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Article

Estimation of the transport factor of the phosphorus index in climatology and climate change scenarios in Jalisco, Mexico

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Abstract:

The phosphorus index (PI) is a planning tool for identifying agricultural or livestock fields with the potential to contribute phosphorus to water bodies and distinguish those nutrient management practices that favor this process. The transport factor of the PI (PITF) implicitly includes non-controllable elements of the environment, such as rainfall, which contributes to agriculture uncertainty, and it is favored by the current climate change process. In Mexico, few studies have considered the PITF; therefore, the objective of this work was to apply the calculation methodology for the PITF and identify those areas that are vulnerable to the loss of phosphorus from land to water bodies in two climate change scenarios and three climates of Jalisco. The PI model of Gburek was applied in two representative routes of concentration of greenhouse gases (CPR): 4.5 and 8.5, with climatologies for 2030, 2050 and 2070, and for 2010 as baseline. The PITF was calculated using ARCGIS and the IDRISI GIS. The results showed levels of vulnerability to the loss of phosphorus ranging from very low to high at the baseline, while in RCP4.5 the PITF was rated very low to medium, and in the RCP8.5, very low to high. An element that stood out in the PITF was the high vulnerability of the plots located near a drainage network or water body.

Key words: Phosphorus loss, Environmental risk, Water quality.

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Introduction

The loss of phosphorus (P) from diffuse agricultural and livestock sources pollution is the main cause of eutrophication of freshwater in the agricultural regions in the developed countries(1,2) and in developing countries like Mexico(3,4). In some regions of Mexico, with high concentration of livestock, such as the Highlands of Jalisco(4), or with a high intensity of land use, such as the central region of Jalisco(5), the effects are visible in the superficial water bodies, due to the excessive growth of algae and aquatic weeds(6-10).

This problem has been addressed by using the Phosphorus Index (PI)(11). In the United States of America, it is used as a common tool for strategic planning of the use of nutrients(12). The PI allows to identify the potential for P contribution from agricultural fields or cattle ranchers to the water bodies and distinguish the management practices that reduce the losses of P and which contribute to preserve the quality of the soil and water(13). The PI has been evaluated and calibrated for the Highlands de Jalisco(9).

The PI address is characterized by two types of factors: 1) The transport factors of P which are soil erosion, the superficial runoff and the distance between the plots and a superficial drainage network or a surface water body (connectivity), and 2) the source of P, constituted by the phosphorus content in the soil, the frequency and method of application of chemical fertilizers, and the organic sources of P(11). The Phosphorus Index Transport Factors (PITF) take into account the transfer of dissolved and adsorbed P in runoff by the sediments that travel from the plot to the surface water bodies or to the superficial drainage network. The PITF implicitly include non-controllable elements of the environment, such as rain, which provides agriculture with a high uncertainty for production, but also with the mechanisms for the phosphorous loss. Each factor is classified into five levels of vulnerability according to its intensity, a rate that is subsequently multiplied by a weighting value. The PITF are the result of the multiplication of each weighted factor in order to obtain vulnerability levels of P loss with values ranging from 0 to 1. Finally, the value of the PITF is multiplied by the source of the P factor in order to obtain the PI(14,15).

From the point of view of climate change, several effects on ecosystems associated with climatological and hydrological processes with extreme events related to floods, large water runoff, periods of drought or drought and forest fires with direct implications for the PITF are expected(16,17,18). However, the effects of rain events of rain that cause soil erosion and cause severe land degradation and environmental deterioration are particular important(1,19,20). The Universal Soil Loss Equation (USLE) is used to estimate the water erosion in the PI(9). The rainfall erosivity factor (R) of the USLE determines the current potential strength of the soil erosion from rain(19,21) as an effect expected in the future due to the climate change(22).

For the above reasons, the changing precipitation patterns and the superficial runoff from the climate modification have caused a high degree of uncertainty for agriculture and stockbreeding in Jalisco, particularly because of the possibility of increases in the diffuse phosphorus pollution that these primary activities generate. Hence the need to evaluate the PITF under different climatologies and climate change scenarios in Jalisco. The aim of the present work was to apply the Phosphorous Index Transport Factor methodology and calculation and identify those areas that are vulnerable to the loss of phosphorus from the land to the water bodies in two climate change scenarios and three climatologies of Jalisco, Mexico.

Material and methods

This study was developed for the state of Jalisco, Mexico. This has a surface area of 1'487.832 ha, of which 3.26 % are forests, 64.82% are utilized for grazing by livestock, 21.84% have an agricultural use, and 10.08% have some other use. Of the agricultural area, 292,903 ha are sown with irrigation crops, and 1'343.167 ha, with rain-fed crops(23). The larger proportion of the surface with livestock grazing is an indicator of the importance of this activity in Jalisco, which is greatly supported by agriculture, also a primary activity that devotes to corn crops 72.1 % of the planted surface area.

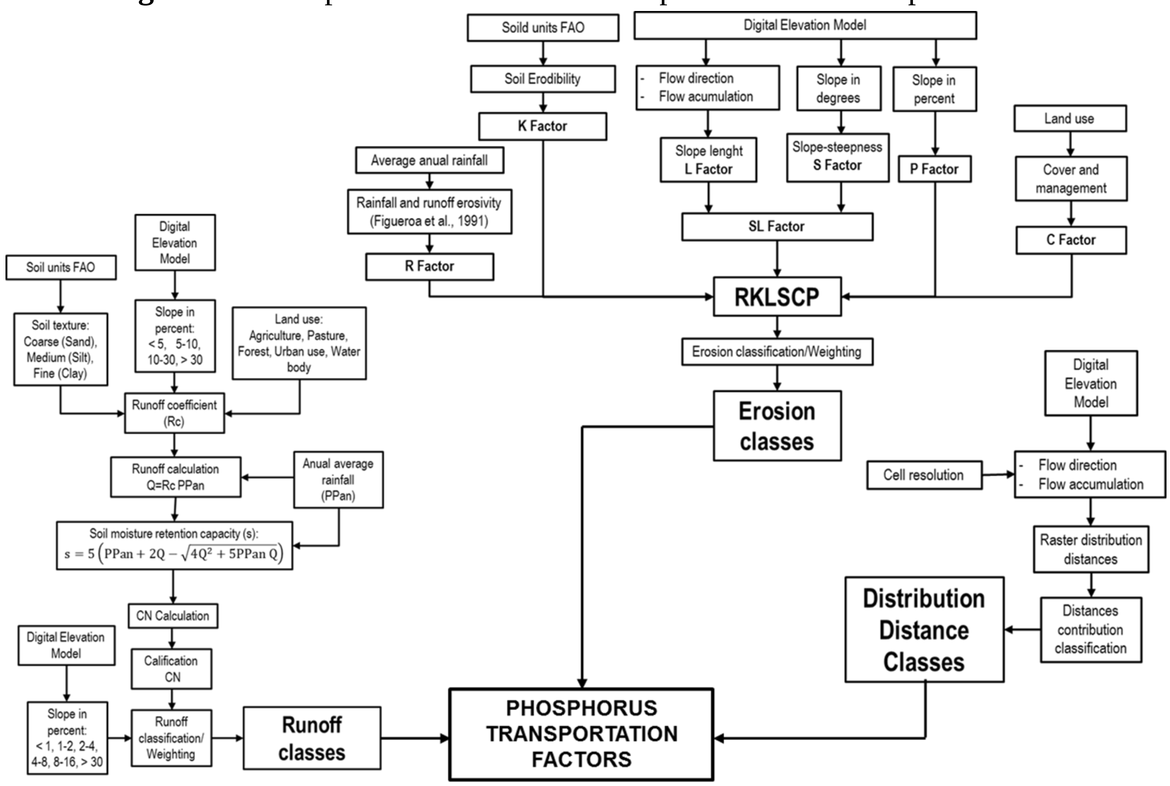
The average annual precipitation in Jalisco in the period from 1961 to 2010 was 897 mm, with a maximum of 1,934 mm and a minimum of 461 mm. In this regard, 82.9 % of the rain is concentrated in the months from June to September, with the highest amount in July.
The Phosphorus Index Transport Factor (PITF) components determined by Gburek *et al*.(11) were utilized. The estimated value of the PITF ranges between 0 and 1, with very low levels

of vulnerability when the PITF is less than 0.15, 0.15 to 0.3; medium, when 0.3 to 0.5; high, when 0.5 to 0.8, and very high when above 0.8[(24)].

Estimation of the Factors of Transport of the Phosphorus Index (PITF)

The conceptual model shown in Figure 1 summarizes the PITF process of evaluation for determining the levels of vulnerability to the phosphorus loss. This figure describes the process of estimating water erosion with the USLE constituted by the factors rainfall erosivity of the soil (R), soil erodibility (K), length and steepness of the slope (LS), soil cover (C), and soil management practices (P); the annual runoff is evaluated with the Curve Number, and the phosphorus contributing distance between a plot and the drainage network or surface water body. The value of vulnerability with the levels of PITF varies from 0.072 to 1.

Figure 1: Conceptual model with the Phosphorus Index Transport Factors



P Transport factors

These include water erosion, surface runoff, and the return period or the distance to the surface water bodies or the surface drainage network. Each of these components is described below.

Water erosion. Water erosion was estimated with the USLE, which was designed to calculate sheet erosion and erosion in furrows of plots(25); it consists in a multifactorial mathematical model that integrates six processes involved in erosion, as indicated by the expression(26):

$$E = R\,K\,L\,S\,C\,P$$

where:

E is the annual loss of soil in (t)·(ha·yr)$^{-1}$,
R is the soil erosivity factor from the rain in (MJ·mm)·(ha·h)$^{-1}$,
K is the soil erodibility factor (in t·ha^{-1})·(ha·h)·(MJ·mm)$^{-1}$,
L is the length of the slope (dimensionless),
S is the factor of the degree of the slope (dimensionless),
C is the factor of crop management (dimensionless),
P is the factor of mechanical practices for erosion control (dimensionless).

The factor R. Maps were generated with the average annual rainfall of the area of study for the 1961-2010, 2021-2040, 2041-2060 and 2061-2080 climate scenarios(27). The R factor was estimated for each climate change scenario with the equations presented by Figueroa *et al*(28), corresponding to regions IV, VII and X of the Mexican Republic, where the state of Jalisco is located. The following models were applied: (Region IV) $Y = 2.8959X + 0.002983X^2$ with R2=0.92, (Region VII) Y=-0.0334X+0.006661X2 with R2=0.98 and (Region X) $Y = 6.8938X + 0.000442X^2$ with R2=0.95, where Y is the value of the annual EI_{30} mm in MJ·mm·(ha·h)$^{-1}$, and X is the average annual precipitation in mm. For Tepatitlán de Morelos, Jalisco, located in region VII, Flores(29) estimated the rainfall erosivity of the soil for 2002 and 2003 with an annual precipitation of 1,074.2 and 1264.75 mm, respectively. This author used the equation of Figueroa *et al*(28) for this region VII and the model of Wischmeier and Smith(26) to estimate the soil erosivity. The model of the region VII has a tendency to increase soil erodibility when the rainfall augments; according to the precipitation data available for the years 2002 and 2003, the soil erosivity was 9,400 and 10,183 (MJ·mm)·(ha·h)$^{-1}$, respectively. With an average annual rainfall in the period of 1983 to 2017 of 890.2 mm, the soil erosivity estimated with the equation for region VII was 5,255 (MJ·mm)·(ha·h)$^{-1}$. This value is lower than those obtained for 2002 and 2003 because in these years the rainfall was above the average of the locality.

The K factor values were used as indicated by Figueroa *et al*(28) for each unit of the soil charts of INEGI(30) in the state of Jalisco, with the FAO soil classification.

The length of the land slope (L). The following function was used for calculating the length of the slope (L): $L = \left(\frac{\lambda}{22.13}\right)^m$, where λ is the length of the slope in m; *m* is an exponent incorporating the amendment proposed by Foster *et al*[31]: $m = \frac{\beta}{(1+\beta)}$, $\beta = \frac{\left(\frac{\text{sen}\,\theta}{0.0896}\right)}{3.0\,(\text{sen}\,\theta)^{0.8} + 0.56}$, where θ is the angle of the slope in degrees. The length of the slope for each pixel is adjusted with the following relationship: $\lambda = \frac{90}{\cos\theta}$ [32]. The average value of each pixel was 90 m.

The slope factor (S) was calculated using the following equations: $S = 10.8\ \text{sen}\theta + 0.03$, if S < 9%, $S = 16.8\ \text{sen}\theta - 0.50$, if S $\geq$ 9, where θ is the angle of the slope in degrees[32].

The crop cover and crop management factor (C). The use of the soil was derived from the vector maps of series IV of INEGI. As for the land with agricultural use, it was considered to be planted with corn, and therefore the factor applied for this use was C= 0,433; grasslands were assigned a value of C= 0.16. Flores *et al*[33] report other values of C for land use.

The mechanical practices factor (P). The values of the P-factor for erosion control in agricultural land recommended by Williams *et al*[34] were used. These are a ratio of the slope percentage to the maximum length of the contour ploughed furrows, and they were applied only to soils used for rain-fed agriculture. On land with other uses (livestock and forestry), the P value was equal to 1, because it was assumed that no mechanical practices are developed in them.

Surface runoff. The effect of surface runoff on the transport of phosphorus is evaluated based on the Curve Number (CN). The CN was calculated using the following procedure:

1) The parameter of moisture retention (s) was estimated using the average runoff volume and the amount of rain, with the following expression[35]: $s = 5\left(\text{MAP} + 2\text{Q} - \sqrt{4\text{Q}^2 + 5\text{MAPQ}}\right)$, where Q is the mean annual runoff sheet flow in mm, MAP is the mean annual precipitation rainfall (mm), and s is a parameter of soil moisture retention (mm). The average runoff volume was estimated by means of the following expression[36]: $\text{Q} = \text{c MAP}$, where Q is the mean annual runoff sheet flow in mm, c is the coefficient of surface runoff, and MAP is the mean annual precipitation in mm[1]. The value of c was determined according to the information about the use of the soil, the slope and soil texture in the study area, with the values indicated by Flores-López *et al*[37]. The MAP served as the basis for the calculation of R in the climatological scenarios studied in Jalisco. The use of the soil was obtained from the INEGI vector maps of series IV; the texture, from soil maps of series III by INEGI, and the slope, from the digital elevation model of INEGI.

2) The CN was determined based on the parameter s, using the following equation[38]: $\text{CN} = \frac{25{,}400}{s + 254}$. The estimated CN is combined with the value of the slope in order to determine the class of runoff.

Distance between a plot and the drainage network or surface water body. The distance from the site of origin to the point of connection with the drainage network or surface water body was determined using ARCGIS, with the commands *flow direction* and *flow accumulation*, applied to the digital elevation model of the INEGI for Jalisco.

Climate change scenarios

These were estimated using the median of 11 general circulation models (GCMs) of monthly precipitation generated by Ruiz-Corral *et al*[27], belonging to the CMIP5 (Intercomparison of Coupled Models Phase 5): BCC-CSM1-1, Ccsm4, GISS-E2-R, HadGEM2-AO, HadGEM2-IS, Ipsl-CM5A-LR, MIROC-ESM-CHEM, MIROC-ESM, MIROC5, MRI-CGCM3, NorESM1-M. The reduced and calibrated results for the rainfall of two representative routes of concentration of greenhouse gases (RCP) were utilized: RCP8.5 and RCP4.5, applied to three climatologies in the study area —2030, 2050 and 2070—, and at the rainfall baseline, the climatology for 1961 to 2010, identified in the analysis as 2010 and generated in previous study by Ruiz-Corral *et al*[27].

Analysis of the information

The PITF was estimated based on the annual rainfall of the climatologies for 2010, 2030, 2050 and 2070, according to the methodology described in raster images with a resolution of 3" for the routes of concentration of greenhouse gases (RCP) 4.5 and 8.5 in the state of Jalisco. The same land use was considered for the future scenarios. The changes in the FTPI were obtained with the subtraction on images of the 2010-2030, 2010-2050 and 2010-2070 periods, a calculation performed with IDRISI Selva. The rate of change in the PITF was evaluated with the linear regression slope between the surface of PITF strata in the years of evaluation for RCP 4.5 and 8.5.

Results and discussion

The Phosphorus Index Transport Factor (PITF) on the RCP4.5 scenario

Figures 2a, b, c and d show the PITF in Jalisco with RCP 4.5 in the climatologies for 2010, 2030, 2050 and 2070, respectively. The PITF for baseline climatology ranged from 0.072 to 0.54; in the climatology for 2030 and 2050, it was 0.072 to 0.491, and in the climatology for 2070, it changed from 0 to 0.486. Table 1 shows the area occupied by the levels of vulnerability to loss of P.

Figure 2: Phosphorus Index Transport Factor for the RCP 4.5 scenario in the climatologies for a) 2010, b) 2030, c) 2050, and d) 2070, in the lands of Jalisco

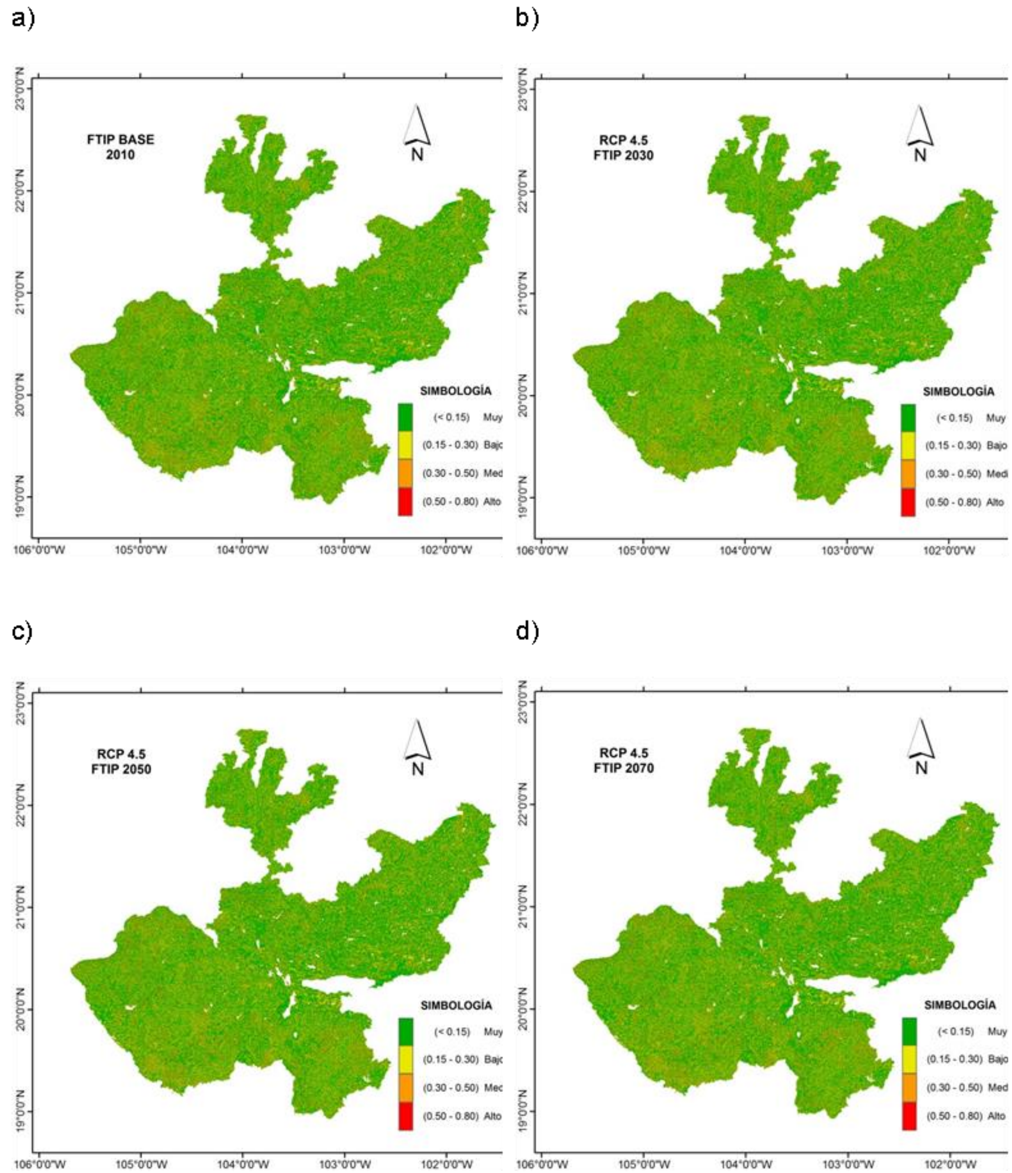


Table 1: Surface area occupied by each stratum with the Phosphorus Index Transport Factor (FTIP) in climate change scenario RCP4.5 with three climatologies

Level of vulnerability		**PITF per year of climatology (thousand ha)**			
Description	PITF value	2010	2030	2050	2070
Very low	< 0.15	4,682.6	4,676.9	4,675.2	4,674.1
Low	0.15 to.30	889.3	906.5	913.7	919.8
Medium	0.30 to.50	2,188.3	2,177.0	2,171.4	2,166.3
High	0.50 to.80	0.109	0	0	0

At the baseline, the level of vulnerability to the phosphorus loss in the land is rated very low to high risk, while in the climatologies for 2030, 2050 and 2070, the level of risk is rated very low to medium, and the high level disappears. The very low level of vulnerability due to the PITF (< 0.15) occupies the largest area, followed by the average (0.30 to 0.50) and low (0.15 to 0.30) levels. The tendency of each layer of the PITF of the RCP4.5 scenario in the climatologies studied with the occupied surface area is depicted with the slopes of linear regression models shown in Table 5. These slopes show that surfaces at the very low and medium vulnerability levels have a greater tendency to decrease per year, while at the low level, the tendency is to increase.

Given that the risk of transport of phosphorus is associated with the mobility generated by water, producing particle detachment due to the splashing of rain water and its contained kinetic energy, the flow of subsurface and surface water(39). This process is identified in the medium and high risk values of the RCP 4.5 scenario and the studied climatologies, associated mainly to plots with close proximity to the drainage networks or bodies of water. This result is consistent with other studies at a watershed scale(40,41,42). For this reason, the value of the vulnerability due to the current PITF with regard to the RCP 4.5 scenario in the assessed climatologies does not reflect major changes, as the precipitations estimated for future climatologies in Jalisco are not expected to increase significantly, and in some areas they are even expected to diminish, causing a decrease in the risk of PITF at very low and medium levels, adding this surface to the very low level of risk that tends to increase. This trend is similar to that estimated in the PITF for Lake Poyang in China(43) in the climate change scenarios RCP2.6, 4.5, and 8.5, even when including changes in the intensity of extreme events and their frequency.

Table 2 shows the comparison between the PITF baseline and that estimated for the climatologies for 2030, 2050 and 2070 in the RCP4.5 climate scenario. The PITF negative changes indicate a higher value of the index in the future scenario; on the other hand, when the change is positive, the index decreases, and the surface area of the future climatology diminishes. Within this context, the positive change in the PITF implies a reduction in the risk due to diffuse phosphorus pollution. The 2010-2030 period exhibits the largest surface with a negative change in the PITF; however, in the 2010-2050 and 2010-2070 periods, the situation is reversed, with higher PITF in 2010 than in 2050 and 2070. This implies a greater risk due to diffuse phosphorus pollution in the 2010-2030 period and a lower risk in the climatologies for 2010-2050 and 2010-2070 in Jalisco.

Table 2: Surface area with expected positive and negative changes in the Phosphorus Index Transport Factor (PITF) in the climatologies for 2030, 2050 and 2070, in relation to 2010, under the RCP4.5 scenario

Level of change in the PITF	**Surface area (thousand ha)**		
	2010 to 2030	**2010 to 2050**	**2010 to 2070**
Negative change (< 0)	7,492.4	11.5	18.5
Positive change (≥ 0)	267.9	7,748.7	7,741.8

The precipitation of the climatologies for 2030 to 2070 in the RCP4.5 climate change scenario expressed no significant increases in the annual rainfall utilized by the PI model. The most important change is expected in rainfall patterns with events of greater intensity[16], but the PITF model uses only the annual rainfall in the climatology of the baseline and future climatologies. With extreme events in the future precipitations, the effects will possibly be reflected in a greater hydric erosion and a larger amount of surface runoff; however, the current knowledge does not allow to identify these characteristics in climate prediction models[16,18].

Transportation Factor of the Phosphorus Index (PITF) in the RCP8.5 scenario

Figures 3 a, b, c and d show the distribution of the PITF for the lands of Jalisco in the climatologies for 2030, 2050 and 2070 in the RCP 8.5 scenarios. Based on these maps, strata were identified by level of vulnerability of the PITF shown in Table 3. The PITF for the baseline climatology and the climatologies for 2030, 2050 and 2070 ranged between 0.03 and 0.54, with generation of the strata with the PITF shown in Table 3. The strata with the greatest surface were very low (PITF < 0.15) and medium (PITF 0.30 - 0.50), with a tendency to reduce the transport factor of the future climatologies, while at the low and high levels, despite having a low surface area, they tended to increase it in the future climatologies.

Figure 3: Phosphorus Index Transport Factor for the RCP 8.5 scenario in the climatologies for a) 2010, b) 2030, c) 2050 and d) 2070

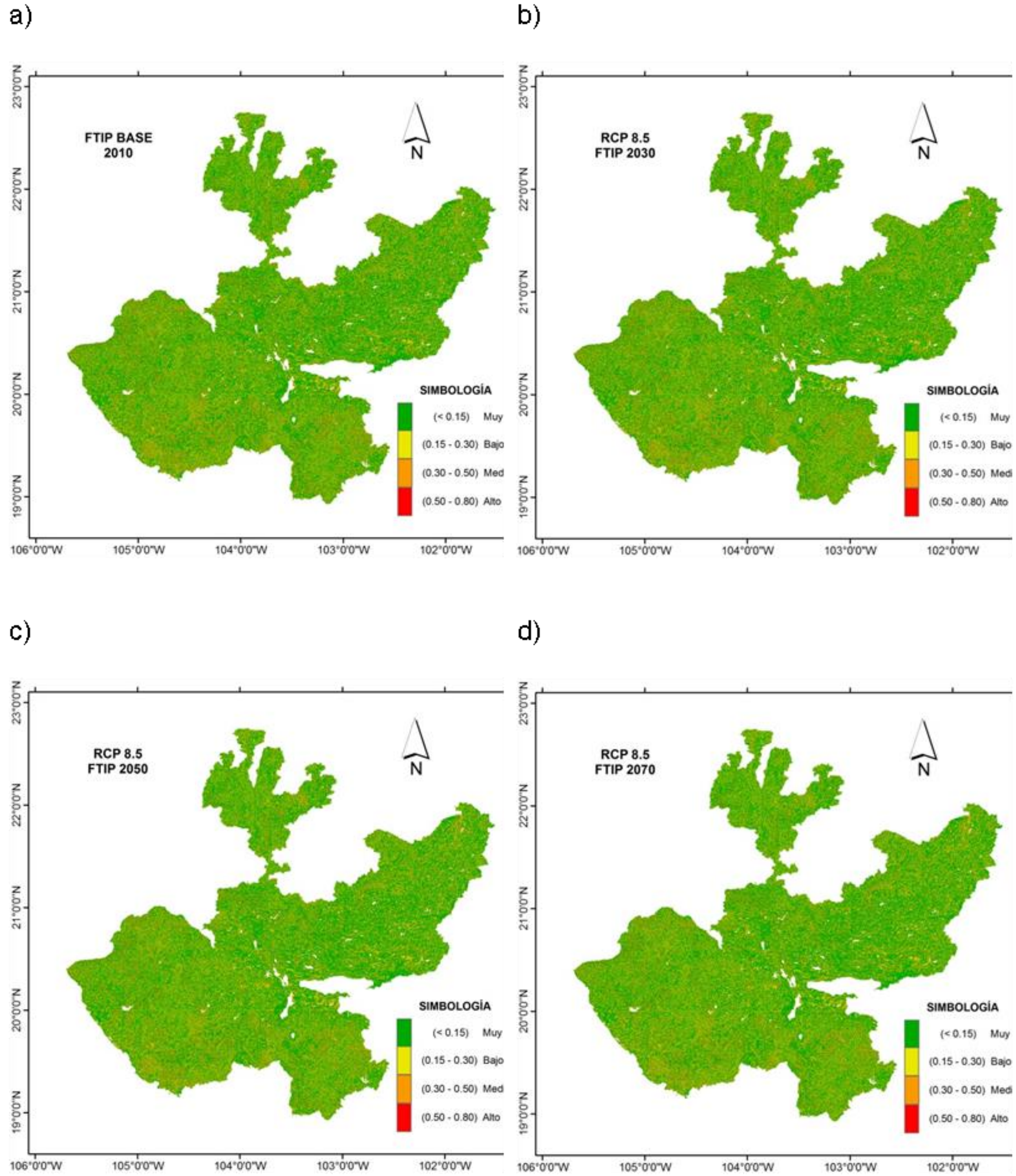


Table 3: Surface area by strata of Transport Factor of the Phosphorus Index (PITF) in the climatology of reference and three future climatologies in the RCP8.5 scenario

Level of vulnerability		**PITF per year of climatology (thousand ha)**			
Description	PITF value	2010	2030	2050	2070
Very low	< 0.15	4,682.6	4,675.1	4,673.9	4,672.0
Low	0.15 to.30	889.3	919.6	931.3	944.2
Medium	0.30 to.50	2,188.3	2,165.3	2,154.5	2,143.3
High	0.50 to.80	0.109	0.269	0.486	0.825

The comparison between the values of the PITF in the climatologies for 2010-2030, 2010-2050 and 2010-2070 is shown in Table 4, which summarizes the change in the surface areas associated with the various levels of the PITF in this scenario and in the studied climatologies. This comparison led to changes in the surface of PITF from less than zero to over 0.10, all of them considered to be very low vulnerability levels. In the level with a PITF below 0, the surface area was larger in 2030 with respect to 2010 by more than 54 thousand ha; however, in the 2010-2050 and 2010-2070 periods this level disappears.

Table 4: Estimated surface area due to the level change in the Phosphorus Index Transport Factor (PITF) in Jalisco, from 2010 to 2030, 2050 and 2070 under the RCP8.5 scenario

Level of change in PITF	**Change of climatology in the RCP 8.5 scenario (Thousand ha)**		
	2010 to 2030	**2010 to 2050**	**2010 to 2070**
< 0	54.6	0	0
0 - 0.05	7,703.5	5,242.2	5,257.6
0.05 - 0.10	0.283	448.8	440.7
> 0.10	1.8	2,069.3	2,062.0

The PITF level of 0 to 0.05 exhibited the largest surface area in the 2010-2030 period, with a significant reduction on the surface for the 2010-2050 and 2010-2070 periods. In the levels of 0.05-0.10 and above 0.10 of the PITF, the surface area increases, particularly in the PITF level above 0.10 in the 2010-2050 and 2010-2070 periods. These changes are attributed to the expected increase in the rainfall, which leads to a greater phosphorus loss in agricultural lands, similarly to those reported for the RCP 8.5 of Lake Poyang in China[(43)].

The exchange rates observed in the surfaces of each level of vulnerability of the PITF and study climatologies of study are shown in Table 5. Although the response observed in the PITF is very low, it is the product of the minimum changes in rainfall of the climatologies for 2030, 2050 and 2070 in the RCP 8.5 scenario; it is also a reflection of the small increase in annual rainfall used by the PI model. For this reason, it is possible that the PITF is being underestimated, as a change in rainfall patterns is expected with events of greater intensity[16,44] that the PITF model does not consider in its components of soil erosion and runoff. In this regard, on September 7, 2003, Flores[29] reported a rainfall event of 150.05 mm in 24 h with its maximum intensity in 30 min of 68.5 mm/h in Tepatitlán, Jalisco. A possible solution is to calculate the water erosion and surface runoff at a monthly or even daily scale, as indicated in the PITF[11], for use with future climate information[27].

Table 5: Linear regression models between the surface areas occupied by each level of vulnerability of the PITF with the year of the climatology

Level of vulnerability		**RCP 4.5 scenario**		**RCP 8.5 scenario**	
Description	**PITF value**	**Model**	**R^2**	**Model**	**R^2**
Very Low	< 0.15	y = -0.136x + 4953.8	0.86	y = -0.165x + 5012.0	0.84
Low	0.15 to.30	y = 0.495x - 101.6	0.94	y = 0.882x - 877.7	0.94
Medium	0.30 to.50	y = -0.357x + 2904.8	0.96	y = -0.729x + 3649.8	0.96
High	0.50 to.80			y = 0.012x - 23.7	0.97

The models to estimate soil erosivity due to rainfall with a monthly scale are achieving good results in recent studies[45,46] and are generating new mathematical functions for monthly and daily time scales[47], which it is important for Mexico to develop, given the predicted expectations of climate change[16], and regarding which there is little progress to date. Although the current models for the calculation of the rainfall soil erosivity[28] show the tendency to increase the aggressiveness of the rains with the increase in annual precipitation, it is advisable to evaluate this index under broader conditions than those referred to in the present study. In addition, however, there is an urgent need to obtain future rainfall estimates at a daily scale, because these events may be underestimated when using a monthly or annual scale[48,49].

Although the surfaces with the PITF were similar in the RCP4.5 and RCP8.5 scenarios in the studied climatologies, the risk of diffuse phosphorus pollution persists with a high level of risk in areas near surface water bodies and drainage networks, which should be addressed, in both the current and future scenarios, by designing good agricultural practices to restrain the diffuse phosphorus pollution in these areas.

Conclusions and implications

The results of this study demonstrate the feasibility of applying the PITF to the conditions of Jalisco with the baseline climatology for 2010 and climate change scenarios with proposed future climatologies. With results obtained, it was possible to identify tendencies in the route of the concentration of greenhouse gases under the RCP 4.5 and RCP 8.5 scenarios in Jalisco. For the RCP4.5 scenario, the negative change in the PITF implied an increase in the P index, which entails a higher risk due to diffuse phosphorus pollution; however, a positive change brings about a reduction of the risk of diffuse phosphorus pollution. In contrast to the RCP8.5 the largest surface area was identified with a very low and medium vulnerability, with a tendency to reduce the PITF, whereas in the strata with low and high levels of vulnerability, the tendency was to increase it. In general, the PITF in scenarios RCP 4.5 and RCP 8.5 of the assessed climatologies do not reflect major changes in the value of vulnerability due to PITF, as no significant increases are expected in the amounts of rainfall estimated for Jalisco in the future climatologies. Because the PITF model is calculated based on the annual precipitation, this time scale does not consider rainfall patterns with high intensity events or the heavier precipitations expected in the climate change scenarios; therefore, it is advisable to develop functions to estimate the rainfall soil erosivity and the runoff at a monthly or even daily scale when calculating the PITF, the surface runoff and the hydric erosion. In the studied RCP scenarios and climatologies, areas with proximity to water bodies and surface drainage network represent a greater vulnerability to the PITF.

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