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Evaluation of trophic state in the Palo Verde estuary (Colima, México), action to regulating agricultural activities*

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ABSTRACT

The agricultural zones subjected to fertilizer use and inland runoff of nutrients leads to accelerated eutrophication with negative effects on coastal ecosystems and therefore significant negative economic impacts. The Palo Verde estuary (PVE) is a shallow estuary (0.4–1.5 m depth) located in the lower area of the sub-basin of the Armería River, in Colima, México. The PVE forms a temporary connection with the sea during unusual extreme meteorological events, but it is otherwise isolated. Freshwater inputs are restricted to discharges from nonpoint sources, such as agricultural runoff, torrential streams, and seasonal input from the Armería River. Farming is practiced along the boundaries of the PVE and involves an area of ~34.36 km^2 such that the estuary is under considerable anthropogenic pressure. The PVE has been recognized as a RAMSAR site (no. 1985), due to the biological, ecological, and socio-economic importance, but the estuary has been the focus of very few environmental studies, and there is a need to demonstrate, quantify and predict the effects of human activities on these interrelated components in space and time. We describe subsidies to agricultural sector the agricultural and activities within the drainage basin through stakeholder's engagement, also assessing the trophic status of the estuary with a trophic state multivariate index (TRIX) and proposing different ecosystem-based management (EBM). Actions intended to improve and control the use of agrochemicals (fertilizers N and P) in order to preserve ecosystem services.

Keywords: Palo Verde Estuary, Eutrophication, Ecosystem-based Management, Agrochemicals.

RESUMO [§]

Avaliação do estado trófico no estuário do Palo Verde (Colima, México), acção para a regulação das actividades agrícolas

As zonas agrícolas sujeitas ao uso de fertilizantes e a escorrência de nutrientes vindas do interior levam à aceleração da eutrofização com efeitos negativos nos ecossistemas costeiros e consequentemente a impactos económicos negativos signi-

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ficativos. O estuário de Palo Verde (PVE) é um estuário pouco profundo (0.4-1.5 m de profundidade) localizado na área inferior da sub-bacia do Rio Armería, na Colima, México. O PVE forma uma ligação temporário com o mar durante eventos meteorológicos extremos pouco invulgares, mas em caso contrário encontra-se isolado. As entradas de água doce restringem-se às descargas provenientes de fontes não pontuais, tais como os escoamentos agrícolas, ribeiras torrenciais e as contribuições sazonais do Rio Armería. A agricultura é praticada ao longo das margens do PVE e envolve uma área de ~34.36 km^2, de tal modo que o estuário encontra-se sob uma pressão antropogénica considerável. O PVE foi reconhecido como um sítio RAMSAR (n.º 1985) de importância biológica, ecológica e socio-económica, mas o estuário tem sido foco de muito poucos estudos ambientais, e é necessário demonstrar, quantificar e prever os efeitos das actividades humanas sobre estes componentes inter-relacionados no espaço e no tempo. Nós descrevemos os subsídios ao sector agrícola, a agricultura e actividades dentro da bacia de drenagem através do engajamento das partes interessadas, avaliando também o estado trófico do estuário com um índice multivariado do estado trófico (TRIX) e propondo diferentes gestões baseadas no ecossistema (EBM). Acções destinadas a melhorar e controlar o uso de agroquímicos (fertilizantes com N e P), a fim de preservar os serviços dos ecossistemas.

Palavras-chave*: Estuário do Palo Verde,* Eutrofização, Gestão com base nos Ecossistemas, Agroquímicos.

1. Introduction

Estuaries are transition zones between inland and open waters (González *et al*., 2006). The unique ecological and hydrodynamic characteristics account for the complexity of these environments but also their fragility (Coelho *et al*., 2007; Taner *et al*., 2011; Jennerjahn, 2012; Alves *et al*., 2013; Jennerjahn and Mitchell, 2013). However, estuaries also provide numerous goods and services to humanity. The economic importance of these ecosystem services (MEA, 2005) has been evaluated using a wide range of methods and econometric techniques (Stolk *et al*., 2006; Espino *et al*., 2013; Arocha *et al*., 2013; Valdez *et al*., 2014). In addition, estuaries have pedagogical potential, as a model for sustainable development (Costa *et al*., 2013).

Among the multifarious anthropogenic activities that impact estuaries (e.g., their touristic, urban, industrial, agricultural functions), agriculture is perhaps the most important, as it is responsible for the direct and indirect discharge of untreated water rich in fertilizer derived nitrogen (N) and phosphorous (P) (Ongley, 1997; Carpenter *et al*., 1998; Esqueda & Rivera, 2004, Espejo, *et al*., 2012).

The agricultural activity as a nonpoint pollution source is the main culprit producing the eutrophication of surface waters; currently, it is the most widespread water quality problem in many nations (Carpenter *et al*., 1998) and thus a cause for reduction in ecosystem services (Verdugo *et al*., 2007). Eutrophication is the result of over-enrichment of nutrients, such as the P and N present in synthetic fertilizers. These nutrient inputs increase primary productivity; thus, eutrophication is a process and not a trophic state (Nixon, 1995), that causes changes in the state trophic of the ecosystems, converting those that are nutrient poor (oligotrophic) to a state of over-enrichment (hypereutrophic) (USEPA, 1995).

While eutrophication is a natural process in coastal ecosystems (USEPA, 1995; Bricker *et al*., 2003), its additional negative associations as a byproduct of anthropogenic activities date back to the middle of the twentieth century, when the "green revolution" resulted in the excessive use of fertilizers in agriculture (Nixon, 1995; Cloern, 1999). Several studies have provided evidence of the contribution of incorrect synthetics fertilizer use to eutrophication (Correll, 1998; Sims *et al*., 1998; Sharpley *et al*., 2003; Siu *et al*., 2007; Espejo *et al*., 2012; Kroger *et al*., 2013).

In Mexico, agriculture is promoted through agricultural policies, including the application of agrochemicals, through the SAGARPA (Secretariat of Agriculture, Livestock, Rural Development, Fisheries and Food). Although implementation of these policies and programs (SAGARPA, 2014) is important to improve agriculture in Mexico, mexican farmers are not provided with the appropriate training. Consequently, agrochemical subsidies and inadequate training are the driving force exerting pressure on coastal ecosystems (Espejo *et al*., 2012).

Several models and indexes have been developed as tools to evaluate eutrophication in marine environments and other coastal-adjacent areas (Franco *et al*., 2010), such as the multivariate trophic index TRIX (e.g., Penna *et al*., 2004; Coelho *et al*., 2007; Silveira & Ojeda, 2009; Alves *et al*., 2013). A model used as tool support to communicate information is the Pressure-State-Response (PSR) framework, originally proposed by the Organization for Economic Co-operation and Development (OECD, 2001). This model has been used to organize data on environmental and societal characteristics, relations, and effects (Morais & Abessa, 2014) and because easily adjusted (OECD, 2001; Vázques-González *et al*., 2014). Therefore, in this study, we integrated data obtained from interviews, sample analysis, and TRIX into a modified (Driver-Pressure-State-Response) DPSR model approach followed the methodological arrangement suggested by OECD (2001).

The actions described herein as “response” are focused on regulating the actual agricultural practices and overuse of fertilizers and thus field´s over-enrichment and increased run-off (pressure) to support and improve decision-making for a sustainable PVE.

2. Materials and Methods

2.1. Study area

Palo Verde estuary (PVE) is located in the Armería, Colima State, Mexico (Fig. 1). At its northwest end, it is open to the Cuyutlán Lagoon, while to the southeast it communicates with the Pacific Ocean through a natural sandbar opening that results from the increased hydraulic pressure exerted by the large volumes of water flowing through the estuary or during the occurrence of extreme weather events. The PVE serves as a biological flyway of resident and migratory birds of the Mexican Pacific region (Mellink & López, 2009). The PVE's flora and fauna are protected under Mexican environmental regulations (FIR, 2009; NOM-059-SEMARNAT-2010), as part of the estuary's recognition as a RAMSAR Site (no. 1985) (RAMSAR México, 2009). Along its main axis it is approximately 4 km long and of varying width, with an estimated total area of ~734,968 m^2.

Along its boundary, there are three ejidos (in México ejido is a portion of land for public use like livestock and agriculture among others) and a small private property farmed (Fig. 1). Regional farming practices include both monoculture and polyculture of crops such as banana, coconut, lemon, and other seasonal crops in an area of approximately ~34.36 km^2. In addition to continental runoff discharges, the PVE is subjected to sedimentation problems. Thus, during the dry season (December to June), its volume is reduced and its water level declines, although both have been attenuated by an artificial floodgate.

3. Conceptual DPSR framework

The PSR framework, originally proposed by the Organization for Economic Co-operation and Development (OECD, 2001) considers that human activities exert *pressure* on the environment that affect both the quality and the quantity of natural resources and therefore their *state*. The *response* of society is to make the necessary changes through environmental as well as general economic and sectorial policies and through changes in awareness and behavior. Specifically, we used DPSR framework to analyze the main driving forces that encourage on the PVE according to scope our work, the pressures exerted on it, and its current trophic state, and to intent simplify communication between of decision-making, because all blame cannot be laid on the decision makers if the information is deficient (Lundberg, 2013). Thus, in this study, we integrated data obtained from interviews, sample analysis, and TRIX into a modified DPSR model approach, followed the methodological arrangement suggested by OECD (2001) to communicate the main message, and to help facilitate of possible responses to managers. The DPSR indicators are described beneath.

3.1. Drivers

The "Drivers" indicators are largely economic and socio-political (industrial or agricultural development, trade, regulations, subsidies, and others) that promote or

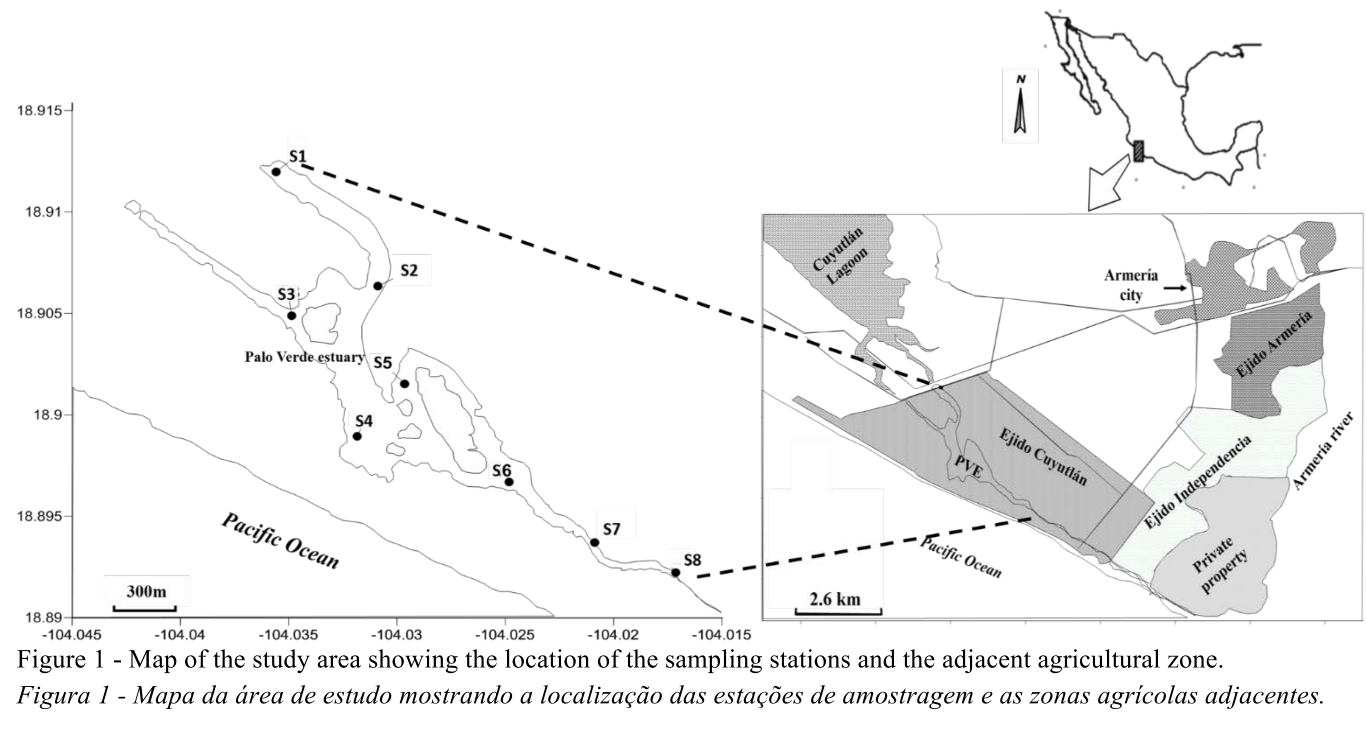

Figure 1 - Map of the study area showing the location of the sampling stations and the adjacent agricultural zone.

Figura 1 - Mapa da área de estudo mostrando a localização das estações de amostragem e as zonas agrícolas adjacentes.

influence environmental pressures in the absence of effective pollution abatement (Ærtebjerg *et al.*, 2001; OECD, 2001). Nevertheless, in addition to subsidies, the inadequate agrochemicals training are the driving promote pressure on coastal ecosystems (Espejo *et al.*, 2012). Thus, to propose work it, "Drivers" indicator to refer to federal subsidies of federal and municipal farming programs in order to synthetic N and P fertilizers acquisition, the lack of training agrochemical programs for farmers, and the lack of knowledge regarding regulations/measures referent to agrochemicals used on the agriculture area (ejidos) to lead it their inappropriate application.

3.2. Pressure

The issue of eutrophication, "Pressure" indicator, is human activities related to agriculture and emissions of N and P in water and soil, runoff from excessive commercial derivate of synthetic fertilizer use (OECD, 2001). Thus, this "Pressure" indicator is represented by agricultural activities in the adjacent zone (fertilizers N and P) that input to PVE trough continental runoff.

In our model both, the empirical data presented and analyzed stems from qualitative approach structured interviews, a method with a flexible structure, i.e. allowing new questions to be brought up during the interview depending on the answers from the former questions (Soriano, 1995; Sampieri *et al*., 2008). The interviewees represent a selection of key informants; commissioner and committee (12 persons). Commissioner and committee consisted mainly of the ejidos: Armería, Independencia, Cuyutlán and small-property owners (Fig. 1). The information of the current situation of subsidies and amount of approximate agrochemical used was for each ejido.

Thus, the structured interview to key informants consisted of 26 open- and closed-ended questions grouped in three sections: a) agricultural activities (7 questions related with: crop types, years of farming practice, time and alternative economic activities). b) farming capacity and agrochemical use (15 questions related with: main types of fertilizers employed, frequency of application/seasonal use, average amount used, training programs on the use of agrochemicals received, knowledge of the effects of the overuse of agrochemicals), and c) agricultural subsidies (4 questions related with: type of subsidies: cash, equipment, agrochemicals, and type and frequency).

In addition we dialogue with authorities (5 persons): Municipality's Director of Rural Development, Direction and Head of the Center for Rural Development Support, State Council of Lemon Producers (citrus production, COEPLIM), the State Council of Coconut Producers (COECOCO), and the Colima State Plant Health Committee (CESAVECOL) that represents the authorities. Also was taken in account the opinion of different stakeholders agricultures suppliers (5 persons), there were the five main regional distributors. They validated information about of fertilizer foremost trade. Information on the recommended doses of agrochemicals was obtained from the Technological Reports of the Development Rural Secretary Mexican National Institute for Forestry and Agricultural Research (SEDER). All interviewed were divided into three groups (Table 1).

3.3. State

The core set indicators in the issue of the eutrophication are the concentration of N and P and BOD/DO (OECD, 2001). However, in this work "State" indicator is integrate of the concentration of dissolved inorganic nitrogen (DIN: nitrate-NO_3^-, nitrite-NO_2^-, ammonia-NH_4^+), dissolved inorganic phosphorus (DIP) (both in μML^{-1}), dissolved oxygen (DO, in mgL^{-1}) and chlorophyll-a (Chl-a, in mg/m^{-3}), and information obtained integrated TRIX used to characterize the trophic state of the PVE.

The TRIX (proposed by Vollenweider *et al*., 1998) was used to measure the trophic state because it consists of a set of aggregated indicators, which reduces the number of measurements and parameters that normally would be required to describe a coastal lagoon environment. In addition, the measurement data can be easily communicated, thus providing an "exact" description of a particular situation, as recommended by the OECD (2001). The TRIX considers four state variables: those directly expressing productivity: Chl-a and oxygen [absolute value of the percentage of DO saturation, (abs|100%|=% O_2)], and nutritional factors: DIN (NO_3^-, NO_2^-, NH_4^+) and DIP. The values are provided in Table 2. The parameters were integrated into the following formula:

$$\mathrm{TRIX} = (\log_{10}\text{-}a \times a\%O_2 \times \mathrm{DIN} \times \mathrm{DIP}+k/m \qquad (1)$$

where: k = 1.5 and m = 1.2 are constants.

3.3.1. Sampling and laboratory analysis

A series of samplings were conducted in the PVE with adequate temporal and spatial coverage such that representative conditions in the estuary with respect to depth, inputs from agricultural runoff, and sediment accumulation zones were included. Eight stations were selected. Their geographical positions were registered with GPS devices (Garmin eTrex). The stations were grouped in three zones with respect to depth: Stations 1, 2, and 3 corresponded to the northern zone (S-NZ: S1, S2, S3), with an average depth of 1m. Stations 4, 5, 6 made up the shallower central zone (S-CZ: S4, S5, S6), with a depth of 0.5m. Stations 7 and 8 comprised the southern zone (S-SZ: S7, S8), with an average depth of 0.8m. In addition, geomorphologic characteristics were considered.

Table 1 - Presentation of the groups of interviewed and the organizations and institutions they represent.

Tabela 1 – Apresentação dos grupos de entrevistados e das organizações e instituições que eles representam.

Group of interviewed	Organization	www-page
Commissioner and committee	Armería ejido, Independencia ejido, Cuyutlán ejido and Small-property owners	
Authorities	Municipal Director of Rural Development	http://www.armeria.gob.mx
	Direction and Head of the Center for Rural Development Support	
	COEPLIM	www.coeplim.gob.mx
	COECOCO	www.coecoco.gob.mx
	CESAVECOL	www.cesavecol.gob.mx
Agricultures suppliers	Hermanos Gómez Fertilizer	www.fertigomez.com.mx/
	Cazares Fertilizer	
	Ducor-Dupont fertilizer	www.ducor.com.mx
	Tepeyac Fertilizer	
	FERMAN Fertilizer	www.ferman.mx/

Table 2 - Values and levels of eutrophication in the TRIX scale for water quality assessment (take from Penna *et al*., 2004).

Tabela 2 – Valores e níveis de eutrofização na escala do TRIX para a avaliação da qualidade da água (retirado de Penna et al., 2004).

Trophic scale	State	Conditions
2-4	High	• Water poorly productive • Low trophic level
4-5	Good	• Water moderately productive • Mean trophic level
5-6	Bad	• Poor water moderate to highly productive • High trophic level
6-8	Poor	• Water highly productive • Greatest trophic level

Samples were collected during three periods: the dry season (March: dry), the beginning of the rainy season (July: Inter D-R) and the heavy-rain season (September: rainy). These periods have been identified as transition phases that strongly influence the ecological behavior of coastal systems (Espinosa *et al*., 1994) and are similar to those considered by other authors (Romero *et al*., 2004; Espino *et al*., 2008).

Superficial water samples for dissolved inorganic nutrient (DIN and DIP), and Chl-a determinations were taken at a depth of 0.2m from the surface using 50-mL and 1-L bottles, respectively. The samples were stored under cold, dark conditions until used in a laboratory colorimetric analysis. DIN and DIP were analyzed using a segmented flow autoanalyzer (Skalar San Plus II) according to the methods of Strickland & Parsons (1972).

Temperature (T), dissolved oxygen (DO) and salinity (S) were determined *in situ* with the Geoscientific field multiparameter instrument YSI85. Depth was determined with the Speedtech Depthmate portable sounder model SM-5. Rainfall data were obtained of Estación: Armería - Municipio: Armería from the Agroclimatological Armería Station of the National Network of Workstations of INIFAP.

Water samples for Chl-a determinations were filtered through Whatman GF/C glass-fiber filters. Pigment was extracted with 90% acetone and measured in a spectrophotometer (Perkin Elmer LAMBDA 35 UV/Vis) following the methods of Strickland & Parsons (1972).

3.3.2. Statistical analysis

The statistical analysis was focused to “State” indicator. Thus, prior to data normality testing, the homogeneity of variance was tested using Cochran, Hartley, and Bartlett's test. Significant differences in eutrophication levels between collection periods and between the samples, collection zones were determined using a one-way ANOVA. Multiple comparisons were performed using Tukey's HSD. Spearman's correlation test was used to evaluate the correlation between the state variables (i.e. Chla, DO, DIN and DIP) and the overall eutrophic state determined with TRIX. All statistical analyses were carried out using the software package Statistic 8.

3.4. Response

The "Response" indicators refer to individual and collective actions and reactions, intended to: mitigate, adapt to or prevent human-induced negative effects on the environment; halt or reverse environmental damage already inflicted; preserve and conserve nature and natural resources (environmental expenditure, environment-related taxes and subsidies, and others) (OECD, 2001). Thus, "Societal response" is considered herein as a corresponding "Response" action proposal (Fig. 2).

4. Results

4.1. Drivers

The absence of government programs regarding education on the use and application of fertilizers was reported in all the interviewees. There was also a lack of awareness about the fertilizer themselves and the doses recommended in the Technological Package of the SEDER (2005). Only recommendations came from the CESAVECOL and the supplier, but only at the time, the fertilizers were acquired. The respondents said that 15% of they were familiar with the municipality's regulations regarding plant health. Lemon producers indicated that, since 2013, they have received increased attention and assistance from government organizations as CESAVECOL and FIRA (Trust Funds for Rural Development) in efforts to combat pests (Huanglonbing: "yel-

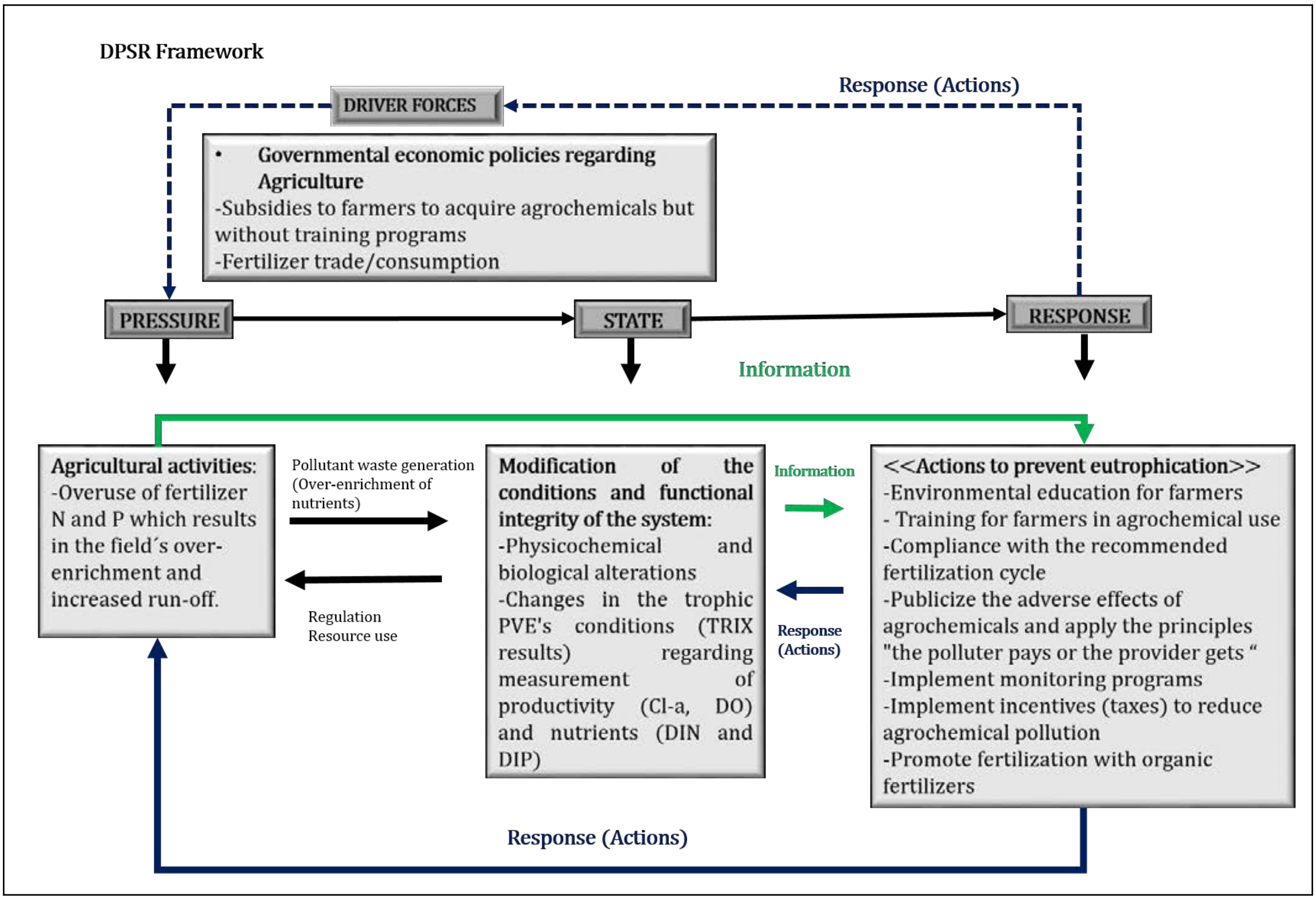

Figure 2 - Flow diagram explaining the indicators integrated in the PSR framework (modified from the OECD, 2001, and from Tenorio *et al.*, 2013). Dark gray boxes: The indicators drivers, pressure, state, and response. Light gray boxes: The actions of each of the indicators.

Figura 2 - Fluxograma explicando os indicadores integrados no quadro PSR (modificado a partir de OECD, 2001, e de Tenorio et al., 2013). Caixas cinzentas escuras: Os indicadores condutores, pressão, estado, e respostas. Caixas cinzentas claras: As acções de cada um dos indicadores.

low dragon") in the region. The authorities informants validated information about the lack of training agro-chemical formals programs for farmers.

According to the respondents, in 2013, the farmers received cash for the purchase of agrochemicals (the amount of money was not specified). In 2014, they received 14 bags of fertilizer (ammonium sulfate) from SAGARPA, who later also gave them $1,100.00 MNX/hectare (ha)/farmer (equivalent to ≈ US $ 84) for the acquisition of nitrogen-phosphorus-potassium (NPK) fertilizer (formulation: 20-10-10) through the Agriculture Development Program in its "Agroincentivos" section. The subsidies ranged from ≈ USD $84 to USD $260 per farmer. The municipality's Director of Rural Development, Direction and Head of the Center for Rural Development Support validated information about subsidies to farmers.

4.2. Pressure

According to the interviewed, 560 parcels of land (Garcia, *et al*., 2013) are managed by 495 farmers, who practice both monoculture and polyculture, including banana, coconut, lemon, and other seasonal crops. Subsidies for farmers are awarded annually.

Respect to the fertilizers used in the agricultural lands, SEDER (2005) recommended N and P, and agrochemical suppliers confirmed these fertilizers as more trade. Thus, the interviewees said that 47% most producers applied sulfates, 35% applied phosphate, and nitrogen fertilizers, and 37% using either of these fertilizers for the lemon crop, monthly or quarterly (1–3 kg /tree). The quantity, frequency, and application period recommended by the SEDER (2005) depends on tree age and the number of trees per hectare and ranges between 1 and 2kg/tree per fertilization cycle. Coconut crop fertilizer (ammoniac sulfate) is annually applied in 43% of the ejidos. Distributors of agricultural supplies confirmed the high demand for fertilizers (N, P, and sulfates).

In addition, pluvial precipitations have consequences over continental runoff from the agricultural zones to the PVE. According to the data registered by Agroclimatological Armería Station, the rainy season in 2014 started in May and lasted until November of the same year. During March, there was no rainfall but values in June reached 245 mm. Rainfall was heaviest in September, with 458 mm.

4.3. State

4.3.1. Physicochemical water quality

A comparison (Tukey HSD test) of the physicochemical variables (T, DO, DIP and DIN) showed spatial variation between zones (Table 3), except Chl-a and salinity not showed differences statistical ($p > 0.05$). Statistically, temporal significant differences between periods are indicated in Table 4, with the exception of DO and DIN statistical test, not showed differences between periods.

A correlation was observed between chlorophyll a and TRIX, which justify the median values, since this index

Table 3 - Show differences between variables by zones and period (Tukey HSD test).

Tabela 3 – Apresentação das diferenças entre variáveis por zona e período (teste Tukey HSD).

		Dry (March)			Inter D-LL (July)			Rain (September)		
	Zone	**N**	**C**	**S**	**N**	**C**	**S**	**N**	**C**	**S**
T °C	**N**	-	0.630	**0.007**	-	0.871	**0.005**	-	0.231	**0.014**
	C		-	**0.014**		-	**0.006**		-	0.076
	S			-			-			-
DO	**N**		0.280	**0.008**	-	-	-	-	-	-
	C			**0.030**		-	-		-	-
	S						-			-
DIP	**N**	-	-	-	-	**0.002**	**0.006**	-	**0.012**	**0.012**
	C		-	-		-	0.788		-	0.886
	S			-			-			-
DIN	**N**	-	-	-	-	**0.003**	**0.001**	-	0.114	**0.044**
	C		-	-		-	0.182		-	0.541
	S			-			-			-

Highlight black correlations are significant at p <.05000. - Not difference

Table 4 - Show differences variables considered between periods (Tukey HSD test).

Tabela 4 – Apresenta as diferenças das variáveis consideradas entre períodos (teste Tukey HSD).

Variables	T°C			Salinity			DIP			Chla		
Periods	**Dry**	**Inter D-LL**	**Rain**	**Dry**	**Inter D-LL**	**Rain**	**Dry**	**Inter D-LL**	**Rain**	**Dry**	**Inter D-LL**	**Rain**
Dry	-	**0.000**	0.071	-	**0.025**	**0.031**	-	**0.01**	0.82	-	0.103	**0.018**
Inter D-LL		-	**0.000**		-	0.994		-	**0.00**		-	0.675
Rain			-			-			-			-

Highlight black correlations are significant at p <.05000. - Not difference.

is more connected to primary productivity. A minor correlation was also observed between the TRIX values and the temperature (Table 5); with this parameter, which relation with ambient temperature and serving to growth of phytoplankton biomass and as a response result of increase of chlorophyll a availability light.

Table 5 - Spearman correlations between considered variables and TRIX index of all periods.

Tabela 5 – Correlações de Spearman entre as variáveis consideradas e o índice TRIX para todos os períodos.

	DIP	DIN	Chla	T	DO	Sal	TRIX
DIP	1.00	**0.82**	-0.16	-0.35	0.15	-0.12	0.15
DIN		1.00	-0.03	0.03	**0.42**	0.12	0.12
Chla			1.00	**0.58**	-0.36	**0.50**	**0.68**
T				1.00	0.01	**0.69**	**0.47**
DO					1.00	0.13	-0.31
Sal						1.00	**0.62**
TRIX							1.00

Highlight black correlations are significant at p <.05000.

The oscillations in superficial water temperature were: 23.5–28.5° C (dry), 28–33.9° C (Inter D-R), and 27–29.2° C (rainy). The minimum values were always at S-SZ and the maximum values at S-NZ (Fig. 3: red circles). Statistically significant differences ($P < 0.05$) were determined for Inter D-R vs. dry and rainy seasons (Tukey HSD; $P < 0.05$). A spatial gradient for temperature was observed according to the distance of the sampling sites, with higher values in S-NZ (S1) and lower values in S-SZ (S8).

Salinity did not follow a defined spatial gradient along the PVE, but there were statistically significant differences ($P < 0.05$) between periods. Minimum values were measured at S-SZ (S7 and S8: 0.4 and 0.7, respectively) during the dry season. Salinity values in the shallower S-CZ (shallower) reached a maximum (1.2) during the Inter D-R and rainy seasons (1.1) whereas at S-NZ the values were more homogenous (0.9) during the three sampling periods (Fig. 3: black triangles). During this study, the PVE did not have a communication with the ocean because of the persisting sand barrier.

DO concentration in the PVE varied from 0.28 to 6.46 mg/L^{-1} (3.2–81.6% oxygen saturation). During the dry period, DO was in the range of 0.3–5.42 (2–77.3% oxygen saturation); in the Inter D-R, 0.22–5.5 mg/L (2.8–70.2% oxygen saturation); and in the rainy period, 0.22–5.53 mg/L^{-1} (2.8–70.2% oxygen saturation) (Fig. 3: blue circles). Hypoxia occurred at S-SZ (DO ≤ 2 mg/L^{-1}) during all sampling periods.

The Chl-a concentration showed the greatest seasonal variation at S-SZ, with an average > 10 mg/m^3 most of the year, except during the dry season, when it was < 4 mg/m^3. Chl-a reached a peak at S3 (47.5 mg/m^3) during the rainy period but was lowest at S1 (0.14 mg/m^3) during the dry period (Fig. 3: green circles). A one-way ANOVA showed significant differences ($P < 0.05$) between the rainy period and the dry period (Tukey HSD; $P < 0.05$).

A comparison of the superficial DIN and DIP concentrations showed an increased spatial tendency from S-SZ towards S-NZ during all sampling periods, but mainly during the rainy season (Fig. 4). Maximum DIN values were consistently recorded at S-NZ during all periods (dry: 14.7–20.72 μM L^{-1}, Inter D-R: 13.8–15.45 μM L^{-1}, rainy: 15.70–21.93 μM L^{-1}). The same pattern was observed for DIP (Fig. 4), with maximum values measured at the NZ during all three sampling periods (dry: 6.20–8.29 μM L^{-1}, Inter D-R: 4.39–4.61 μM L^{-1}, rainy: 8.04–9.95 μM L^{-1}). The exception was at S7, where the values of DIN and DIP during the dry period were higher than those of the other stations (14.34 μM L^{-1} and 7.28 μM L^{-1}, respectively). Differences between the zones during all periods were more obvious in summer ($P < 0.05$).

The level of eutrophication increased gradually from 3.5 to 5.0 during the study period. During the dry period the eutrophication level and water quality were characteristic of a poorly productive system, with a low level of eutrophication (3.61: March) whereas during the rainy period eutrophication increased (4.92: September),

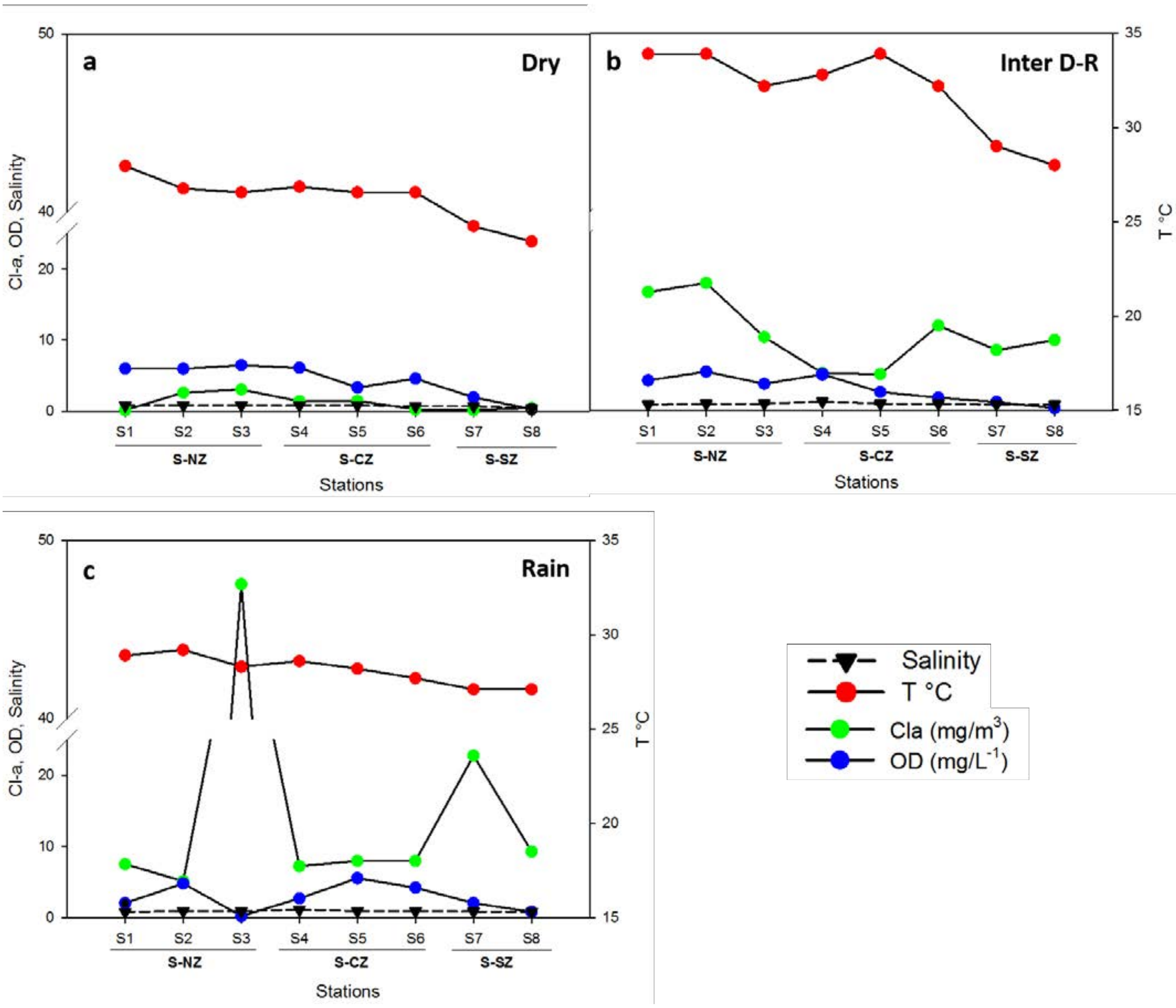

Figure 3 - Seasonal variation in the physicochemical parameters of the water (temperature, salinity, dissolved oxygen) and in the chlorophyll-a concentration at the sampling stations. a) Dry (March), b) Inter D-R (July), and c) rainy (September).

Figura 3 – Variação sazonal dos parâmetros físico-químicos da água (temperatura, salinidade, oxigénio dissolvido) e na concentração de clorofila-a nas estações de amostragem. a) Seco (Março), b) Entre S-C (Julho), e c) Chuvoso (Setembro).

although water quality was acceptable and the water was also moderate-highly productive (Fig. 5a). However, a high eutrophication level (5.34) was reached at most of the stations at S-NZ, although the water remained moderate-highly productive (Fig. 5b). Eutrophication at S-NZ was also reflected in the TRIX value.

4.3.2. Response

The driver indicators demonstrate the existence of subsidies to agricultural sector that has not been accompanied by government actions to improve agrochemicals use, to reduce the generation of polluting waste or nutrient supply. There are also deficits in the implementation of environmental regulations aimed at improving agrochemical use in agricultural activities and a lack of knowledge regarding the doses for diverse crops as recommended in the Technological Report of the SEDER (2005).

Pressure indicator showed the fertilizer N and P use in agricultural activities and the emission and input of nutrient through continental runoff to PVE. State indicators, (high nutrients concentrations) which reveal an eutrophication process in progress confirmed this. Thus, the analysis of DPS indicators allows suggesting management actions as response to improve trophic conditions of the PVE. Actions to be implemented can be, environmental education and training for farmers in agrochemical use, compliance with the recommended fertilization cycle, publicize the adverse effects of agrochemicals and apply the principles "the polluter pays“

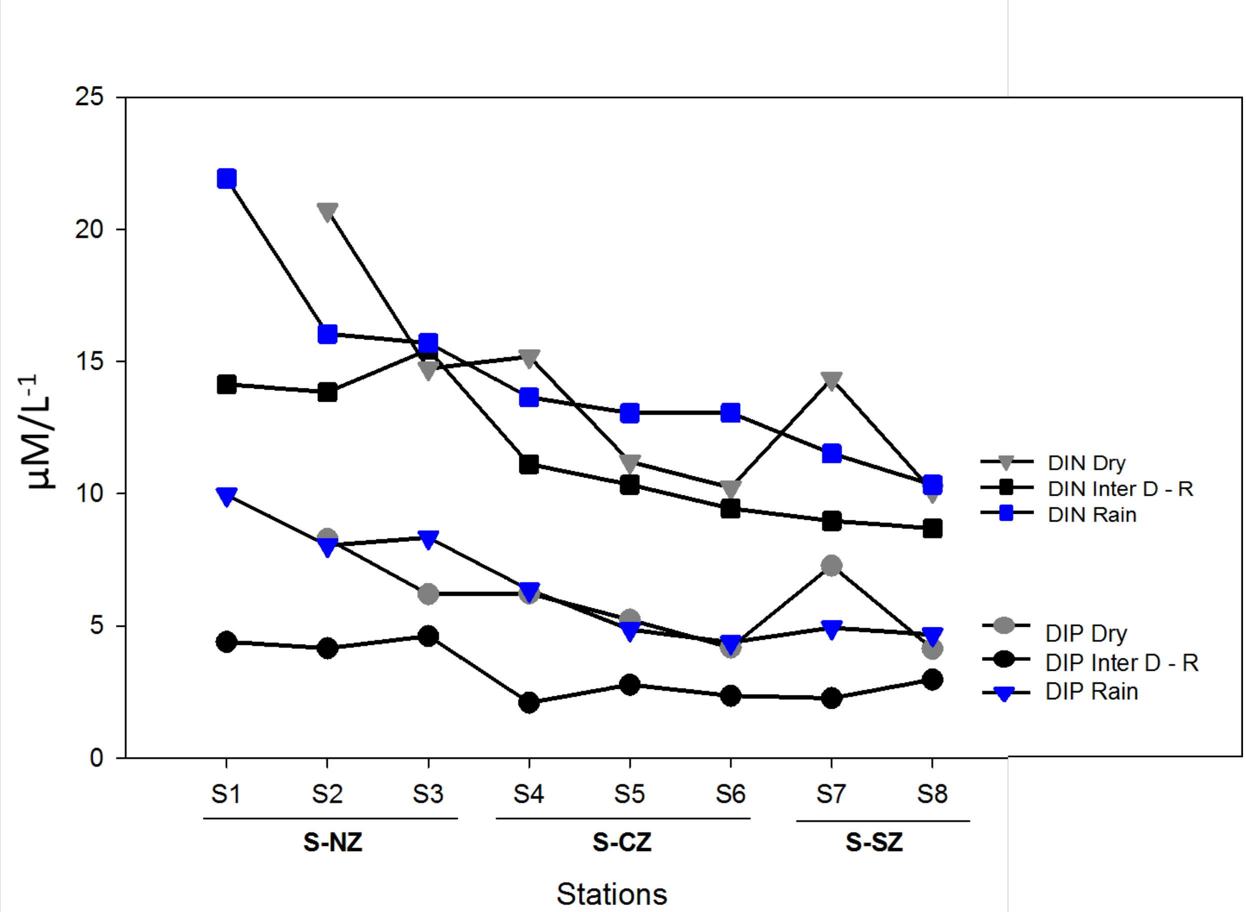

Figure 4 - Seasonal variation of nutrient concentrations at the sampling stations. DIN: dissolved inorganic nitrogen: (NO^{3-}, NO^{2-}, NH_4^+; in μM L^{-1}). DIP: dissolved inorganic phosphorus (in μML^{-1}). Dry (March), Inter D-R (July), and rainy (September).

Figura 4 – Variação sazonal da concentração de nutrientes nas estações de amostragem. DIN: azoto inorgânico dissolvido: (NO^{3-}, NO^{2-}, NH_4^+; em μM L^{-1}). DIP: fósforo inorgânico dissolvido (em μML^{-1}). Seco (Março), Entre S-C (Julho), e Chuvoso (Setembro).

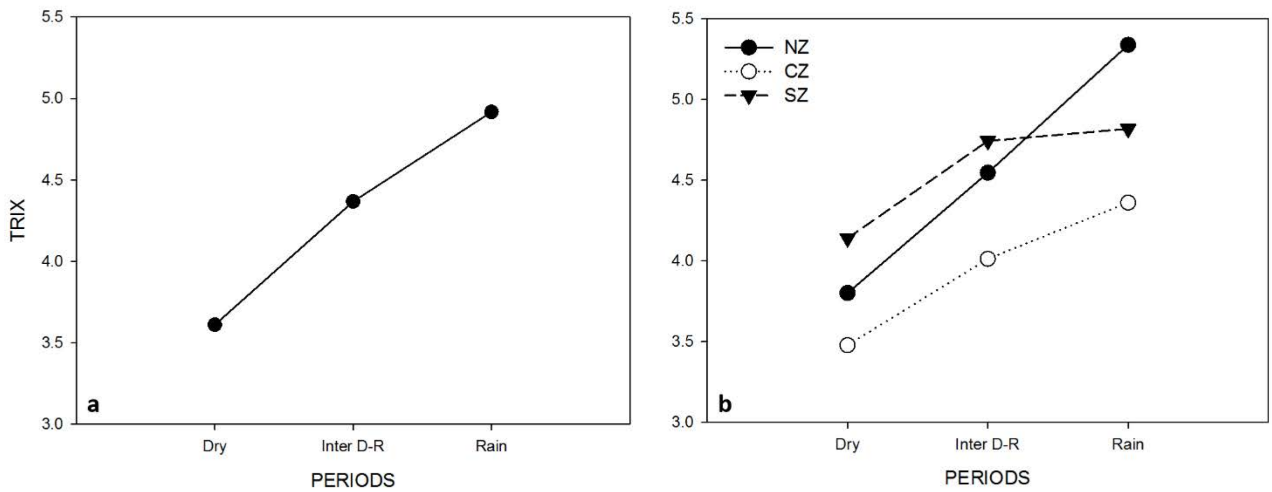

Figure 5 - a) Seasonal variations in the trophic state index (TRIX). b) Seasonal variation in TRIX at the three zones. NZ: northern zone, CZ: central zone, SZ: southern zone.

Figura 5 - a) Variações sazonais no índice do estado trófico (TRIX). b) Variação sazonal do TRIX em três zonas. NZ: zona norte, CZ: zona central, SZ: zona sul.

or "provider gets", implement monitoring programs and incentives as taxes to reduce agrochemical pollution and promote fertilization with organic fertilizers (Fig. 2). These actions would be needed to avoid the pollution loads from diffuse agricultural sources, which are an issue in many countries, and implies integration considerations in agricultural sectorial policies trough of an integrated management based on the ecosystem approach, and thereby preserving its ecosystem services as explain to OECD (2001).

5. Discussion

According to Espejo *et al.*, (2012), the subsidies are a driver to overuse of agrochemicals, also the absence of strict penalties for polluting the water generate environment pollution due the delegation of the responsibility to farmers and to the agrochemicals suppliers, who "provides" technical assistance, but finally, farmers do not consider that it is their responsibility to oversee water quality. Further, in opposition to the belief of the majority of Mexican economists, is documented that our country, relative level of subsidies to its agriculture is similar to those in the United States of America and Canada, its main commercial partners Estrada & Bustos, (2006), which puts into context the amount of fertilizer used in our México.

Respect to pressure detected in PVE, the use of N and P are recommended because are basic nutrients to play role in nutrition of the plants (Correll, 1998; Kroger *et al.*, 2013). However, importance, its generate waste and is recognized that intensity of use of N and P fertilizers in agriculture, reflected through apparent consumption in tons of active ingredients (N and P per km^2 of agricultural land) represents potential pressure on the environment in the absence of effective pollution abatement (OECD, 2001). As shown by Siu *et al.*, (2007), 20–40% of N fertilizer is lost as ammonium in coastal systems through continental runoff. Whether a similar process occurs in the PVE remains to be determined. However, although qualitative information about the use of agrochemicals was obtained through interviews; exact information about amount used was difficult to estimate because neither farmers nor the authorities haven´t a precise record agrochemical applications. Nevertheless, is possible that applied doses can easily exceed the doses recommended in the Technological Report of the SEDER (2005), confirmed by high nutrients concentrations registered in the PVE. Thus, the overuse of agrochemicals results not only in unnecessary costs to farmers but also in excess inputs of inorganic nutrients into the PVE.

The seasonal and spatial variations of physical, chemical and biological parameters in PVE are determined by variations in rain and other freshwater contributions, mainly nonpoint agricultural continental runoff. The intermediate site (S-CZ) remained fairly stable and thus differed from the two other zones. During all periods, the gradient between the zones was maintained, with highest values consistently in the S-NZ and lowest values in the S-SZ. At the S-NZ, a floodgate between PVE and basin IV of the Laguna of Cuyutlán reduces flow. In addition to restricting flow, the floodgate causes the retention of water that generates nutrient accumulation. Results about prolonged exposure to nutrients and photosynthetically active radiation in water systems, have shown that promotes biological activity (Bonilla *et al.*, 2005), this sequence of events would explain the high values of nutrients, Chl-a, DO, and temperature at S-NZ.

The conditions of the PVE were those of an oligohaline environment. Salinity did not follow a spatial gradient along but statistical differences ($P < 0.05$) between periods were observed. During the study period, there was no communication with the ocean, which prevented the establishment of optimal estuarine conditions. Thus, the system showed a seasonal pattern of salinity corresponding to period 2 as described by Arancibia *et al.*, (2014), in which due to the disconnection from the sea freshwater inputs predominate and are greater than evaporation, such that salinity decreases to as low as 5. In the PVE, the seasonal patterns of the physicochemical and biological parameters resulted mainly from continental runoff during rain and namely from the input of groundwater during the dry season.

The hypoxic conditions recorded in S-SZ during all periods were likely due to the rapid consumption of oxygen by bacteria in their degradation of suspended organic materials (USEPA, 1995; Zink *et al.*, 2004). The presence of suspended organic material in this zone can be attributed to: a) the turbulence, and thus the resuspension of sediments, caused by the propellers of motor boats (Kelty & Bliven, 2003) carrying eco-tourists and the motor boats of fishermen, which constantly transit through this zone and b) continental runoff during the Inter D-R and rainy seasons, which causes material inputs and high turbulence, increasing the oxygen demand and decreasing the DO content of the system.

Coinciding with the hypoxic conditions in the PVE were minimum values of Chl-a, most likely due to resuspension of the sediments. Concentrations in the S-SZ can probably be explained by the presence of phytoplankton as *C-* and *CR-strategists*, defined as mixing-dependent opportunistic-invasive species with high growth rates that proliferate in permanently mixed systems (Reynolds, 1984; Sommer, 1993; Huszar *et al.*, 1998; Bonilla *et al.*, 2005). These species are favored by the shallowness of the PVE's waters. Furthermore, S-SZ forms a channel approximately 5m in width, with low solar radiation exposure due to the height of the resident mangroves, which prevent the penetration of light and therefore of photosynthesis and primary production, despite the available nutrients.

On the other hand, similar hypoxic conditions (<-2 mg/L^{-1}) were reported by Romero *et al*., (2004) during the same seasonal periods in a lagoon system adjacent to an important agricultural area in southern Mexico. There, continental runoff was shown to cause material inputs and high turbulence, increasing the oxygen demand. This could have happened in S-NZ where concentrations of DIN and DIP increased during the rainy season due to adjacent agricultural inputs, which may have been magnified by the interruption of the flow due to the floodgate and autochthonous processes of remineralization of nutrients due to degradation of organic matter in this area of PVE. Several authors (Espinoza *et al*., 1996; Newton *et al*., 2003; Coelho *et al*., 2007) have reported that in coastal lagoons increases in DIN and DIP can be attributed to continental runoff, such that nutrient concentrations are an indicator of the proportion of the surrounding agricultural land area.

The concentrations of Chl-a in the PVE were higher than those reported by Avalos *et al*., (2013) for Cuyutlán lagoon system located at 4 km, who classified this lagoon as a eutrophicated system according to the OECD's definition (1982). Chl-a values in PVE were higher than the threshold of 8–25 mg/m^{-3}proposed by the OECD (1982) for a eutrophic system. Moreover, the values of DIN and DIP exceeded the 16 and 1.1µM L^{-1} proposed by the Crouzet *et al*., (1999) as the maximum permitted level of nutrients in areas of coastal/marine water transitions. In line with both the OECD and Crouzet, *et al*., (1999) values, the PVE is a eutrophic estuary.

The DIP concentrations measured in the PVE were above the mean range (0.01–5.0 µM L^{-1}) in 69% (27) of 39 coastal lagoons in Mexico (19 in the Gulf of Mexico and 20 in the Mexican Pacific Ocean) that maintain different hydrological regimens, including terrigenous entrainment (Espinoza *et al*., 1996). Their analysis showed that coastal lagoons with high concentrations of phosphates (> 5 µM L^{-1}) are characterized by higher trophic states and greater anthropogenic pressure like agriculture.

In this study, the eutrophication level was determined by the integration of Chl-a, DO, DIN, and DIP values in the TRIX, which showed oligotrophic to eutrophic conditions in the PVE and the good to bad water quality characteristic of moderate to highly productive waters. High productivity was mainly found at S-NZ during the rainy period. The results are consistent with the levels of agricultural activity in the area of the PVE, which increase nutrient loads from continental runoff, as in similarly impacted areas (Coelho *et al*., 2007; Silveira & Ojeda 2009; Alves *et al*., 2013).

DIP was the nutrient most closely linked to eutrophication of the PVE, together with Chl-a and to a lesser extent DIN, coinciding with those reported by Penna *et al*., (2004). During the dry period (March), the conditions in the PVE corresponded to a poorly productive system with a low level of eutrophication. By contrast, during the rainy period, there was a slight shift to a higher eutrophication level, with acceptable water quality and moderate-highly productive water. The higher eutrophication level at S-NZ was presumably related to the moderate-highly productive water and its prolonged exposure to continental drainage, together with the influence of the seasonal variations in continental contributions.

In the absence of previous data from scientific monitoring, the TRIX proved to be an important tool for assessing the eutrophic state of PVE. The results from studies conducted in the coastal region of Mexico using the TRIX and other models (Silveira & Ojeda, 2009) were similar to those obtained in this work, with the worst trophic conditions determined at sites with the greatest influence of anthropogenic activities. In addition, the results of the TRIX corresponded well with those derived from others models.

Based on the highest TRIX value (6.43), Alves *et al*., (2013) reported that the worst water quality was associated with the wastewater of major continental downloads, in an area of the studied estuary that was farthest from marine influences. Similar conditions were observed in this study, with seasonal rain causing major continental runoff that accelerated eutrophication of the system.

During the study period, tendency significant spatial and temporal eutrophication occurred, as reflected in the values typically used to assess coastal ecosystems. Thus, the cumulative driver-pressure-state indicators showed a spatial and temporal deterioration that resulted in modified conditions and a negative influence on the functional integrity of the PVE. These changes can be attributed to improper handling of fertilizer, and the lack of understanding of ecosystem functioning by the farmers who use the fertilizer supported by economic policies that promote agricultural development but which are not accompanied by training programs.

A eutrophicated water body represents ecological, economic, and social costs (Bricker *et al*., 2003; Savage *et al*., 2010; Junior *et al*., 2013). Accordingly, actions aimed at preventing eutrophication are desirable because they are ultimately less costly than ecological and economic rehabilitation and restoration (Lizárraga *et al*., 2009). The conservation of ecosystems and sustainable management of resources requires scientific knowledge that can be used as a tool to detect environmental trends. Of equal importance is communication of that knowledge so that it can be used as a baseline for decision making (Lomelí, 2004; Lizárraga *et al*., 2009; Costa *et al*., 2013; Arancibia *et al*., 2013; Arancibia *et al*., 2014). Thus, the analysis "State indicator" offer the understanding system functioning, which is basic for sustainable management of coastal ecosystems and system functioning can be serve as a management tool in the management implications (Arancibia *et al*., 2014). According with these authors, the ecosystem-based management (EBM) has emerged as an approach that reflects the relationships among all ecosystem components, including the influence of humans, and the environment in which they live, and ultimately combines ecology and human dimensions in an integrated way that is transdisciplinary ecosystem management.

Thus, our study of the current trophic status of PVE shows that it is not necessary to restrict agricultural activities in the surrounding region. Nevertheless, there is much to be gained by coupling these activities with others that do not endanger the PVE. As mentioned by Estrada & Bustos, (2006) rather than to increase agricultural subsidies, Mexico should invest considerably more in investigation, education capacitation, among others.

Therefore, the proposed management options should be multiple and progressive: first awareness on possible impacts of too much fertilizer, then training on best practices for using fertilizers. This may be achieved providing environmental education to farmers to facilitate an integrated perception of the environment and its rational use, with benefits for social development and the environment. The assimilation of knowledge and modification of behaviors will ensure the preservation of resources as established by the General Law of Ecological Equilibrium and Protection of Environment (LGEEPA, 2015). According to Cortinas de Nava (2000), the implementation of training can provide the knowledge necessary for the proper handling and use of agrochemicals, which in addition to preventing and mitigating environmental risks reduces production costs, which is of obvious interest to local farmers.

It is also important to involve agrochemical suppliers in training and programs for farmers so that a mutual understanding regarding good agrochemicals practices is established. As shown by Espejo *et al*., (2012), the promotion of accountability by providers of agrochemicals contributes to the rational use of agrochemicals. By monitoring the implementation of the recommended dose in the fertilization cycle, as proposed by the SEDER (2005), the effectiveness of fertilization and the need for actions to improve it can be evaluated. By applying the principle, "the polluter pays" or "the provider gets" and strict monetary fines for violating regulations regarding agrochemical use, will radically change the perception that water polluting can continue without fear of punishment.

Equally importance is the needs to upgrade agrochemical programs to farmers, as there are offered incentives to reduce agrochemical use; these incentives could include taxation rather than the subsidization of agrochemicals. Although from the environmental point of view, it would be reasonable, to tax the agrochemicals from the perspective of farmers would be unacceptable, but this would motivate them to change to organic fertilizers (Espejo *et al*., 2012; Ahodo & Svatonova, 2014).

In addition, the implementation of continue monitoring program in the PVE will generate awareness about the conditions leading to ecosystem eutrophication. It results can serve as a reference for decision-makers, because should be noted that the feasibility of the proposed alternatives and of others will change with time; thus, any plan must be dynamic and able to respond to changing interests, conditions in situ, and potential problems that may emerge regardless of whether a given alternative has been implemented consistently and has reached its goal like have been proposed by Cohen *et al*., (2011).

6. Conclusions

The assessment of current conditions using both the TRIX and the PSR framework in the PVE offered a fast and practical approach to identify the main drivers that exert pressure (changes) on the PVE and to devise possible solutions (Fig. 2). The main driver identified in this study was inadequate economic policies that promote the acquisition of agrochemicals, without appropriate training programs regarding their use and therefore maintain their improper application by farmers in the agricultural area adjacent to the PVE.

The inadequate fertilizer used in the agricultural activities generate residues, which exerting pressure through continental runoff representing a constant potential risk to eutrophication of the system. State indicator showed tendency serious spatial and temporal eutrophication during the study period. The response actions discussed herein are intended to improve and control agrochemicals use, by changing their mode of use. We do not claim that our proposed action is the one most suitable to the PVE, but it is certainly worthy of serious consideration and a preliminary test of its effectiveness.

In a first approximation, our comprehensive study of coastal systems provides: a) a baseline to interested users and local policy-makers for managing the PVE and b) a support to description of the environment regional system that identifies sources of pressure. The results of this study allow for focused and efficient management strategies to prevent human-induced negative effects on the environment, thus promoting the preservation and conservation of the PVE and its natural resources.

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