dynamics' aftereffects when system dynamics have reached a point of

* Corresponding author.

E-mail address: roncorstanje@cranfield.ac.uk (R. Corstanje).

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stability and have locked in the new basin of attraction. Even though the threshold's location cannot be pinpointed, if there is a lack of return to the pre-disturbance regime, that may be a sign that it exists. Although thresholds cannot be found, pertinent information on which sorts of intervention are insufficient or may be necessary to push the ecosystem back to the pre-disturbance regime can be provided. However, a recurring issue in experimental ecology is that it is frequently unfeasible to manipulate disturbance regimes at the ecosystem and landscape scales in order to determine thresholds for ethical, pragmatic, and ecological reasons. In actuality, a constant natural regime of shocks and fluctuations disturbs the majority of systems. As a result, they rarely bounce back from a disturbance before the next one appears. Because of this, the fictitious stone in the cup keeps moving, and every now and then a series of minor but coordinated “perturbations” will cause the system to cross the boundary of the basin of attraction (Dakos et al., 2008).

Stability landscapes, in terms of ecosystem resilience, contain multiple possible regimes each with a particular parameterisation around equilibrium, resilience, tipping points and can contain multiple possible pathways (good or bad) based on the efficacy of adaptation. Regime shifts with stability landscapes are changes that arise when an ecosystem has a nonlinear or discontinuous response to a disturbance event causing it to undergo radical change. The critical slowing down (CSD) results in generic changes in dynamical behaviour that can be used to signal the approach of a critical transition, instead of trying to predict regime shifts by estimating critical values. When an ecosystem approaches a critical transition its dynamics “slowdown” resulting in increases in summary statistics like variance and autocorrelation.

This study is seeking to use advanced analytical techniques such as wavelets to investigate ecosystem complexity and those dynamic properties that emerge from functioning systems, such as resilience to perturbation, using intensely monitored flow data, water quality, and nutrient loads in managed large scale wetland ecosystems, the Everglades Stormwater Treatment Areas in South Florida, USA. These are large-scale wetlands were constructed in the 1990s and 2000s to treat stormwater runoff prior to discharging to the Everglades ecosystem. These systems are subjected to perturbations, such as hurricanes, high flow conditions, and droughts. To identify indicators of CSD across, this study uses wavelet analysis to describe changes in variation and autocorrelation in STA behaviour, in response to external perturbations. Understanding and predicting the ecosystem resilience to disturbance events (e.g. hurricanes) will allow us to identify which STAs are most sensitive under disturbance, which are expected to increase under climate change, but also opens up opportunities for hydrological resilience research in STA's systems.

We are particularly interested in the most and least resilient zones of the Stormwater Treatment Areas. It has been hypothesized that slow internal critical transitions often made STAs less resilient over time, setting them up for transition change. Sudden changes in the dominant plant communities have been observed within these systems, changes such as a fully vegetated emergent marsh shifting to open water communities, with associated effects on biogeochemical cycling and water quality. We investigate whether the variation observed in concentrations of total phosphorus concentrations and loads (TP-mg/L) into and out of the STA, can indicate STA to disturbances such as hurricanes, high flow conditions and droughts.

2. Materials and methods

2.1. Study area – location of the STAs

Five STAs were constructed from the 1990s to 2000s and encompass 62,000 acres just north of the Everglades Protection Area (EPA), in the State of Florida. They were built to remove excessive phosphorus (P) primarily from agricultural and urban runoff, to enhance the quality of water that enters the EPA (Armstrong et al., 2023).

2.2. Background

The Everglades STAs are the largest treatment wetland system in the world that retain nutrients through complex biogeochemical processes including vegetation growth and the accumulation of dead plant waste. History on design and build as well as sampling stations with emergent aquatic vegetation (EAV) and submerged aquatic vegetation (SAV) is described by Armstrong et al. (2023). Zhao and Piccone (2020) evaluated STA performance by comparing annual and long-term average annual flow-way and treatment cell TP flow-weighted mean outflow (FWMC) concentrations, TP load retention percentage, and TP FWMC reduction percentage. The results of an evaluation of the effects of annual hydraulic loading rate, annual phosphorus loading rate, annual average hydraulic residence time, inflow TP FWMC, and annual average water depth on annual flow-way TP FWMC showed that TP settling rate alone is insufficient to assess STA treatment performance, particularly when hydraulic loading rates vary. Under controlled steady-state settings, the P retention mechanisms acting in this sizable SAV wetland may be sustained. However, it is still a top research priority to determine how vulnerable SAV is to extreme environmental perturbations in these and other wetlands.

The South Florida Water Management District (SFWMD) operates a system for regional flood protection, water supply, and quality improvement in the South Florida ecosystem, including the Everglades. Effectiveness depends on vegetation, inflow water quality, hydraulic loads, and flow events.

Since the inception of STA's operations, their nutrient removal effectiveness has been closely monitored. The improvements in water quality are verified by monitoring the concentration of total and inorganic P levels in the inflow and comparing them to concentrations in the outflow (Juston and DeBusk, 2006). Factors like hydraulic and phosphorus loading rates can affect efficiency. The Everglades STAs aim to maintain a daily target depth of 0.4 to 0.5 m for plant health and TP retention. These wetlands are efficient biological engineering solutions to reduce nonpoint source pollution but require specialised design, operation, and maintenance. Agriculture and soil oxidation have also altered the Everglades' water quality by increasing dissolved nutrients, particle matter, and pesticides in stormwater runoff (Zhao and Piccone, 2020).

2.2.1. Disrupting events and challenges to their operation

In 2005 Hurricanes Francis & Jeanne wreaked havoc on STA-3/4, but little damage was seen in the wetlands (Pietro et al., 2006). SAV in Cell 2B was somewhat damaged by Hurricane Wilma in 2006, whereas the emergent vegetation was moderately damaged (Pietro et al., 2006). In 2018, South Florida was hit by two major hurricanes, Michael, and Irma. In 2011, a regional drought resulted in dry out and damage to the SAV in treatment Cells 1B, 2B, and 3B. The Cells 3, 4N, and 4S in STA-1E Central Flow-way (1E-CFW) had to be put into operation earlier than expected in response to storm flows from Hurricanes Frances and Jeanne in 2004 (Pietro et al., 2006). Among all the FWs under study, this flow-way generated some of the most fluctuating yearly outflow TP concentrations, going through periods of good and bad performance around every two to four years. Poor vegetation coverage resulting from windstorm damage can be blamed for the 1E-CFW's poor performance in these early years.

3. Data and analysis of the data

Monthly summed flow and load data from the 5 Everglades Stormwater Treatment Zones (STAs)-STA-1E, STA-1W, STA-2, STA-3/4, STA-5/6 (Fig. 1) was received (according to SFWMD) for each STA in a single spreadsheet of data with daily measurements aggregated by month for further analysis. Station records were merged and summarised for each flow-way depicted in Fig. 1. In order to prepare the data for time series and other statistical analyses several steps were taken (Rstudio). First,

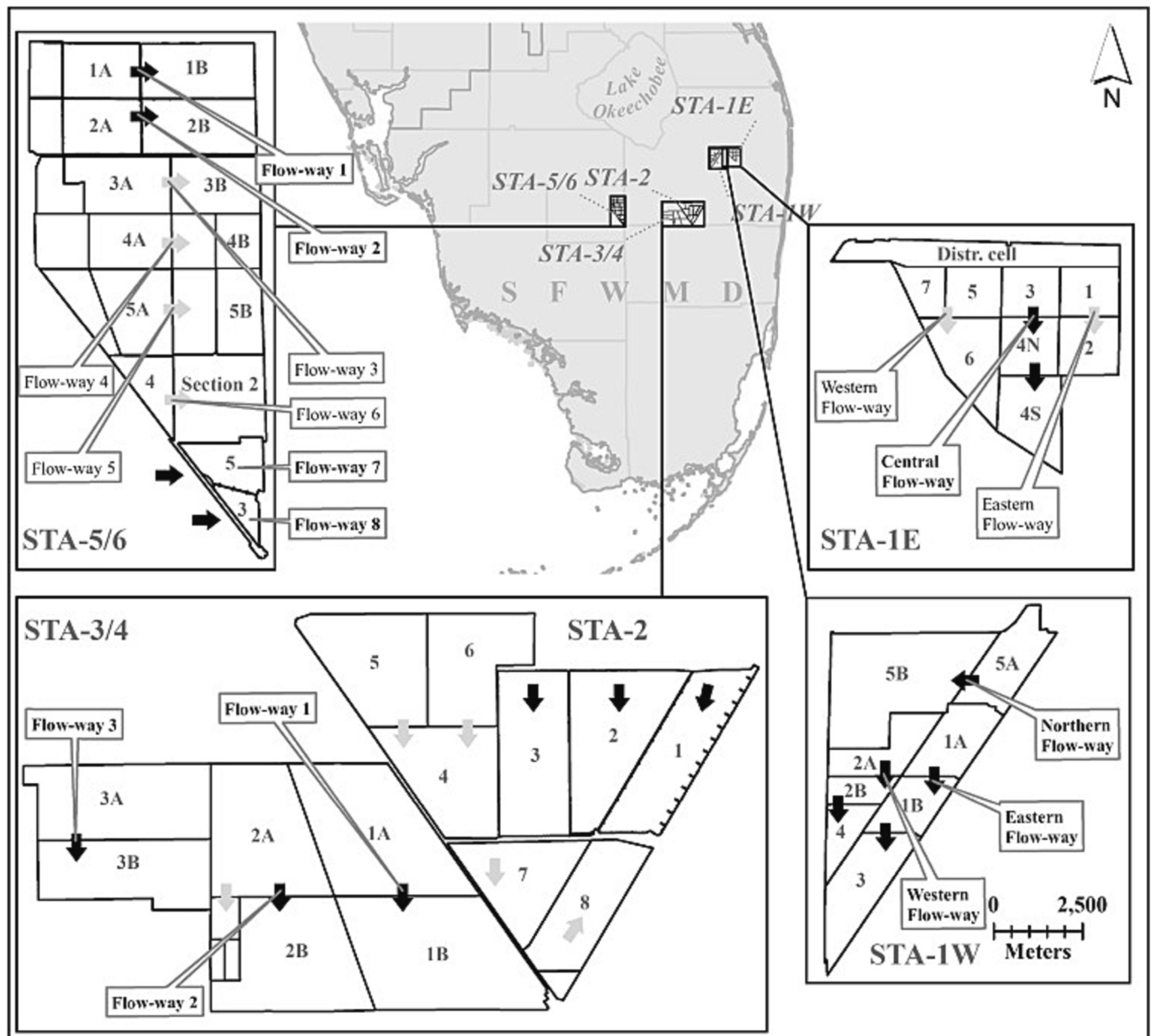


Fig. 1. Locations of the Stormwater Treatment Areas in South Florida, USA, indicating individual treatment cells and direction of flow with bolded flow-way names and darkened arrows denoting flow-ways in STA-1E, STA-1W, STA-2, STA-3/4, and STA-5/6 (source: R. Corstanje, J. Zawadzka, 2016).

all records containing only flow data were deleted to leave only those providing water quality data. Secondly, different chemical measurements focused on phosphorus (Inflow-Outflow total and dissolved phosphorus concentration (mg/L)-loading(kg)), and auto and grab samples were kept separate due to exhibiting statistical differences. Water quality measures included calcium (Ca), ammonia (NH₃), nitrate and nitrite (NO_x), sulphate (SO₄), soluble reactive phosphorus (SRP), total alkalinity (T. Alk), total dissolved phosphorus (TDP), total Kjeldahl nitrogen (TKN), and total phosphorus (TP).

In this paper, we follow a similar pre-processing methodology described by Rust et al. (2019), which, in summary, consisted of centering the time series on the long-term mean and normalized to the standard deviation to produce a time series of anomalies. This procedure allows spectra between dates and phosphorus concentration and between STAs across South Florida to be more easily compared.

The wavelet transformations had been carried out on streamflow data, TP loads. Flow stations in STAs recorded automated sampling data

of total phosphorus (TP) at regular intervals. These time series are analysed to test for the occurrence of temporal trends versus random noise, determine the periodicity of any cyclical behaviour present in the data, but more the spectral power, which was used as a proxy for autocorrelation, and consider a smoothing model to forecast the data and test for fit. Typically, wavelet analysis methods require that the time series compare a series of measurements that have been made at regular intervals in time. Gaps in the data make it difficult to estimate wavelet variance and correlation, and interpretation may also be compromised (Milne and Lark, 2009). To perceive significant modifications in variation and correlation throughout the time series, the alternate detection methods discussed in Lark and Webster (2001) were employed. These methods were used to detect significant changes in the wavelet variation between STA inflow and outflow characteristics. Any wavelet transform for which the wavelets are discretely sampled is known as a (DWT). It captures both frequency and time, which is a fundamental benefit over Fourier transforms. These were applied to the water quality data from

the STA's.

Wavelet Analysis was used with an R package called “WaveletComp” to examine the data from the STA's and try to assess their resilience. ‘WaveletComp’ employs a tiny waveform known as a wavelet to calculate the strength of different periodicity length along any type of continuous data, often time-series data in this case. The output is a power diagram describes the variance of different periodic components across the time series. Shifts from low power to high power, over time, are indicative of changes in variance within the data.

4. Results

4.1. Comparison of STA-1E and STA-3/4 wavelet power spectra in terms of variance

All the STAs analysed for the fundamental shifts that occur in systems when they pass bifurcations (see supplementary material). Here, STA-1E and STA-3/4 wavelet power spectra compared in terms of variance.

Resilience, as expressed as an increase variance, was illustrated through wavelet power spectrum plots which are often called ‘scalograms’ in terms of variance with concurrent TP concentration (mg/L) inflow-outflow in month's period (Figs. 2, 3). The more variable a time series is, the hotter the wavelet intensity spectrum becomes, as can be

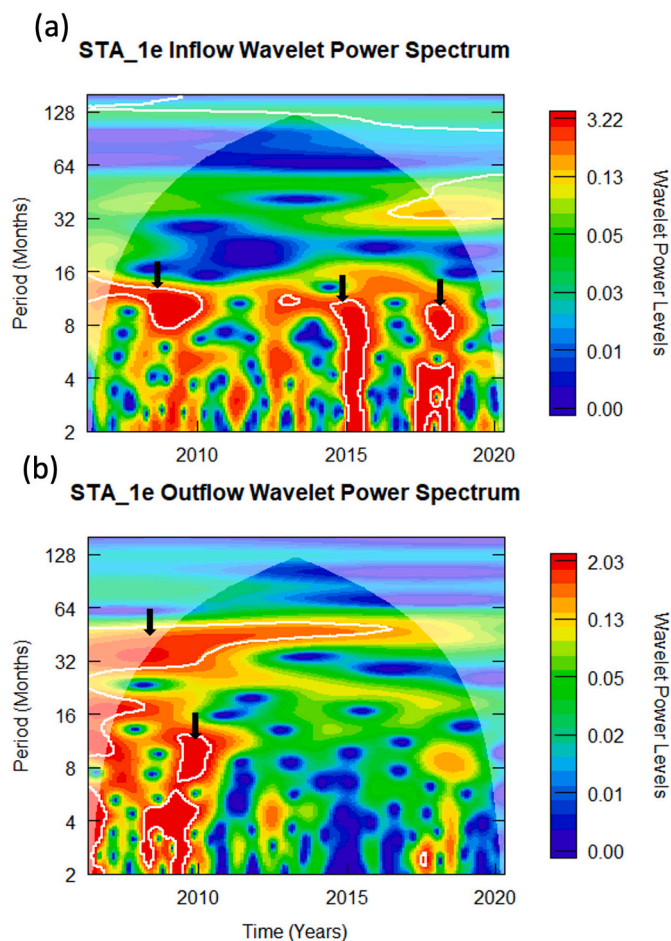


Fig. 2. The Wavelet Power Spectrum of (a) STA_1E inflow, (b) STA_1E outflow as a function of frequency. The figure shows the realizations of variance of the time series, and the variance increases in red areas and decreases in blue areas. The black arrows indicate the perturbation events occurred in STA_1E for which the segments trend statistic is higher than the trend statistic prior to the event. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

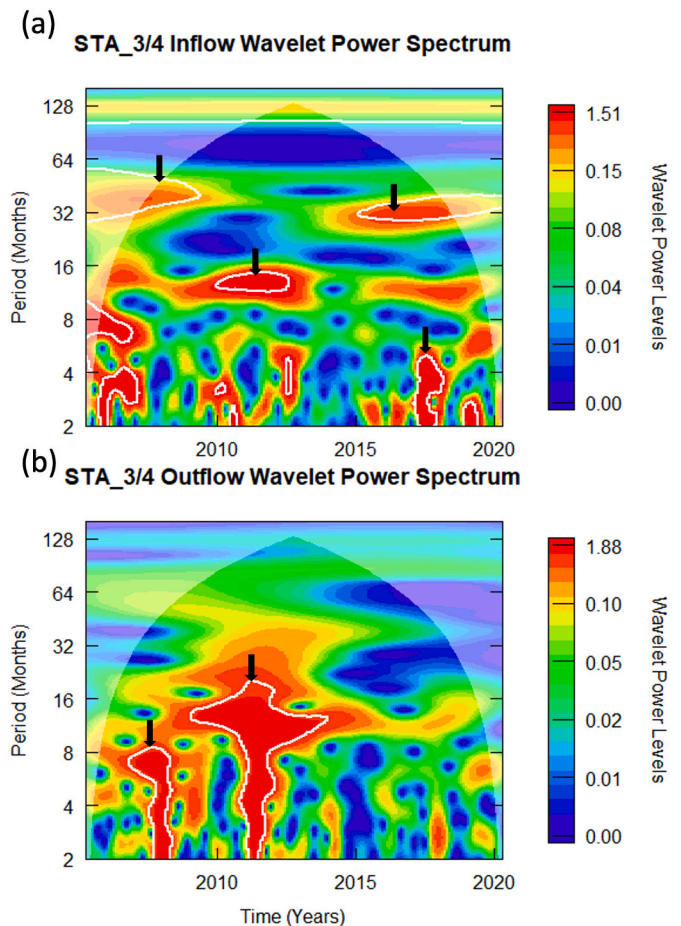


Fig. 3. The Wavelet Power Spectrum of (a) STA_3/4 inflow, (b) STA_3/4 outflow as a function of frequency. The figure shows the realizations of variance of the time series, the variance increases in red areas and decreases in blue areas. The black arrows indicate perturbation events occurred in STA_3/4 for which the segments trend statistic is higher than the trend statistic prior to the event. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

seen in periods around 2008–2010, 2015 and 2018 in Fig. 2a; 2008–2010 in Fig. 2b. The black arrows denoting the white envelopes denote where the variance becomes significant in these figures. High variability in the inflow would denote a period of intense instability in the inflow and consequently a possible disturbance event on the STA. The consequential response in the outflow would denote a possible indication of CSD, i.e. the STA system is unable to mitigate the disturbance. The associated period gives an indication of the extent over which the disturbance occurred, and the length of the possible STA response in the outflow. Although entirely diagnostic in nature, this gives an indication of the period of instability and the ecosystem response to this, the time at which and over which this occurs, which, in aggregate, start forming indicators of CSD.

4.2. Evaluation of STA-1E and STA-3/4 accumulated rolling autocorrelation

An ACF plot is used to determine where in our time series data there is autocorrelation presence, allowing for a better interpretation of the observed temporal patterns.

In Figs. 4 and 6, accumulated rolling autocorrelation analysis is plotted with lagged months-TP (mg/L) (Fig. 4a, b and Fig. 6a, b) and autocorrelation analysis of TP inflow-outflow at different lags with maximum lag of =24, one plot for each inflow or outflow (Fig. 5a, b and

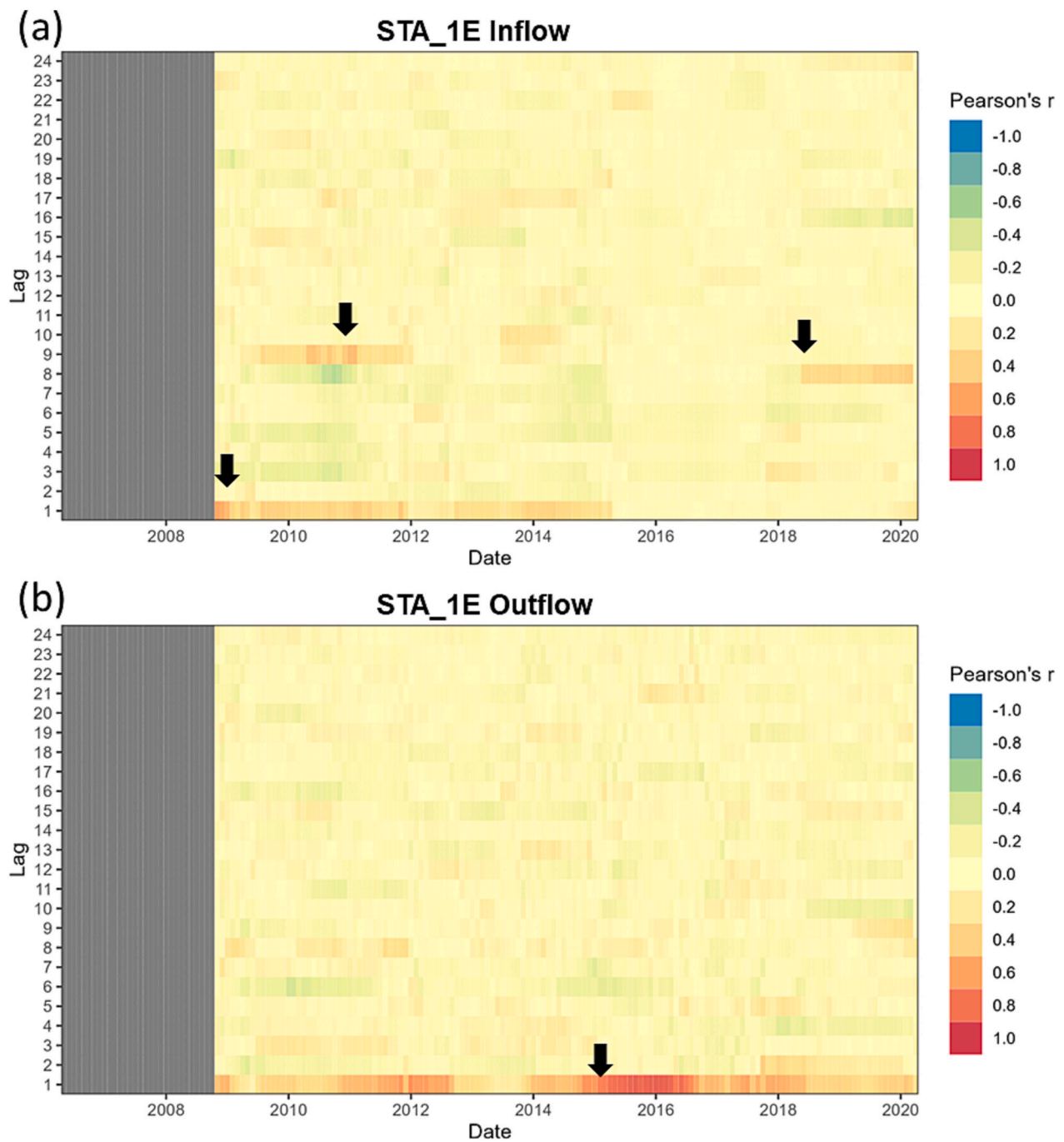


Fig. 4. Rolling Autocorrelation plot of (a) STA_1E inflow, (b) STA_1E outflow as a function of Dates. We indicated with black arrows the regions where the critical transitions were observed through time in rolling autocorrelation plots and according to Pearson's method.

Fig. 7a, b). In these figures, black arrows indicate the regions where the critical transitions were observed through time in the rolling autocorrelation plots. The colour bar graded from blue to red shows the correlation of the values. The CSD relationship and the points where disturbance events took place are represented by the direction of the black arrows (Figs. 4 and 6). Whilst the ACF plots show some noise in the data, there are signs of autocorrelations in time indicated by horizontal stretches of pixels of the same hue. The highest positive autocorrelations in the inflow occur for lag of 1 month which may indicate seasonality in TP input to the STA 1E.

4.3. CSD indicators in STA-1E and STA-3/4 through estimated correlation metrics

The influence of resilience in STAs was detected by generating plots of total phosphorus concentration (mg/L) versus Lag Outflow (Figs. 8a, b and 9a, b). We highlight with blue arrows the most resilient points on the graphs, and these points are features that were observed to align along the direction of high resilience areas. Estimation of resilience involves investigating the specific indicators through these lagged patterns where points are focused near zero and the y axis, then we have the least resilient areas, and vice versa, with less resilient areas for more distributed points. The correlations were determined and calculated as $r = 0.088$, $R^2 = 0.0078$, $p = 0.25$ for STA_1E and $r = -0.0095$, $R^2 =$

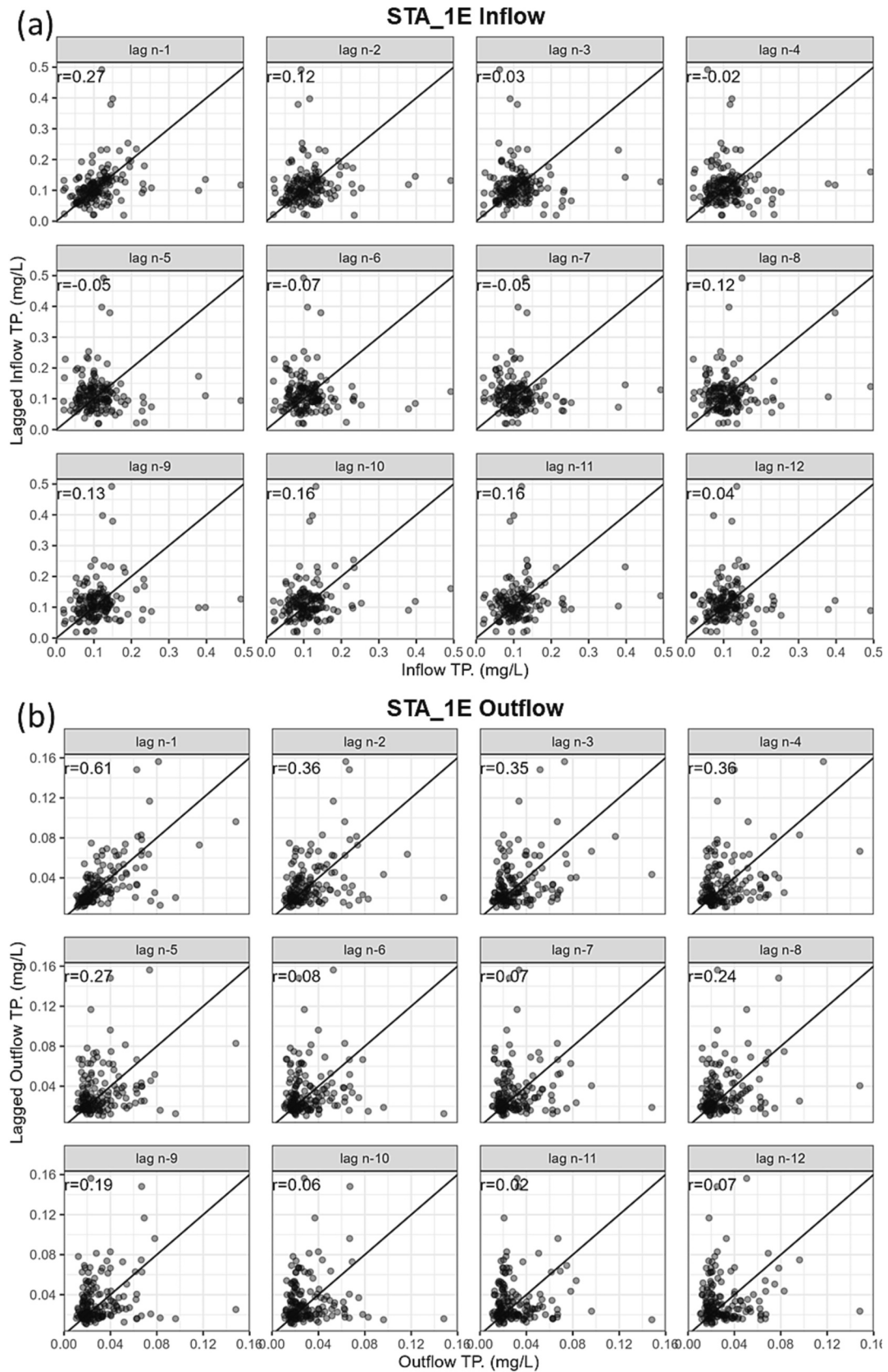


Fig. 5. ACF plots at different lags of (a) STA_1E inflow, (b) STA_1E outflow. Statistical properties of our indicators of loss of resilience illustrated in the results. The more distributed points in autocorrelation figures indicate at lag1 lower autocorrelation with rising resilience and focused points indicate loss of resilience based on each segment of lags in the system.

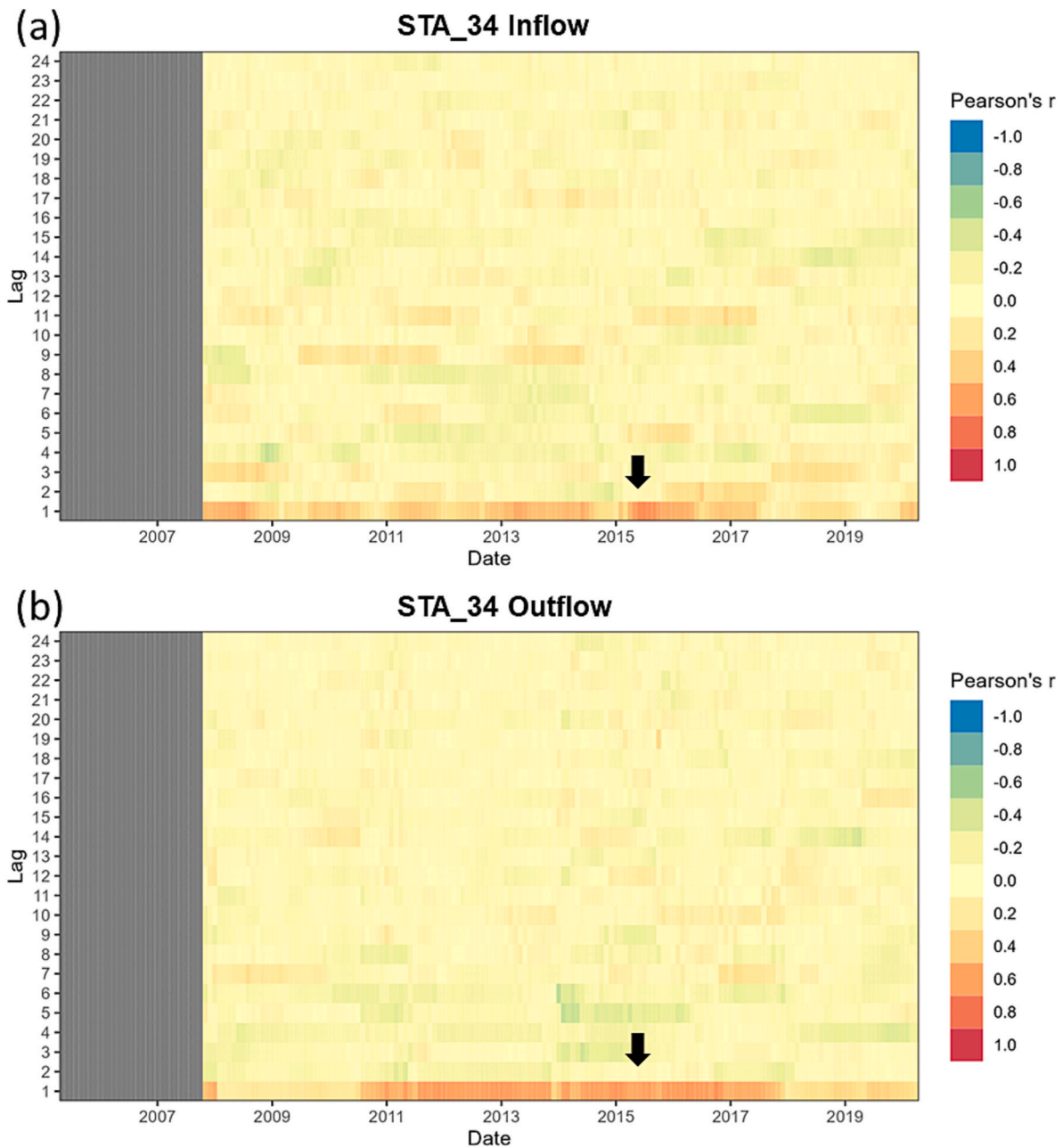


Fig. 6. Rolling Autocorrelation plot of (a) STA_3/4 inflow, (b) STA_3/4 outflow as a function of Dates. We indicated with black arrows the regions where the critical transitions observed through time in rolling autocorrelation plots and according to Pearson's method.

0.0091, $p = 0.2$ for STA_3/4 regarding [TP]-mg/L and comparing with TP(kg) loading (for STA_1E, $r = 0.15$, $R^2 = 0.022$, $p = 0.053$ and for STA_3/4, $r = 0.27$, $R^2 = 0.074$, $p = 0.00022$) where the figures show that the most resilient areas are close to zero. As the TP FWMC correlations are not significant the system show resistance.

Illustrating generic indicators of proximity to a tipping point from a normal to an alternative stable state, generally STA systems are mitigate disturbances effectively when comparing the autocorrelation terms across input parameter space to that of the outflow parameter space, disturbances occur over short periods of time (Lag 1) and mitigated effectively as there was no autocorrelation signal in the longer lags (> Lag 1).

Statistical treatment of the obtained results was performed by the correlations calculated between the inflow-outflow of the observed flows of the critical STA's using "Pearson's method" (Table 1., 2.) and were examined. Overall, the most vulnerable to transition treatment

Table 1

Correlation analysis between inflow-outflow TP dynamics of STA_1E (mg/L) → concentration and loading→(kg) and environmental-hydrodynamic variables. Indicated values are significant for the analysis.

STA_1E	in_tp.c	out_tp.c	in_tp.l	out_tp.l
in_tp.c				
out_tp.c	0.190 (0.014)			
in_tp.l	0.708 (<0.001)	0.084 (0.281)		
out_tp.l	0.529 (<0.001)	0.493 (<0.001)	0.718 (<0.001)	

Computed correlation used Pearson-method with listwise-deletion.

area was STA-3/4 indicating a negative correlation (Table 2). The results suggest that performed and worked better the STA-1E and it was more resistant and resilient than STA-3/4.

Table 2

Correlation analysis between inflow-outflow TP dynamics of STA 3/4 (mg/L) → concentration and loading→(kg) and environmental and hydrodynamic variables. Indicated values are significant for the analysis.

STA_34	in_tp_c	out_tp_c	in_tp_l	out_tp_l
in_tp_c				
out_tp_c	−0.107 (0.160)			
in_tp_l	0.600 (<0.001)	−0.233 (0.002)		
out_tp_l	0.421 (<0.001)	−0.021 (0.784)	0.757 (<0.001)	

Computed correlation used Pearson-method with listwise-deletion.

5. Discussion

According to our knowledge, this is the first study to investigate indicators of CSD in intensely managed ecological system such as the STAs of South Florida. We observe that one of the most resilient areas is STA-1E with the least evidence of critical slowing down.

Regarding the total phosphorus loading (kg) by response to resilience, the most resilient area is STA-1E and the least resilient is STA-3/4, as we observe a weak positive correlation between inflow-outflow, because a strong positive correlation between inflow and outflow TP concentrations means that their performance is impaired (Fig. 8b, 9b). In a sequence of reduced resilience, beginning from the most resilient we have: STA-1E→STA-1W→STA-2→STA-5/6→STA-3/4, but this sequence could change if the system moves into a different stability space due to a critical transition and the equilibrium position moves in a different direction. Moreover, comparing in pairs the STAs responses to resilience we have: STA-1E→STA-1W, STA-1W→STA-2, STA-2→STA-5/6, STA-1E→STA-2, STA-2→STA-3/4. When the points lie in the straight line, which has a negative gradient, this shows that as the inflow TP increases, the outflow TP decreases, and this can be observed in STA-3/4, which seems to be more resilient area in terms of total phosphorus concentration (mg/L) (Fig. 9a).

Examining of autocorrelation within a time series (e.g., outflow) the high autocorrelation is one of the indicators of CSD, however we observed that after a period of high autocorrelation, there seems to be system response leading to a period of stability, i.e. less autocorrelation. According to Piccone et al. (2014), P removal and TP outflow concentrations in STA flow-ways are influenced by internal factors. Concentrations at the outflow structures are an accumulation of upstream flow-way performance, with the marsh parcels closest to the outflow structures having the highest relative influence. More or less resilient areas are differentiated by distinct processes than low TP concentrations (13–25 g/L) and ultra-low outflow TP concentrations (13 g/L).

It is observed in Figs. 4 and 6 that the rise in autocorrelation is likely a more direct of CSD indicator than the rise in variance. This is because change in variance can be confounded by several mechanisms, for instance, a trend in variance may be related to a trend in the mean, so a coupling of variance to mean may partly explain the trends we observe in the indicators of CSD. The analysis of trends in the power spectrum illustrates that rising variability in all STAs (red areas in Figs. 2 and 3) may be an observable indicator of CSD associated with an elevated risk of an impending transition within the system, however, it is not clear whether the observed effect in variance might be an effect of increased external perturbations (noise) and not a result of CSD. As temporal autocorrelation and cross-correlations are independent of the means as well as the amplitude of noise, the trends in correlations may be our most robust indicator of CSD (Figs. 5 and 7). We can better evaluate the effects of isolated flow events as well as the impacts of multiple, sequential high flow disturbances as time series of TP concentrations lengthen and modelling tools advance. Even though it is difficult to isolate and quantify functional resistance and resilience due to the short intervals between high flow events, including dynamic flow in our assessment of alternative regimes is an essential next step towards a more comprehensive understanding of frequently disturbed ecosystems

(O'Donnell and Hotchkiss, 2022).

We have concentrated on linear dynamics near equilibrium, as is the case with most ecological stability theories. In contrast, nonlinearity is well-known for generating transients that are both longer and greater in size. In basic discrete-time predator-prey models (Hader and Gerstmann, 1990; Neubert and Kot, 1992) and spatial models of single populations, it can cause extended, chaotic transients (Hastings and Higgins, 1994). May and Leonard (1975) found that a nonlinear model of non-transitive rivalry can generate solutions that are asymptotically close to cycle- graphs, but not completely transitory.

Ecosystems nearing a tipping point lose their ability to withstand disturbances and shift towards an alternate state. Recently, it has been suggested that an ecosystem's loss of resilience might be identified by an increase in autocorrelation as well as variability in the fluctuations of the ecosystem's state Lenton et al. (2012) (Figs. 4 and 6, indicated by the black arrows). As shown in Figs. 4 and 6, in the study period, autocorrelation and variance (Figs. 2 and 3) are useful measures of CSD and/or system stability. However, analysis and simulations do indicate that some measures of CSD (e.g. variance) be less sensitive (e.g. in 2012, Fig. 2b). When comparing the power spectra of the inflow vs outflow in STA 1/2 and 3/4, the presence of a number of disturbances are noted in the inflows (Fig. 2a, 3a as shown with black arrows indicating the extreme events with periodic characteristics of 8–20 months), which correspond to a degree in observed variance in the outflows. These figures indicate that generally the STAs are able to effectively mitigate disturbances, and have become more adept at doing this as time has progressed with STA 1 earlier than STA 3/4. Stochastic changes in the environment can limit the ecosystem's ability to track high-frequency fluctuations, and this can occur when the ecosystem is less sensitive to these changes as it approaches a threshold. However, the preponderance of areas with high at low time frequencies might consequently lead to an underestimation of variance when data is scarce (Fig. 2b(period 2012–2020), 3b(period 2015–2020) as shown the blue regions during the study period).

To the contrary, autocorrelation is consistently increasing when it comes to important points in our study, as shown when we plotted accumulated rolling autocorrelation analysis with lagged months-TP (mg/L) (Fig. 4a, b) and autocorrelation analysis of TP inflow-outflow at different lags with maximum lag of 24 months, one plot for each month (Fig. 5a, b).

There are a variety of indicators that can be beneficial in different types of systems, but there are also number of limits. When it comes to extremely complicated systems such as ecological systems, the largest insights may come from using a variety of techniques as we have demonstrated in this study by using a combination of, moving window correlation and continuous wavelet transform (CWT),to determine changes in autocorrelation and variance as measures of CSD. We do show that resilience may be measured using a set of generic indicators that can be applied to a wide range of data sets.

6. Conclusions

This study used a new integrated approach, based on a combination of wavelet and correlation analysis, which might offer possibilities to monitor measures of CSD in such systems globally. According to these alternate interpretations, disturbance, heterogeneity, and the presence of several stable states all have a significant impact on ecosystem dynamics. Similar to nonequilibrium ecology, state-and-transition models were initially organised around resilience theory to describe both equilibrial dynamics within states and the occurrence of numerous states. The concept of resilience was developed to explain how dynamic ecosystems may continue to function as self-organised systems. It assumes that ecological processes acting as feedback mechanisms and regulatory factors to restrain community fluctuation in response to disturbances and sustain community structure.

Our findings support efforts to secure landscape resilience, because

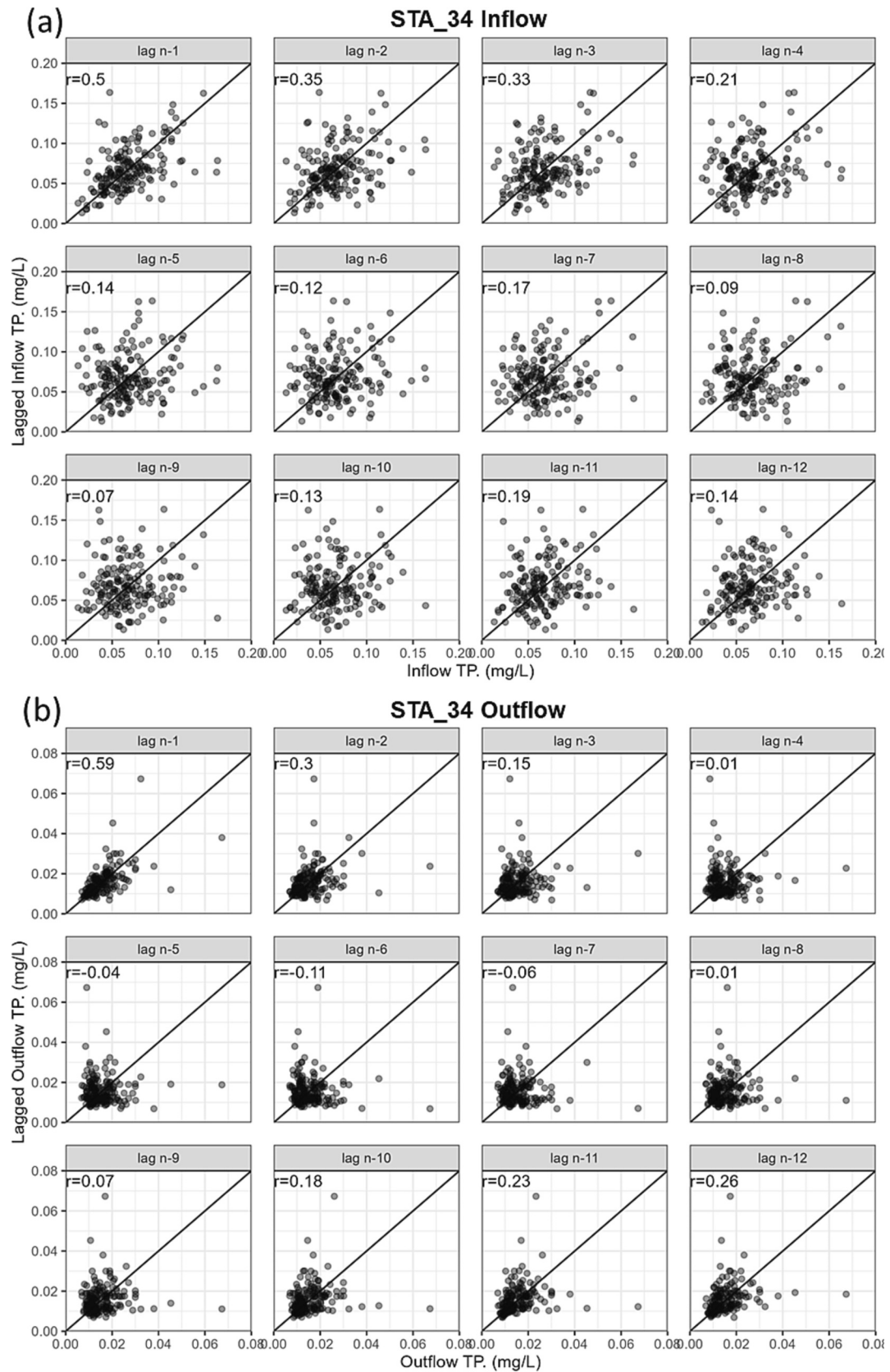


Fig. 7. ACF plots at different lags of (a) STA_{3/4} inflow, (b) STA_{3/4} outflow. Statistical properties of our indicators of loss of resilience illustrated in the results. The more distributed points in autocorrelation figures indicate at lag1 lower autocorrelation with rising resilience and focused points indicate loss of resistance based on each segment of lags in the system. The Lag 1 in outflow is more correlated than others (b).

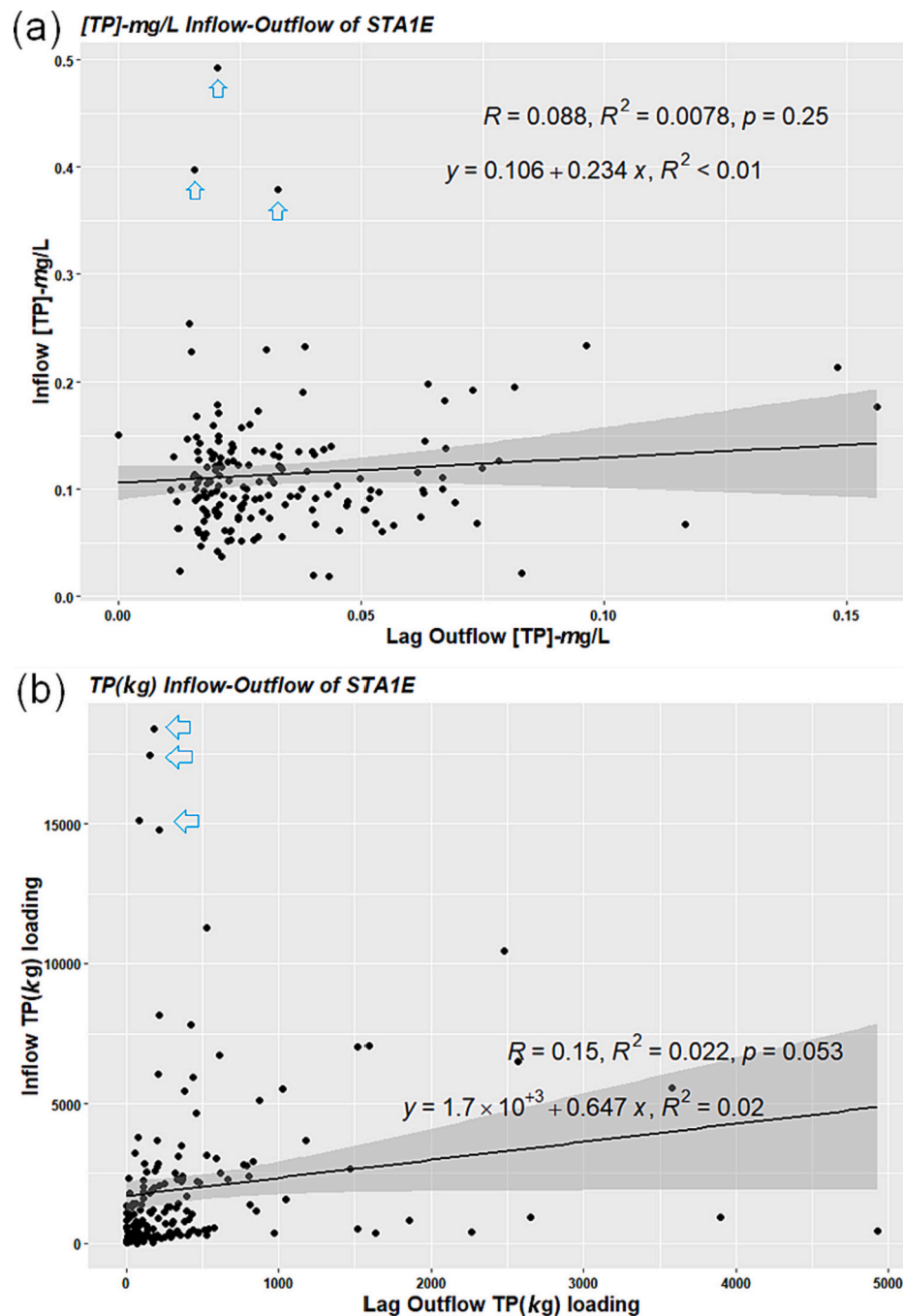


Fig. 8. Inflow-Outflow of STA1E (a) Total phosphorus concentration (mg/L), (b) Total phosphorus loading (kg) by response of resilience. The blue arrows indicate the most resilient points on the graphs and these points are features that were observed to align along the direction of high resilience areas. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

reduced resilience potentially leading to changes in functional ecosystem characteristics. Finally, the results indicate an anthropogenic environmental influence, which shows that is responsible for detectable environmental changes. Our analysis suggests that the primary distribution of TP in the STAs after perturbations through flow-ways are associated with autocorrelation, accumulated or not, and may begin to follow the variance, as indicators of resilience, measuring such traits not just for preventing collapse, but also for improving the success of ecological restoration.

CRediT authorship contribution statement

Nikolaos Toumasis: Writing – original draft, Formal analysis, Data curation, Investigation. **Daniel Simms:** Formal analysis, Software, Supervision. **Will Rust:** Formal analysis, Software. **Jim Harris:** Funding acquisition, Supervision, Conceptualization. **John R. White:** Writing – review & editing, Validation. **Joanna Zawadzka:** Writing – review & editing, Validation. **Ron Corstanje:** Funding acquisition, Supervision, Conceptualization, Writing – review & editing, Formal analysis, Investigation.

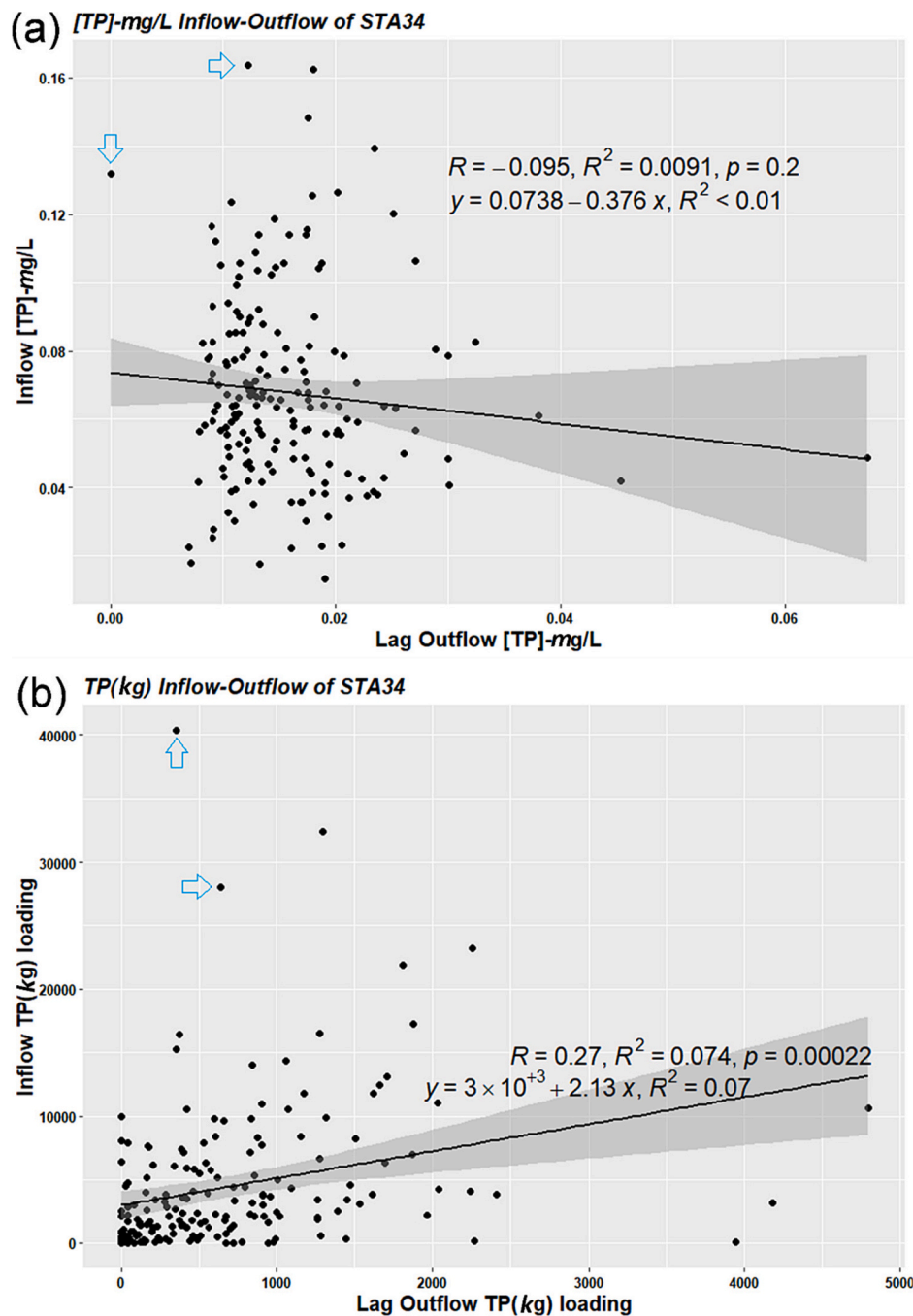


Fig. 9. Inflow-Outflow of STA_{3/4}(a) Total phosphorus concentration (mg/L), (b) Total phosphorus loading (kg) by response of resilience. The blue arrows indicate the most resilient points on the graphs and these points are features that were observed to align along the direction of high resilience areas, and the shadow band shows the confidence interval. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Nikolaos Toumasis reports financial support was provided by Natural Environment Research Council.

Data availability

Data will be made available on request.

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STA's region of South Florida in 2016; Dr. Joanna Zawadzka, Dr. Will Rust, Nikolaos Toumasis executed analyses; Nikolaos Toumasis wrote the paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecoleng.2023.107151>.

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