EXPOSURE OF RAINBOW TROUT FARMING TERRITORY AND LIVELIHOODS TO POTENTIAL EFFECTS OF GLOBAL WARMING IN VERACRUZ, MEXICO †

[LA EXPOSICIÓN DEL TERRITORIO Y MEDIOS DE VIDA DE LA TRUTICULTURA A LOS EFECTOS POTENCIALES DEL CALENTAMIENTO GLOBAL EN VERACRUZ, MÉXICO]

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SUMMARY

Background. As this century passes, the effects of climate change are being felt in various productive activities, including aquaculture. In particular, trout farming in tropical countries may be at some level of vulnerability to the warming of the water in which it is farmed. **Objective**. To quantify the degree of exposure, as a component of vulnerability, of trout farming to the possible occurrence of the global warming forecasted effects. **Methodology**. A spatio-temporal model was constructed to assess one aspect of the vulnerability of finfish aquaculture, by measuring the exposure of the territory and livelihoods of rainbow trout farming to the potential global warming effects in the Neotropical, coastal state of Veracruz, Mexico. Air temperature data from a 100-plus year period, averaged and raster-mapped was used as the baseline, transformed to estimated water temperature, and spatially processed to find the geographic areas suited to grow rainbow trout, or Potential Trout Farming Territory (PTFT). Using the same procedure, optimal water temperature areas were outlined with raster maps from a climate change scenario for three forecasted horizons —short, medium, and long terms—. With these data, the potential loss of territory and livelihoods for trout producers in the area was quantified. **Results**. The PTFT would undergo a surface reduction of 21.06 km^{2}year^{1}, and at the same time will displace to higher altitudes, given the onset of the chosen climate change scenario RCP 8.5 Wm^{-2}. By the end of the century, Veracruz would have lost 1,851 km^{2}, about 37.6 % of the original PTFT. When this reduction was contrasted in the model with the real trout farming territory (TFT), defined by the actual location of trout farms, a number of farms were being left out of the PTFT on the sequential horizons, at a rate of 0.927 farms year^{-1}. This would mean a 58% exposition of the livelihoods in the long term. **Implications**. The exposure caused by the reduction of territory and the loss of livelihoods would further affect certain groups of producers, who are exposed a priori. These producers are those who live in poverty below the national average, which significantly aggravates their condition. **Conclusion**. The results show that global warming potential effects may negatively affect the territory and livelihoods of tens of families, some of which were found to be already in a social and economic degree of vulnerability. This should bring up attention to the implementation of urgent vulnerability-reduction measures.

Key words: Aquaculture; fish farming; poverty; climate change; vulnerability; GIS modeling.

RESUMEN

Antecedentes. A medida que avanza el presente siglo, los efectos del cambio climático están afectando diversas actividades productivas, incluida la acuicultura. En particular, el cultivo de trucha en países tropicales puede tener cierto nivel de vulnerabilidad al calentamiento del agua en la que se cultiva. **Objetivo**. Cuantificar el grado de exposición, como componente de vulnerabilidad, del cultivo de trucha a la posible ocurrencia de los efectos previstos del calentamiento global. **Metodología**. Se construyó un modelo espacio-temporal para evaluar un aspecto de la vulnerabilidad de la acuicultura de peces, cuantificando la exposición del territorio y los medios de vida del cultivo de trucha arco iris a los posibles efectos del calentamiento global en el estado neotropical costero de Veracruz, México.

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Los datos de temperatura del aire de un período de más de 100 años, promediados y mapeados en forma de ráster se utilizaron como línea de base, se transformaron a temperatura estimada del agua y se procesaron espacialmente para encontrar las áreas geográficas adecuadas para el cultivo de trucha arco iris, o Territorio Potencial de Cultivo de Trucha (TPCT). Utilizando el mismo procedimiento, se delinearon áreas óptimas de temperatura del agua con mapas ráster de un escenario de cambio climático para tres horizontes pronosticados —corto, mediano y largo plazo—. Con estos datos se cuantificó la pérdida potencial de territorio y de medios de vida para los productores de trucha en el área. **Resultados.** El TPCT sufriría una reducción de superficie de 21.06 km^{2}año^{-1}, y al mismo tiempo se desplazaría a mayores altitudes, dada la ocurrencia del escenario de cambio climático elegido RCP 8.5 Wm^{-2}. Al finalizar el siglo, Veracruz habría perdido 1,851 km^2, alrededor del 37.6 % del TPCT original. Cuando se contrastó esta reducción en el modelo con el territorio real de cultivo de truchas (TCT), definido por la ubicación real de las granjas de truchas, varias granjas quedaron fuera del TPCT en los horizontes secuenciales, a una tasa de 0.927 granjas año^{-1}. Esto supondría un 58% de la exposición de los medios de vida a largo plazo. **Implicaciones.** La exposición causada por la reducción de territorio y la pérdida de medios de vida afectarían aún más a ciertos grupos de productores, los cuales se encuentran expuestos a priori. Estos productores son los que viven en situación de pobreza por debajo de la media nacional, lo cual agrava su condición significativamente. **Conclusión**. Los resultados indican que los posibles efectos del calentamiento global pueden afectar negativamente el territorio y los medios de vida de decenas de familias, algunas de las cuales ya se encuentran en un grado de vulnerabilidad social y económica. Esto debe llamar la atención sobre la implementación de medidas urgentes para reducir la vulnerabilidad.

Palabras clave: Acuacultura; cultivo de peces; pobreza; cambio climático; vulnerabilidad; modelación en SIG.

INTRODUCTION

Trout farming

In Mexico, aquaculture is a food production activity still in the development stage, compared with other economies, mainly Asian countries (Zetina Córdoba *et al*., 2006; Betanzo-Torres *et al*., 2020). Even so, it is one of the fastest-growing food-production activities (Sosa-Villalobos *et al*., 2016), being its growth rate higher than the World´s mean (Betanzo-Torres *et al*., 2021). The country is considered of great aquaculture potential, given its wide climate range, diversity of natural resources, and the potential of indigenous species available (Avilés-Quevedo and Vázquez-Hurtado, 2006; Cortés *et al*., 2021). Freshwater species rearing is the activity with the greater development in Mexico, with more than 80% of the operations being low-tech and low-yield, and where exotic species are preferred over autochthonous species (Norzagaray *et al*., 2012). According to official statistics (CONAPESCA, 2024), rainbow trout (*Oncorhynchus mykiss* Walbaum, 1792) is the third freshwater fish species in harvested volume, and the second in production value. Even when its southernmost natural range reaches Northwestern Mexico (Gall and Crandell, 1992; Hendrickson *et al*., 2002), it is considered an exotic species in the rest of the country (Espinosa-Pérez and Ramírez, 2015), being its adaptation process almost 60 years old at present (Hershberger, 1992).

Trout's commercial production farms spread irregularly over inland Mexico, from the USA border, down to the Guatemala border (Ortega and Valladares, 2017). Much of the trout farms are family-operated, and the profile of the average trout farmer is that of a present or former farmland and/or livestock owner growing fish as a complementary activity, mainly in high-altitude, rural, marginalized and poor areas (García-Mondragón *et al*., 2013; 2021). Given this, the need to refocus trout farming in Mexico, from a developmental and subsistence activity to one of profitable production, has been stressed (Ortega and Valladares, 2017 *op. cit*.). As for now, rainbow trout stands only as a contributor to the household livelihood for farmers, not in terms of direct nutrition or health as sometimes is referred (Little *et al*., 2010), but as an income complement because of its high market price. Figure 1 shows trout production in Mexico from 2005 to 2022.

Aquaculture and Global Warming

There are many factors, both biotic and abiotic, that define the distribution of fish natural populations (Planque *et al.*, 2011), the temperature being one of the main (Golovanov, 2013). This variable becomes of major importance in culture situations, where one of the main concerns of the farmer is to offer the best conditions for good growth, high conversion efficiency, a disease-free environment, and animal welfare (Segner *et al*., 2019). For all this, the definition of geographic regions in which they will have a temperature range suited for better growth conditions should be one of the first things to consider in site selection (Falconer *et al*., 2020*a*).

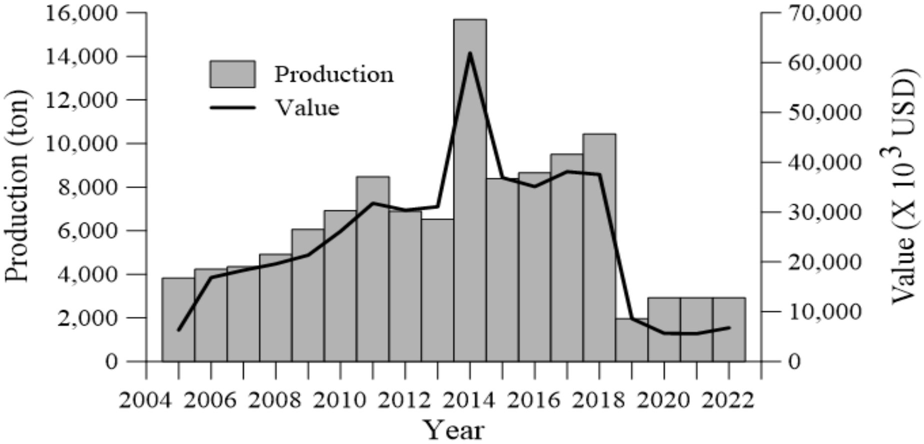

Figure 1. Mexico's National rainbow trout production in years 2005-2022. Source: SADER (2024).

There's a wide consensus among academics in that, even when there is a debate about the certainty of some of the projected changes and their causes, the warming of the global climate systems, also known as Global Warming (GW), is unequivocal (Santos *et al*., 2021; Van der Linden, 2021). GW is shifting climate patterns at local, regional, and global scales, an effect called Climate Change (CC), and its study is termed Climate Change Science (King, 2004). The effects on climate regimes are assorted and vary among geographical zones, but overall they include a rise in temperature, alteration of rain patterns, and changes in the location, frequency, intensity, and spanning of drought and storm seasons (IPCC, 2023). This shift and its effects are now evident in the climate regime in the state of Veracruz, México (Vázquez, Brunet and Jones, 2008).

An increase in global temperature would very likely locally affect both, the aquatic ecosystems (Prakash, 2021) and the fish individually (Harrod *et al*., 2019), by altering physiological functions such as thermal tolerance, growth, metabolism, food intake, reproductive success, and its capability to maintain internal homeostasis (Ficke, Myrick and Hansen, 2007; Reid, Filgueira and Garber, 2015). In the occurrence of one of the possible CC scenarios, the onset of complex modifications in wild fish populations, driven by water warming through both direct and indirect effects in its metabolism, biotic interactions, and geographic distribution would be expected (Keleher and Rahel, 1996; Jeppesen *et al*., 2010; Xia *et al.*, 2017). When in the wild, fish may look for conditions that are more suitable by swimming towards colder waters if necessary (Ebersole, Liss and Frissell, 2001; Jeppesen *et al*., 2010; Xia *et al*., 2017 *op. cit*.). Thus, there is the possibility of an alteration in the spatiotemporal distribution of fish species in case of thermal stress, contributing to population declines and even local extinctions (Jarić *et al*., 2018). In culture conditions, there is no such a possibility, and because of this, the projected warming effects would imply direct impacts on the production through modifications of the metabolic rate, which can affect the yield and ultimately the viability of the operations (Li *et al*., 2016). Dabbadie *et al*. (2018) present a thorough review of the effects of CC on aquaculture.

The reported negative effects that rainbow trout farming operations undergo, because of temperature rising situations, are mainly the onset of parasitic diseases (Richter and Kolmes, 2005; Okamura *et al*., 2011; Islam, Kunzmann and Slater, 2022) and hypoxia (Abdel-Tawwab *et al*., 2019; Zhou *et al*., 2019).

Exposure to Global Warming

The measure of how any perturbation, such as GW, can affect something or someone is a function of its vulnerability. It is defined as the susceptibility to be harmed and is influenced by the build-up or erosion of the elements of social-ecological resilience (Adger, 2006). As it arises from the complex interaction between socio-economic, institutional, and environmental systems, vulnerability measurement is complex (Krishnamurthy, Lewis and Choularton, 2014) and multi-dimensional (Huq *et al*., 2020). The concept of vulnerability is a frequent-use, but vague and under-theorized (Racine and Bracken-Roche, 2019) and can be analyzed using many disciplines like economics, sociology/anthropology, disaster management, environmental science, and health/nutrition (Alwang, Siegel and Jorgensen, 2001). However, even when having different meanings among disciplines, when used inside the combined frameworks of CC, livelihoods, and territory, the vulnerability concept includes an exposure component (Barange *et al*., 2018).

A cycling relationship between poverty and CC has been established, stressing how poverty makes people vulnerable to CC, and how it can increase poverty itself and even affect poverty alleviation efforts, arguing that the poor are already vulnerable —and thus exposed— to CC (Leichenko and Silva, 2014). Development processes in Latin America can be explained in part through the vicious circle of marginalization, poverty, and under-development (Camberos and Bracamontes, 2007). Poverty is an objective concept, evaluated through objective measuring indexes (Atkinson, 2019), which use a poverty line as a base for calculation. A poverty line can be defined as the money needed to achieve the minimum level of "well-being" that is required to not be deemed "poor" (Ravallion and Lokshin, 2006). However, being poverty a multifactorial-natured parameter, it can be best measured by a multifactorial index, such as the Human Development Index or HDI (Little *et al*., 2012). Margination, another way to measure poverty, is defined as a situation in which a group of individuals and families that live inside a locality or municipality, either urban or rural, are not satisfying the basic needs, following criteria determined by well-recognized institutions such as the United Nations Development Programme (UNDP) and the World Bank (Camberos and Bracamontes, 2007 *op. cit*.). It is measured with the Margination Index (MI), which is derived from the ponderation of nine socioeconomic variables (CONAPO, 2021). In this context, exposure to GW effects is related to the availability of the existing infrastructure and institutional framework, including government-sponsored social safety programs (Kalikoski *et al*., 2019), all evaluated by changes in HDI and/or MI.

Territory needs to be understood in terms of its relation to space (Elden, 2010), and territory's space can be lost to CC (Jain, 2014). Moine´s definition of territory (Moine, 2006), is a geographically contiguous area in which human activities occur that is managed by local stakeholders, whose representations —individual, ideological, and societal— of the territory influence their decisions. Under that concept, it is fair to assume that losses happen when one of the variables that define territory is drastically modified by a given process. Thus, being temperature one of the factors defining trout-farming territory, any deleterious modification to temperature, such as the changes expected by GW, will cause a net loss of the territory's area. This is because some stakeholders may lose the temperature conditions required to grow trout, and in terms of Climate Change science, they would become exposed, and their exposure degree can be measured as a function of their territory loss rate.

Geographic information systems (GIS) can be used as a tool for territory definition and planning (Nitschelm *et al*., 2016; de Lima Medeiros, Terra and Passador, 2020), even when it´s clear that territory should be defined by more than geographic criteria (Agnew, 2020). The use of GIS tools for the definition of proper areas to set aquaculture facilities, i.e. fish-farming territory, has solid scientific background (Gimpel *et al*., 2018; Falconer *et al*., 2020*b*; Shunmugapriya *et al*., 2021), and is well documented on literature, mainly for marine and brackish water species and environments. Works developed on continental waters were set mainly in the coastal zone for selecting sites for the construction of shrimp (Giap, Yi and Yakupitiyage, 2005; Rajitha, Mukherjee and Chandran, 2007) and prawn (Hossain and Das, 2010; Abdullah *et al*., 2021) ponds, while in strictly freshwater environments, scientific research has been comparatively lower. In recent years, tough, several works on GIS-aided rainbow trout farm site selection have been published (Baruah *et al*., 2020; Calle Yunis *et al*., 2020; Aghmashhadi *et al*., 2022; Ganie *et al*., 2023).

Aim and scope of the study

Given the above issues presented, it was considered very useful to develop a methodology to draw the limits of the rainbow trout-farming territory, to estimate its probable change in size and/or location as a function of GW projections, and to evaluate the effect of this change on the livelihoods of the stakeholders by the possible onset of a specific Climate Change Scenario (CCS). This work considered trout farming as a complex system of food production, which can be analyzed inside the framework of territoriality, and as the livelihood of hundreds of families, most of them already vulnerable to CC due to poverty. The aim of this work was, first, to model the geographic distribution of estimated water temperature to determine the present size and location of the areas suitable for the culture of rainbow trout, —herein designed as Potential Trout Farming Territory or PTFT— in Veracruz, México in the grow-out stage, as a baseline. Once completed, a second goal was to fit into the model the estimated water temperature data for short, middle, and long-term projections of a well-known, widely-used CCS, and thus simulate the probable change of size and location of PTFT in time. The results were used to assess the exposure degree of the system to possible global warming effects, a situation that was considered highly probable, given the geographic location of the area of study and the temperature requirements of the trout. Issues of margination and human development of the trout farmers that are prone to be affected were contrasted with the results and analyzed inside the Climate Change science framework.

MATERIALS AND METHODS

Study area

The study area was restricted to the territory of the State of Veracruz, Mexico. Veracruz is in the southernmost part of North America (GEV / INEGI, 2017), having a total surface area of 78,815 square kilometers (GEV, 2023). It is located at the northern boundary of the Neotropical, and the southern limit of the Nearctic Biogeographic Regions (Espinosa *et al*., 2008). Veracruz has a wide and diverse set of climate zones, for the terrain is very variable, with altitudes ranging from zero to more than 5,700 meters above sea level; its eastern limit is to the Bay of Campeche, in the southwest of the Gulf of Mexico, and to the west, its border is just beyond the leeward limit of the Sierra Madre Oriental mountain range (Soto Esparza and Geisser Kientz, 2011). Figure 2 shows the area of study.

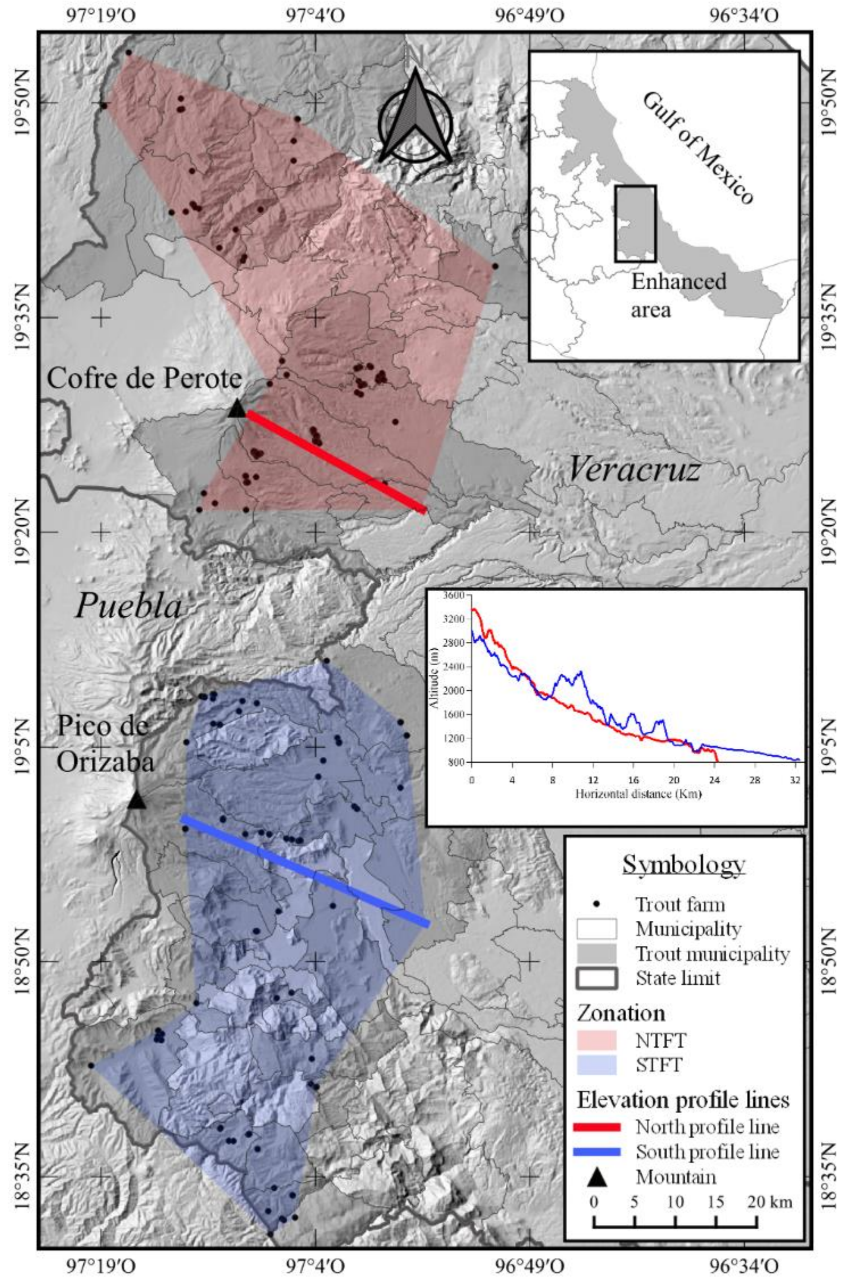

Figure 2. Map of the area of study in the mountain range of central Veracruz State, Mexico. The study area is the trout-farming territory (TFT). The inset plot represents topographic profiles drawn from lines red and blue on the map, respectively. With data from Reta-Mendiola and Asiain-Hoyos (2010).

Territory and livelihoods

The object under study was defined as the Trout Farming Territory (TFT), delimited by a convex-hull GIS procedure on a trout-farm dot GIS-layer shapefile generated from worksheet data in Figure 2. Trout farm locations and overall information were obtained from Reta Mendiola and Asiain Hoyos (2010). The system was integrated by 179 trout farms, producing a total average of 1,670 T yr^{-1} of trout of 350 g median weight, on a total water surface of 50 ha, and a total farm surface of 1,170 ha, generating 427 direct jobs. The total area of the TFT is 4,300 km^2, split into two zones, north (TFTN) and south (TFTS). The total surface of the 33 municipalities occupied by trout farms in the area of study is 4,200 km^2. Trout are raised mainly on concrete ponds and/or raceways, water being sourced from surface-water courses, mainly creeks and small rivers, neither pre- nor post-treated. Acosta-Jimeno *et al*. (2018) presented a typology of the producers in Veracruz's TFT. Farm location, trout-producing municipalities, and TFT zonation were also presented in Figure 2.

Spatio-temporal model building

The model was constructed using common GIS tools, such as raster calculator and raster statistics. The averaged values of mean air temperature were obtained as raster map files, published in the Digital Climatic Atlas of Mexico by the Atmosphere Sciences Centre's Informatics Unit for the Environmental and Atmospheric Sciences (UNIATMOS, 2024) of the National Autonomous University of México (Fernández Eguiarte, Romero Centeno and Zavala Hidalgo, 2014). The aforementioned authors explain that those raster files were constructed by spatially interpolating daily mean temperature data from weather stations all over the country from 1902 to 2011, averaged by month, and uploaded as TIFF-format, georeferenced (GEOTIFF) raster maps to the UNIATMOS website. Those maps, clipped to the shapefile of the boundaries of the State of Veracruz, were used as the baseline scenario for the model built. All GIS products were set at the World Geodetic System of 1984 (Slater and Malys, 1998).

The projections of the mean air temperature on a climate change scenario (CCS) were also obtained from the UNIATMOS website (Fernández Eguiarte *et al*., 2014). The GEOTIFF raster maps downloaded represented projections of mean air temperature derived from the global circulation model coded CNRM-CM5.1, corresponding to phase 5 of the Coupled Model Inter-comparison Project from the National Centre for Meteorological Research—Atmospheric Meteorological Research Group and the European Center for Research and Advanced Formation in France. Voldoire and coworkers (2013), describe the process of construction and the underlying assumptions of the model. Those projections were also downloaded from UNIATMOS as monthly averaged mean air temperature raster maps for three projected time-horizons: near —years 2015 to 2039—, middle —years 2046 to 2069—, and far —years 2075 to 2099—.

The raster files selected for this study have a spatial resolution of 30 X 30 arc-seconds, so each pixel covers approximately 0.86 km^2 of the ground, at the central part of the state of Veracruz. The CCS, coded RCP8.5 (Riahi *et al*., 2011), was chosen because of its severe radiative forcing, with a Representative Concentration Pathway (RCP) of 8.5 Wm^{-2}, often referred to as the "worst-case scenario" (Schneider, 2009), in order to assess the model under extreme CC stress. Moss *et al*. (2010) explain details concerning CCS, radiative forcing values, and its use in the definition of those scenarios through the RCP.

Water temperature —the variable that matters in aquaculture, rather than air temperature— was estimated indirectly from the raster data, as it has been proven that the air temperature of a given zone is closely correlated to the water temperature in an aquacultural waterbody (Kutty, 1987; Szyper, 2002). Erickson and Stefan (2000) developed a linear equation that estimates stream temperature from monthly air temperature averages. The relationship is expressed as:

$$\boldsymbol{T}_w = 3.1 + 0.74\boldsymbol{T}_a \qquad \text{(equation 1)}$$

where $\boldsymbol{T}_w$ is the estimated water temperature and $\boldsymbol{T}_a$ is a value of mean air temperature averaged by month.

Given all the above, equation 1 was applied to the four series of 12 monthly raster maps, those of the baseline, and those of each of the three —short, medium, and long-term projected time-horizons— mean air temperature maps of the CCS selected using a raster calculator.

Species and its characteristics

The species selected for this study was the rainbow trout (*Oncorhynchus mykiss* Walbaum, 1792). The optimal water temperature range for trout growth, from fingerling to harvest, to be considered as an input for the model is discussed elsewhere (Acosta-Jimeno, Devezé-Murillo and Méndez-Guerrero, 2018). Thus, the monthly average temperature raster maps obtained from the linear transformation for the Baseline and the three Projected Time-Horizons (BL&PTH) were reclassified, assigning a value of 1 to all the pixels whose $\boldsymbol{T}_w$ scored into the selected temperature range, and a value of 0 to those pixels out of range.

The time required to grow a rainbow trout to commercial size was defined using both, the preferred size for commercialization in Mexico, which is 350 grams (Ávalos Gutiérrez, Cibrián Ramos and Ávalos Calderón, 2012), along with the growth data published by Davidson *et al.* (2014). The growth data were obtained from the published plot using digitizing software and then fed into a data curve-fitting software. Thus, the chosen grow-out time for rainbow trout was fixed to eight months.

Simulations

With the above information, and as the last step of the process, the 12 monthly-reclassified raster maps for BL&PTH were added —algebraic sum— within their time horizon. The sum, however, was conditional, so the resultant map was assigned the value of 1 (one) only for those pixels that were contiguous by month from 8 months on, notwithstanding the position of those months in the year, and 0 (zero) if the pixels were only contiguous only for 7 or fewer months. It means that the group of at least 8 contiguous months with the optimal temperature could be intra-annually or inter-annually contiguous. Figure 3 shows graphically the temporal-contiguity relationship among pixels. In this figure, red pixels represent optimal water temperature year-round, so they are being represented in the output (FINAL) raster as a 1, while green pixels and blue pixels represent intra-annual and inter-annual contiguity, respectively, of at least 8 months of optimal water quality, also represented on the output raster with a 1. Purple pixels sum 8 months but without contiguity, and black pixels are less than 8 along the year, thus both are represented in the final raster with zeroes (blank pixels). All the raster map statistics, every map algebra operation, and the final mapping were performed using open-source GIS software.

Trout farm data were fed to the spatiotemporal model simulation output GIS as a point vector layer, to quantitatively assess if and when those farms would be exposed to possible changes in the water temperature ranges in that area for all temporal horizons (BL&PTH). Linear regression analysis was performed on both, the area-change values, and the exposed farm values to estimate the rate of loss of the suitable area and the number of farms to be exposed in time. Open-source software was used for all statistical analyses.

Data on the technological level, margination, and human development

Technological Level Index (TLI) was included in the farm data from Reta Mendiola and Asiain Hoyos (2010 *op. cit.*). GIS layers in shapefile format (ESRI, 1998) the Margination Index (MI) and Human Development Index (HDI) were obtained from Mexican Government sources: the National Population Commission and the National Commission for the Knowledge and Use of Biodiversity. Both TLI and MI data were obtained as comma-separated value files (CSV) and loaded to the project´s GIS to get a point-type shapefile. HDI data was downloaded directly as a polygon-type shapefile layer. The shapefiles were spatially processed to assign values of both socio-economical indexes as attributes to each farm, either directly —for TLI—, or through GIS spatial-join algorithm based on contiguity —for the point spatial-layer of MI— and inclusion —for the polygon spatial-layer of HDI—. The indexes were used to assess the socio-economic environment of the farms and their surroundings, which were exposed to possible global warming effects in the simulation's output and evaluate its potential aggravating effect on their exposition.

RESULTS AND DISCUSSION

The estimated water temperature

All the raster maps of $\boldsymbol{T}_{\mathrm{w}}$ resulted in a temperature range lower than the one in the original average mean air temperature maps, the average difference in temperature being –2.7 °C. The use of data of air temperature for the estimation of water temperature is a long-pursued task, which has had several approaches other than the linear fit. Kapetsky and Nath (1997) used a model for the estimation of fishpond water temperature, which required the input of several constants inherent to water, like density and heat capacity among others, but also required variables only available from site-specific data gathering research, such as the interfacial heat transfer. Mohseni, *et al.* (1999), with a general circulation model —different than the one used in the present work—, developed a four-parameter nonlinear model to predict changes in water temperature in a CCS, being one of those parameters the upper bound stream temperature, thus rendering the fit useless for the present work's modeling task. Morrill *et al.* (2005) found, using linear and nonlinear fits in the analysis of data from streams collected worldwide in the temperate zone, that the majority of streams showed an increase in water temperature of about 0.6–0.8°C for every 1°C increase in air temperature. The output results of the water temperature of the model tested here are consistent with those results, for all the resultant raster maps show colder ranges than the input maps.

Change of size of trout farming territory

Figure 4 shows the spatial range of the $\boldsymbol{T}_{\mathrm{w}}$ optimal for rainbow trout grow-out by month for the baseline scenario (BL) only. The surface available is at its lowest in May. The low area of optimal $\boldsymbol{T}_{\mathrm{w}}$ from March to November is because of the occurrence of high

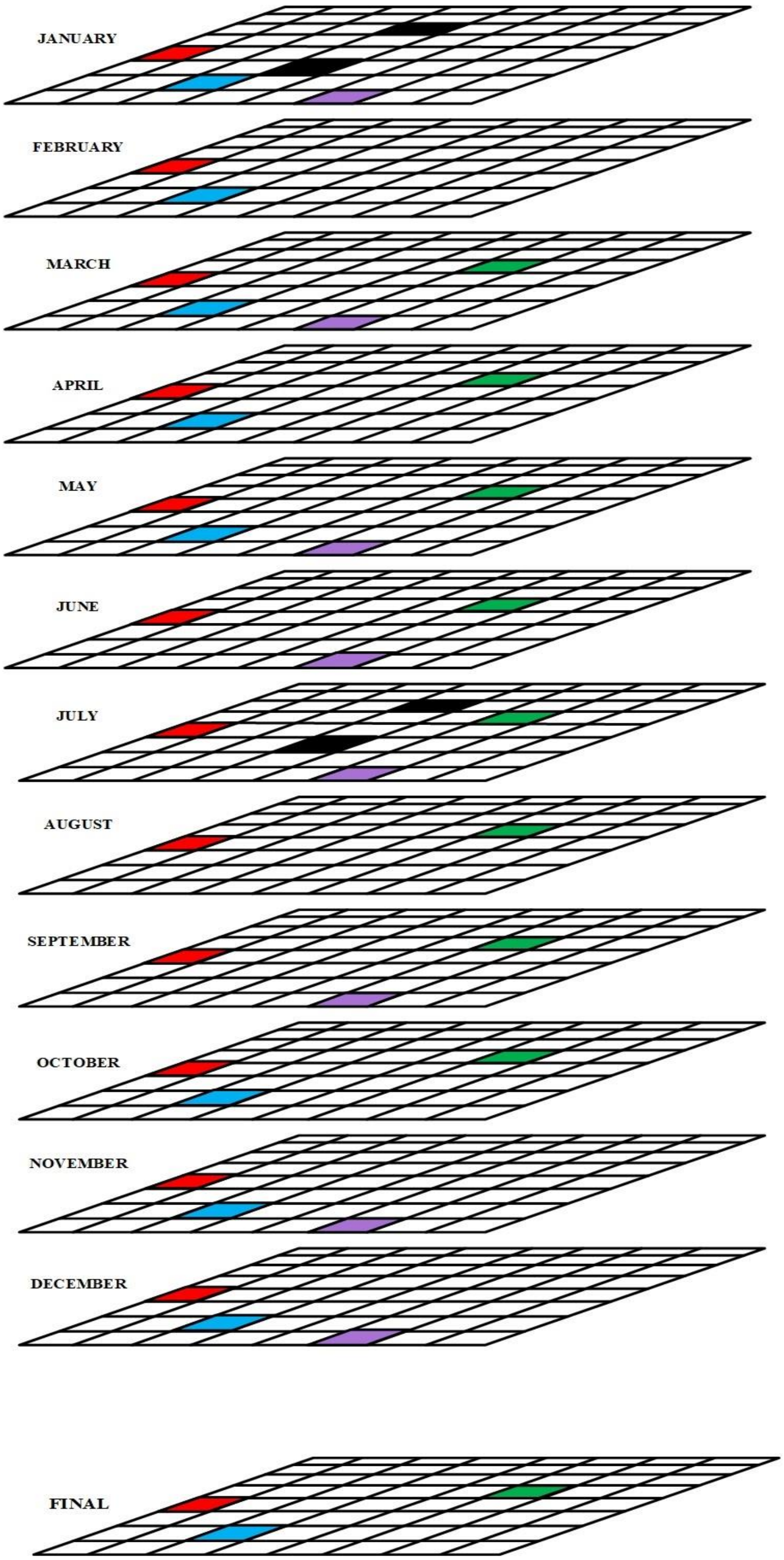

Figure 3. Representation of the problem of pixel temporal contiguity among monthly 8 X 8 pixel raster maps –the overlaid grids labeled "January" to "December"–, and the selection criteria algorithm's result on the output raster –bottom grid–. Colored pixels match the temperature interval for trout grow-out, pixels that make it to the output final match the eight-month minimum grow-out period.

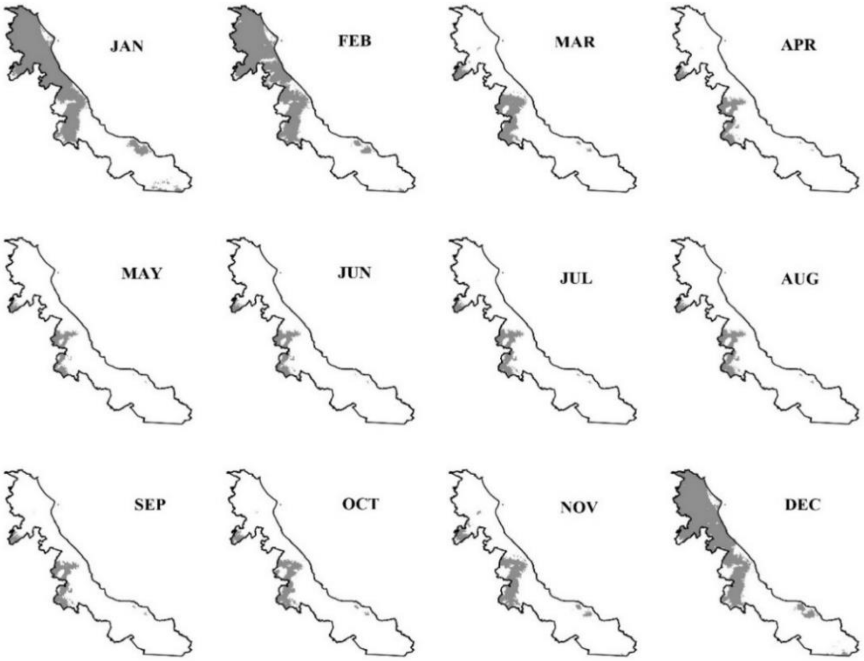

Figure 4. Intermediate simulation output: spatial range of estimated water temperature ($\boldsymbol{T}_w$), by month, on the baseline model time-horizon in the state of Veracruz, México. Shaded areas are those pixels of Tw for each month of a year-cycle falling inside the ranges of optimal growth for rainbow trout.

temperatures through most of the year, which limits the range of suitable conditions for growing trout. The rest of the year the reclassified $\boldsymbol{T}_w$ spreads only over a restricted area corresponding to the mountain ranges of central Veracruz and in the mountain range of Los Tuxtlas, southeast of the study area. Zones to be also regarded as non-optimal are the small areas in the middle of the mountain ranges in central Veracruz, near the western State border. In those areas of high altitude, the temperature was unsuited for the growth of trout because of its low $\boldsymbol{T}_w$, which was below the optimum range for the growth stage, but probably suited for fry rearing. The problem in those areas is inaccessibility and margination by the lack of infrastructure and services like roads and electricity.

Figure 5 shows the variability of $\boldsymbol{T}_w$ areas available by month on each of the projected horizons used in the simulations. It can be seen that the potential territory is very different in the baseline and three simulated horizons, for it gets reduced and the differences among the warm months and the cold months shorten as the simulation time progress from short to long term. This was the first level of analysis, and it allows a first glimpse of a severe reduction in the area available for trout farming from the short-term on.

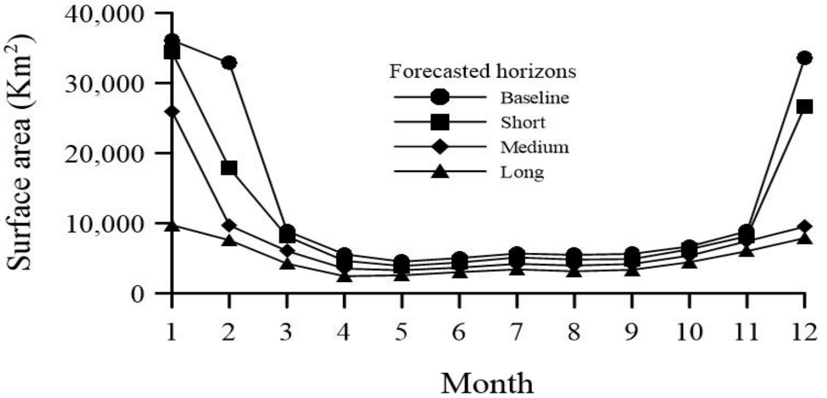

Figure 5. Simulation's intermediate output of the surface-area monthly variation of the Potential Trout Farming Territory in Veracruz, México, for the baseline and the three projected time-horizons, showing the potential effect of global warming on the total surface left available.

Figure 6 presents the final output of the spatiotemporal simulations for each BL&PTH, including the 179 trout farms. The area in gray are patches of pixels representing 8 or more contiguous months with optimal estimated water temperature $\boldsymbol{T}_{\mathrm{w}}$ for growing rainbow trout, herein termed as the Potential Trout Farming Territory (PTFT). East of the shaded area in the maps, a slope ends at the Gulf of Mexico's coast. Westward lays the Sierra Madre Oriental. Veracruz's trout farms are located on the windward slope of the mountain range. In the baseline horizon map, there are several farms outside the PTFT, downslope from it. Those farms, as part of the TFT, are in a zone where the PTFT occurs during less than eight months each year, being the water warmer than the optimal. On the opposite side —westward to the PTFT— several farms are also located in zones in which the PTFT occurs in less than 8 months each year. There, the water temperature is colder than required, so those farms should have problems like a slower growth rate, opposite to the former farms, whose problems are more likely the onset of diseases and probably a lower-than-ideal oxygen concentration. As time moves forward in the simulation, PTFT reduces its size and moves to a higher altitude.

The analytic surface area for each raster map generated by the simulation is plotted against time in figure 7. In the baseline, the PTFT available is 4,919 km^2, accounting for 6.8% of Veracruz's territory, while at the long-term horizon, the PTFT reduces 37.6% to a final surface area of 3,068 km^2. The reduction rate, estimated by the linear regression's slope value, is 21.06 km^2 year^{-1} ($R^2 = 99.6\%$, $p < 0.05$).

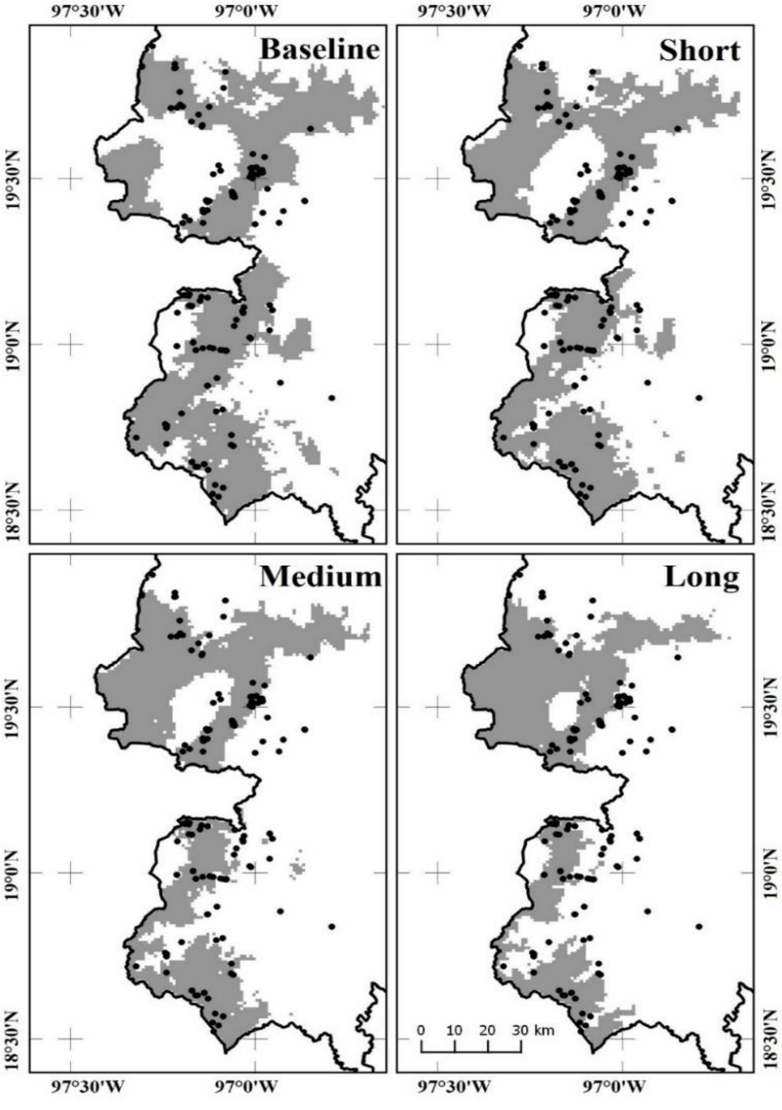

Figure 6. Maps of the trout farming territory (TFT) delimited by the farm dots, and the potential trout farming territory (PTFT) in gray, for the baseline and three projected time-horizons, in central Veracruz, México. The shaded areas are the simulation's final output for the 8-month-minimum occurrence of rainbow trout-grow out optimal estimated water-temperature time-contiguous pixels. The black line sets the limits of the state.

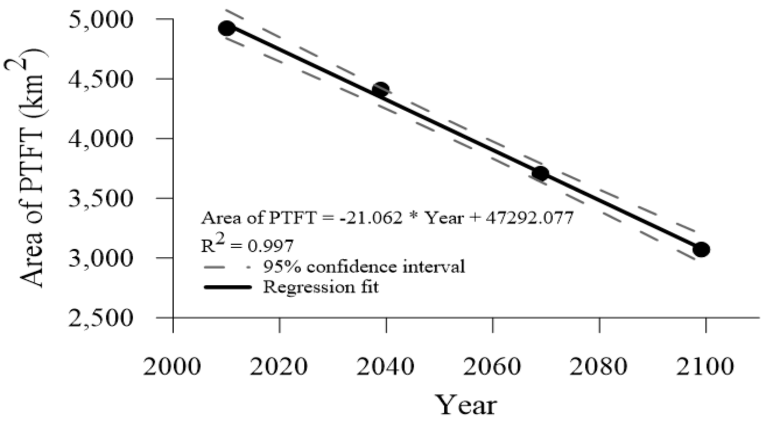

Figure 7. Linear regression fit and 95% normal confidence interval for the values of the area of potential trout farming territory (PTFT) in central Veracruz, México, on the baseline and projected time-horizons. The plot includes the regression equation, being the slope the PTFT area reduction in km^2 to be lost each year, given the climate change scenario used for the simulation.

Misplacement of farms

There are two probable causes for part of the TFT, at the baseline, to be located outside the PTFT. The first is related to the accuracy of the model results, which depend on the accuracy of the inputs, such as the optimum temperature interval chosen and the time required to get to the harvest size. On the former, the variability of both averages (upper and lower limits) used have an average standard deviation of 2.4°C (Acosta-Jimeno, Devezé-Murillo and Méndez-Guerrero, 2018), so those temperatures may vary, hypothetically, from less than 10 to more than 20 °C, thus potentially incorporating more farms to the PTFT. Then there is the genetic variability of the trout strains tested in each of the works revised by Acosta-Jimeno, Devezé-Murillo and Méndez-Guerrero (2018, *op. cit.*). Morkramer *et al*. (1985) identified important variability in growth from different populations of European rainbow trout under intensive production conditions, while Sumpter (1992) stresses the influence of the combination of genetics and environment to determine the growth in trout and its inherent variability. Moreover, it has been reported that *O. mykiss* can be adapted to temperatures higher (Molony, Church and Maguire, 2004), and lower (Bouchard and Guderley, 2003) than its optimum range. All this can explain in part both, the broad range of the results found in the literature through genetic variability and adaptation, and the fact that some of the farms were sited outside the optimum-temperature geographic range calculated by the model for the baseline. A more detailed run of the model will require the use of temperature data input that is valid for the strain or strains of rainbow trout commonly used in Mexico. Those data are yet to be obtained, preferably by bioassay. The issue of the time required to acquire the harvest size is also one of genetic causes. Morkramer *et al.* (1985) showed that the coefficient of variability in terminal weight at the grow-out stage of European rainbow trout is almost 30%. This value is higher than the reported for tilapia at 25% (Nguyen *et al*., 2010) and 21.1% (Mengistu *et al*., 2021), and much higher than for raceway-farmed grass carp at 3.5% *(*Gharti *et al*., 2023) and for a common carp control group at 2.8% (Sándor *et al*., 2021).

Another cause for the misplacement of trout farms may be related to the aquaculture-funding government's policies. As stated by Oliveros (1995) for Latin America, by dispensing with planning tools for development, it is ultimately shaped by the pressures of interest groups, and so there's been the common practice in Mexico's government of granting economic resources equally to both, consolidated and novice producers. Hence, most of the small and medium-size trout farmers are grant-dependent (Rosales Estrada *et al*., 2013) and, on many occasions, those resources are granted to people without previous experience or that do not require them at all, in what is termed "perverse subsidies" (Myers, 1998). The resources, thus, are used sometimes without previous aquaculture professional experience and none or minimal technical supervision, often resulting in several design deficiencies, among which misplacing the farm is one of them.

Territory displacement westward

Note in Figure 6 that, as the modeled time horizons are onset in the simulation, more farms would be reached by the PTFT zone to the West, because of altitude reasons, and the opposite would happen to the East as more farms would be left exposed at lower altitudes. Therefore, in the event of the occurrence of this CCS, it is expected that a number of farms presently located inside the temperature range during the number of months that enables the farmers to grow rainbow trout up to 350 grams, may be left outside the PTFT at some time in the present century.

Loss of livelihoods

For a quantification of the level of exposition to the CCS of the trout farms in Veracruz, Figure 8 presents the exposed-farm rate from the simulations. In the baseline horizon, 90% of the farms are located inside the PTFT. As the model runs forward in time, it renders warmer water, and the number of farms to be left out of the PTFT increases. The rate of loss of farms to warmer water is of almost one farm per year (R^2 = 97.2, $p < 0.05$). This means that, by the end of the century, trout farming would be exposed by almost 58%, for the number of farms to be left out of the PTFT is 97. This will happen mainly in the Southern Trout Farming Territory (STFT), as it includes areas of much lower altitude than at the North, which can be observed in the altitude profile plots of Figure 2.

In terms of Climate Change Science, the results of the present study show that the freshwater aquaculture activity, specifically the rainbow trout culture, is in a moderate-to-high degree of exposure in the area of study. This parameter is part of the variables required to assess the CC vulnerability of an activity, which in this context is defined as "the susceptibility of individuals or groups to the damages resulting from climate changes" (Daw *et al*., 2009). Furthermore, vulnerability is a function of the type, magnitude, and rhythm of the climate variation to which a system is exposed, its sensibility, and its adaptation capability (McCarty *et al*., 2001; Allison *et al*., 2005).

At a socioeconomic level, the livelihoods of those directly or indirectly related to aquaculture are vulnerable to these changes, as Handisyde and coworkers (2017) have stressed. Rainbow trout in Mexico is the primary livelihood of thousands of families in several States. Its value-network stretches to branches such as tourism (Franco-Maass *et al*., 2009; Salazar Arzate, Zizumbo Villareal and Garduño, 2010; García-Mondragón *et al*., 2013; Guzmán Hernández, Garduño Mendoza and Mendoza Vilchis, 2013), gastronomy (Sepúlveda Hernández *et al*., 2021; 2023), and even conservation (López-García, Manzo-Delgado and Alcántara-Ayala, 2014). What was found in this work for Veracruz State can be also true for other parts of the country. The main issue with rainbow trout in Mexico is that, in great proportion, it is farmed by an economically vulnerable sector of the rural population (Ortega and Valladares, 2017; García-Mondragón *et al*., 2021), being this proportion higher than 97% in Veracruz (from data by Reta-Mendiola and Asiain-Hoyos, 2010). The production is oriented both, farm-door to wholesalers, and retail-sell to neighboring rural dwellers (García-Mondragón *et al*., 2021 *op. cit*.). The very nature of the trade, requiring cold, clean water, forces the location of the farms up to remote, marginal areas (Gauchan *et al.*, 2008). In those places, income-generating and employment opportunities are scarce, so rainbow trout aquaculture helps people to ensure employment and steady incomes (López-García, Manzo-Delgado and Alcántara-Ayala, 2014) from a generally weak activity (Ávalos Gutiérrez, Cibrián Ramos and Ávalos Calderón, 2012). The question here was to assess if poverty further aggravates the exposure level of trout farmers in central Veracruz.

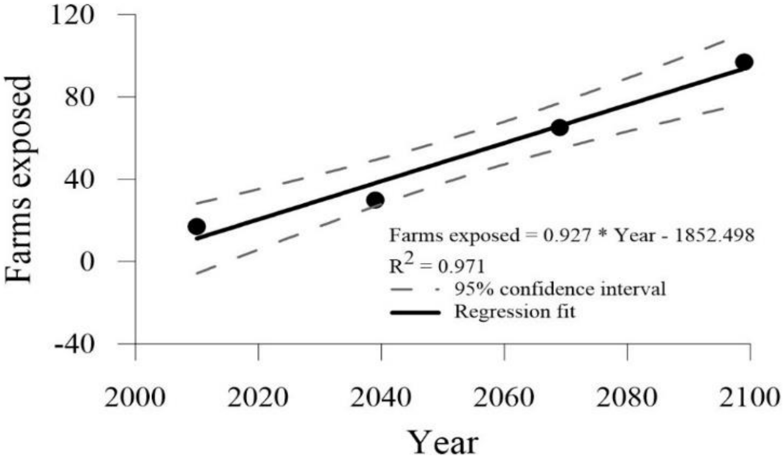

Figure 8. Linear regression fit and 95% normal confidence interval for the trout farms in central Veracruz, Mexico, that could be left outside the potential trout farming territory (PTFT) on the baseline and projected time-horizons, given the global warming scenario used for the simulation. The plot includes the regression equation, being the value of the slope the number of farms that would be left out of the PTFT each year.

Acosta-Jimeno *et al*. (2018) rendered a typology of the trout farmer in central Veracruz with the same set of data used in the present work. Among other results, they found that TFT municipalities and rural locations showed Human Development Index (HDI) values statistically lower than the State and National averages, and Margination Index (MI) values statistically higher than state and national averages. Besides, they found that the average trout farmer used very low-technology processes, measured with a technology level index (TLI) to grow their fish. They further used multivariate statistical methods to group farmers into three types. Figure 9 presents a ternary plot for the three types of farmers and their relation to HDI, MI, and TLI. Type 1 farmers resulted to be the fewer (only 8 out of 179), older, and less productive group. Although they were the better-ranked group in TLI, MI and HDI, this farmer type ranks among the lower-altitude. Moreover, farms of many of them are already outside the PTFT on the baseline scenario, which renders them highly GW-exposed.

Poverty-related indexes showed a measurable direct effect in increasing the exposition of the system to potential global warming effects for this particular study. The ranking of those indexes, for trout farming in central Veracruz, is inversely proportional to altitude, presenting worse scores in farmer types 2 and 3, averaging 1,500 and 2,300 m of altitude above sea level, respectively (Acosta-Jimeno *et al.*, 2018 *op.cit*.). Thus, for the present work, the farmers using lower technology, and located at more marginalized and less developed areas of the TFT are less exposed to the potential GW effects given their high altitude, and thus lower average temperatures. On the opposite end, some of the older and less productive farmers are already out of the PTFT at the baseline time horizon, which means a severe aggravation of their exposition to the potential GW effects on trout production, but the number of farmers in this situation is low. The type 1 farmers and their livelihoods, thus, are on a very high GW-effects *a priori* exposure.

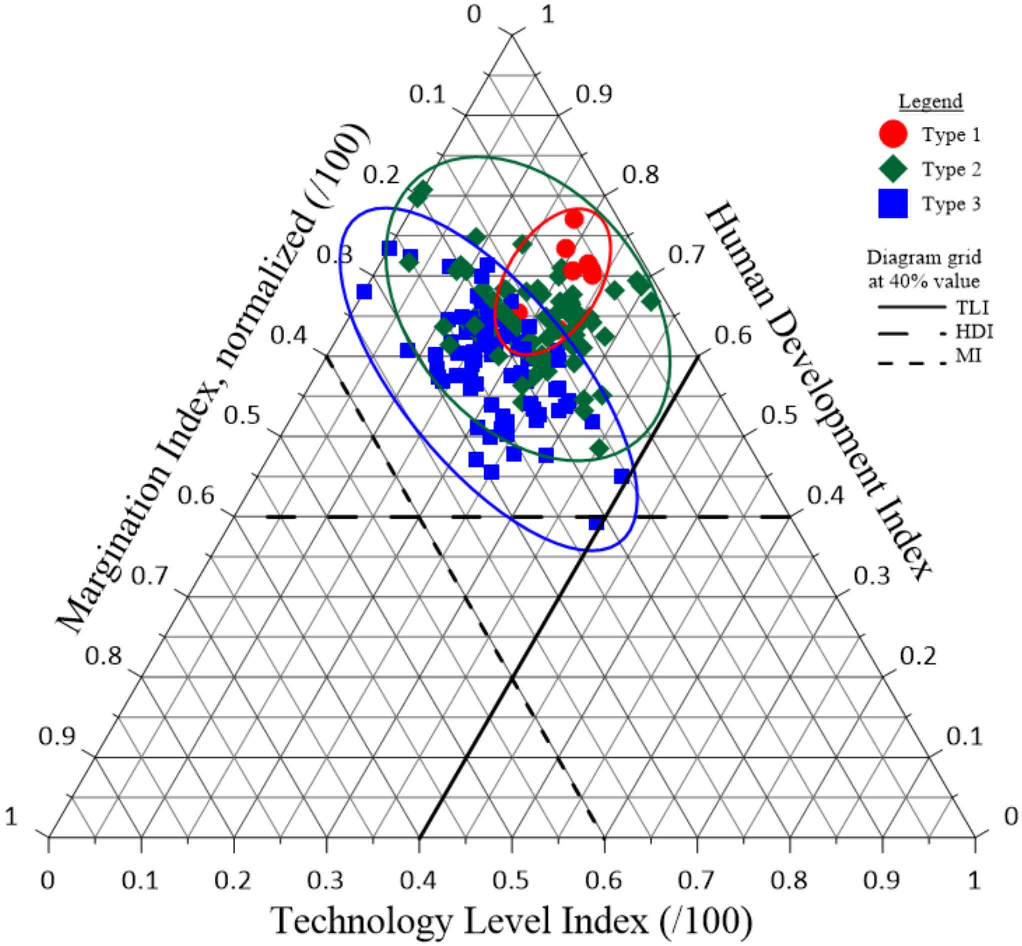

Figure 9. Ternary diagram of the trout farms in central Veracruz, Mexico, classified using multi-parametric statistical methods. Colored symbols represent the types of trout farmer classification and colored ellipses delimit their maximum spread over the chart. Indexes explained in text. With data from Reta-Mendiola and Asiain-Hoyos (2010) and Acosta-Jimeno *et al*. (2018).

CONCLUSIONS

In Veracruz, Mexico, a coastal tropical state having mountain ranges with temperate to cold climate, a moderate to severe exposition of the rainbow trout aquaculture system to the potential effects of Global Warming may be expected in the medium and long term. It can result in great damage for the livelihoods not only of farmers but for all the rainbow trout production system, given the onset of the conditions projected by the CCS selected for the simulation. Those effects are not to be assumed as exclusive for the TFT at the area of study, but also for other states with similar orographic, climatic, and socio-economic characteristics where rainbow trout is farmed in Mexico.

There is still further research to be done in order to fully assess the vulnerability to global warming of freshwater aquaculture. Yet, the present results show that rainbow trout culture can be in a moderate-to-high degree of exposition in Veracruz, México, given the simulation parameters used. If besides, the yet-to-be-determined sensibility of the trade is high and the system's adaptation capability is low, the activity can be in a moderate to severe level of vulnerability. Authorities and farmers are prompted to start actions to reduce this potential vulnerability by developing strategies in joint efforts with the Academy, for the livelihoods of several hundreds of families depend directly and indirectly of the trout farming and commercialization may be at risk in the middle term.

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Conflict of interest. All authors declare no conflict of interest whatsoever in the research and publication of the present work.

Compliance with ethical standards. For its characteristics, this research does not require an ethics committee approval

Data availability. Program scripts and classification algorithms are available with the corresponding author upon reasonable request.

Author contribution statement (CRedit). **J. Acosta-Jimeno**—Conceptualization, Data curation, Formal Analysis, Methodology, Software, Visualization, Writing – original draft, review and editing. **J.L. Reta-Mendiola**—Conceptualization, Formal Analysis, Supervision, Validation, Writing – review and editing. **D.E. Platas-Rosado**— Formal Analysis, Supervision, Validation. **A. Asiain-Hoyos**—Conceptualization, Formal Analysis, Supervision, Validation, Writing – review and editing.

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