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Current Potential Distribution of el Dorado (*Coryphaena hippurus*) in the Pelagic Ecosystem of the Southeast Coast of the Mexican Pacific Ocean

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Manuel Alejandro Ruiz-Mayorga[1]
alex21530@outlook.com • ORCID: 0009-0008-8753-8976
Tamara Rioja-Paradela[2]
tamara.rioja@unicach.mx • ORCID: 0000-0003-2127-0790
Arturo Carrillo-Reyes[3]
arturo.carrillo@unicach.mx • ORCID: 0000-0001-8351-5496
Francisco López-Rasgado[4]
franciscoj.lopez@unicach.mx • ORCID: 0000-0002-2982-3110
Leonel Santizo-López[5]
leonel.santizol@e.unicach.mx • ORCID: 0000-0002-1290-5072

1 Master of Science in Sustainable Development and Risk Management Faculty of Engineering, Universidad de Ciencias y Artes de Chiapas
2 Postgraduate Degree in Sustainable Development and Risk. Management, Faculty of Engineering. Universidad de Ciencias y Artes de Chiapas
3 OIKOS: Conservación y Desarrollo Sustentable, A.C. San Cristóbal de Las Casas, Chiapas, México
4 Universidad de Ciencias y Artes de Chiapas Instituto de Ciencias Biológicas, Sede Tonalá, Chiapas México
5 Doctorate of Science in Biodiversity and Conservation of Tropical Ecosystems. Institute of Biological Sciences, Universidad de Ciencias y Artes de Chiapas

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— Abstract—

Anthropogenic activities have led to accelerated global warming that is raising the average temperature of the Earth's atmosphere and oceans; the poor management of productive activities in the oceans results in environmental problems, such as overfishing and pollution, negatively affecting the distribution and population dynamics of many marine fauna species. One of the important species in the pelagic ecosystem is the Mahi-Mahi (*Coryphaena hippurus*), one of the main marine predators whose ecological function is to control the populations of herbivorous fish and thereby maintain the balance of the food web; therefore, the extinction of this fish can produce a "top-down" imbalance in the pelagic ecosystem. The present research aims, for the first time, to model the current potential distribution of Mahi-Mahi (*C. hippurus*) along the entire Mexican Pacific coast (using the Maximum Entropy algorithm or MaxEnt), based on the contrast of ecological and climatic factors with the species' records reported in scientific databases such as SNIB-CONABIO (National System of Information on Biodiversity-National Commission for the Use and Knowledge of Biodiversity) and Gbif. The results suggest that Mahi-Mahi (*C. hippurus*) is distributed along the entire Mexican Pacific coast, expanding the distribution area previously reported in the scientific literature to the north coast of the United States of America. The three variables that most contributed to explaining the potential distribution model were Maximum Temperature at Minimum Depth, Minimum Temperature at Medium Depth, and Nitrate with a Range at Maximum Depth. These results provide key information to determine the priority conservation areas (sustainable management) of Mahi-Mahi (*C. hippurus*) on the Mexican coast and the environmental variables that influence its distribution.

Keywords:

Distribution; sustainable management; modeling; fishes; geographic information systems

The ocean is the cradle of life on our planet and also represents the most extensive habitat in the biosphere. Oceans have a great biodiversity (Duarte, 2006). At a fundamental level, marine life contributes to determining the very nature of the planet, since marine organisms produce much of the oxygen we breathe (Pérez, 2020).

Anthropogenic activities have led to accelerated global warming that is raising the average temperature of the Earth's atmosphere and that of the oceans. The planet's surface temperatures are increasing at a great rate, since in the last 100 years, the global average temperature has increased by 0,76 °C (Pérez, 2020; Agustín, 2023). In addition, the mismanagement of productive activities in the oceans has resulted in serious environmental problems, such as overfishing, uncontrolled tourism activities, and pollution; these problems have negatively affected the distribution and population dynamics of a large number of species of marine fauna, including fish (Olson & Magaña, 2002).

El Dorado (C. hippurus) is a fish considered one of the main predators of the pelagic marine ecosystem, so it is very important to control the population of herbivorous fish and maintain the balance of the food web; its extinction would hurt the local and regional trophic cascade (Verheye et al., 1998). On the other hand, this species plays an important role not only in commercial fisheries (widely consumed in Mexico) but especially in sport fishing along the entire Pacific coast in North America (CONAPESCA, 2016).

According to Palko et al. (1982), historically, this species has been distributed in tropical and subtropical waters. However, Salvadeo et al. (2020) recorded its potential distribution along the northern Pacific Ocean, from the northern United States of America to the state of Baja California Sur in Mexico, its potential distribution along the rest of the Mexican Pacific coast is currently unknown.

Therefore, the objective of the present study was to determine the current potential distribution of dorado (*C. hippurus*) in the Mexican Pacific pelagic ecosystem, using the Maximum Entropy algorithm (MaxEnt), based on the contrast of ecological and climatic factors with the records of the species reported in scientific databases such as SNIB-CONABIO (National Biodiversity Information System - National Commission for the Use and Knowledge of Biodiversity) and Gbif. (Guisan & Thuiller, 2005). This information will be key to identifying not only priority conservation areas (sustainable management), but also to identify which environmental variables influence the distribution of this species, and thus propose future sustainable management plans for commercial and sport fishing of this fish along the Mexican Pacific coast (Botsford, 1997; Fonteneau & Tellería, 2012).

METHOD

Study Area

The study area covered the entire Pacific coast of Mexico, between the coordinates of 14°33'15 "N 92°15'37 'E and 32°28'48 'N 117°06'20 "E. This coastal region is made up of eleven of the thirty-two states in the country, concentrating 46% of the municipalities in all of Mexico. Overall, the study area covered an area of 804,000 km, that is, 41% of the national territory, and has a coastline of 7,828 km of the Pacific Ocean (70% of the total Mexican coastline; López, 2018; Figure 1). Not only is 80% of Mexican fishing potential located in this area, but it also concentrates the greatest fishing activity of massive species of high commercial value, such as shrimp, oyster, sardine, lobster, anchovy, tuna, abalone, and sargassum (Poo et al., 2002).

Database of C. hippurus records and marine environmental variables

The presence records of the species were downloaded from the scientific databases SNIB-CONABIO (National Biodiversity Information System-National Commission for the Use and Knowledge of Biodiversity) (CONABIO, 2008), and Gbif (GBIF, 2022); only records with clear coordinates were used. To eliminate any errors in the modeling, the records were debugged in the Qgis software (QGIS.org, 2022), eliminating all those with doubtful or repetitive data, and those that were found over the continental area or within 500 m. At the end of this first cleaning, there were a total of 18,728 records of *C. hippurus* (obtained from 2000 to 2022). Subsequently, a second cleaning was carried out to eliminate the spatial autocorrelation, considering the size of the species' home environment, which consists of 40 km/day in horizontal movements (Merten, 2014). This process was carried out with the R-Studio software (RStudio, 2022) and the "spThin" package (Aiello et al., 2015; R Core Team, 2022). Finally, we worked with a total of 726 presences of the species.

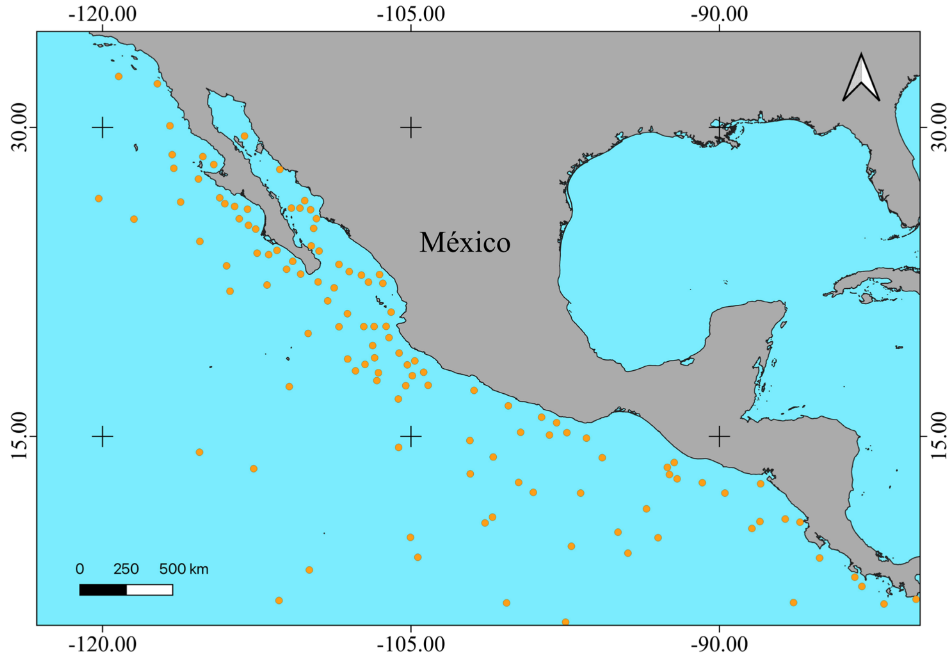

Figure 1. Records of the presence of Coryphaena hippurus on the coast of Mexico, available in scientific databases

On the other hand, 76 environmental layers (each corresponding to an environmental variable) of the marine system were obtained from the Bio-ORACLE v2.0 website (Tyberghein et al., 2012), among which some can be mentioned such as the number of nitrates, primary productivity, temperature, chlorophyll concentration, and water speed, just to name a few. These environmental layers are presented in the form of raster that provide geophysical, biotic, and environmental data for the benthic and surface marine kingdoms. They are projected with spatial resolutions of 5 arc minutes (~9 km per side) and are updated and available for download in the 2017 version. The layers were trimmed to cover the entire Mexican coastline.

Current Potential Distribution

For the current potential distribution modeling of el dorado (*C. hippurus*), the Maximum Entropy algorithm (MaxEnt) was used, which has a precise mathematical formulation, whose basic idea is to estimate (approximate) the probability of unknown distribution of a species (Phillips et al., 2006). The technique first forces the distribution model to group certain features (environmental layers) of empirical data (presence data), to choose the probability condition that satisfies these limitations (Buehler & Ungar, 2001). Thus, MaxEnt contrasts ecological and climatic factors and relates them to the occurrences (records) of the species (Guisan & Thuiller, 2005).

Once the inputs (species records and environmental layers) were ready, MaxEn was run using the default attributes for the model configuration. 10 replicates were run, and using a Jackknife analysis in the calibration stage of the model, the percentage of contribution of the rest of the uncorrelated variables was evaluated. Finally, those variables with the greatest contribution to the model and with the greatest biological contribution were selected, according to the scientific literature (Zúñiga-Flores, 2008).

The final mapping of the current potential distribution map was carried out using the QGIS software (QGIS.org, 2022), based on the result of the MaxEnt algorithm.

RESULTS

Current Potential Distribution

The model result indicated that el dorado (*C. hippurus*) is distributed along the entire Mexican Pacific coast, having a higher probability of presence (0.8862) in the areas near the coasts of the states of Sinaloa, Baja California, Baja California Sur, Nayarit, Chiapas, and the lower part of Sonora (Figure 2).

According to the model, nine environmental variables explained 80% of the probability of potential distribution of el dorado (*C. hippurus*): Maximum temperature at minimum depth, Minimum temperature at medium depth, Nitrate with a range at maximum depth, Maximum temperature at maximum depth, Maximum chlorophyll concentration at maximum depth, Water speed with a range at maximum depth, Minimum temperature at minimum depth, Temperature with a range at medium depth, and Minimum nitrate at medium depth. The three variables that contributed the most were the Maximum to Minimum Depth Temperature, the Minimum Temperature at medium depth, and Nitrate with a range at maximum depth (Table 1).

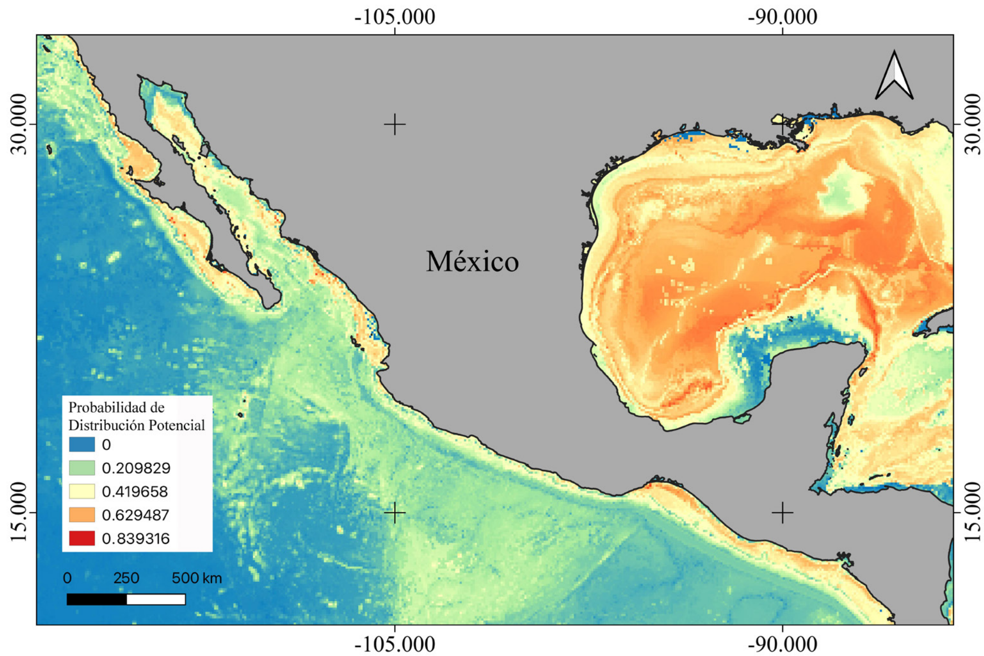

Figure 2. Current potential distribution of el dorado (Coryphaena hippurus), in the pelagic ecosystem of the Mexican Pacific coast

Table 1
Variables that helped explain the distribution model of el dorado (C. hippurus)

Variables	Percentage of contribution (%)
Maximum temperature at minimum depth	39.2
Minimum temperature at medium depth	10.4
Nitrate with a range at maximum depth	6.6
Maximum temperature at maximum depth	5.8
Maximum chlorophyll concentration at maximum depth	5.1
Water speed with a range at maximum depth	4
Minimum temperature at minimum depth	3.9
Temperature with a range to medium depth	3.6
Minimum nitrates at medium depth	3.3

DISCUSSION

The current potential distribution model makes it clear that the appropriate environmental conditions for the presence of el dorado (*C. hippurus*) are located along the entire Mexican Pacific coast, from the coast of Baja California Norte (coinciding with reports by Salvadeo et al. in 2020 in their study conducted for the coast of the United States of America) to the coast of Chiapas. Our results also coincide with the historical distribution of the species reported by Palko et al. (1982), who stated that this species is distributed in tropical and subtropical waters, both in coastal waters and in the open sea, since the MaxEnt model indicated that there are also areas suitable for the presence of el dorado (*C. hippurus*) in open sea areas around the Revillagigedo islands and other Mexican Pacific islets.

Our results are likely explained by the fact that the abiotic (temperature, depth, nitrates) and biotic (food, mates) factors necessary for el dorado feeding and reproduction are found along the entire Mexican Pacific coast, as well as in the areas close to these islands (*C. hippurus*); that according to Jonsen et al. (2003), the distribution of organisms in the oceans is determined by complex interactions between these factors, which are essential for species fitness. Hernández (2015) stated that, on the coast of Baja California Sur, the horizontal (distance to the coast) and vertical movements of el dorado (*C. hippurus*) are related to their feeding habits and these, in turn, are influenced by oceanographic and geographic variables (thermocline-depth), moving away from the coast up to an average of 38 km and diving deeper at night to hunt their prey. In addition, Gibbs and Collete (1959) pointed out that the appropriate conditions for the presence of this fish are located in isotherms of 20 °C.

The three variables that contributed most to explaining the potential distribution pattern of el dorado (*C. hippurus*) were Maximum Temperature at Minimum Depth, Minimum Temperature at Medium Depth, and Nitrate with a Range at Maximum Depth. These variables are of great importance for the population dynamics and, therefore, for the distribution of many species of epipelagic predatory fishes, even in different parts of the world, in oceanographic regions and thermal structures similar and different from those of el dorado (*C. hippurus*), have shown a similarity in their preference for warm surface and average temperatures (Chiang et al., 2011). Clear examples of this are the blue marlin (*Makaira Nigricans*) in Hawaii, which spends much of its time in depths of no more than 10 m with warm waters ranging from 26°C to 27°C (Block et al..., 1992); or in juvenile bluefin tuna (*Thunnus thynnus*) in the western North Atlantic, which prefer to spend most of their time in waters above 15 m, with temperatures of 20 °C (Brill et al., 2002). For el dorado (*C. hippurus*), being a pelagic predator, surface and mid-depth temperatures are very important, since as pointed out by Hernández (2015), this fish moves during the day at the surface, but dives to greater depths during the night to obtain its food. However, Merten et al. (2014) explained that there is a direct relationship between abiotic factors such as temperature and the possible movements of fish prey, while Lasso and Zapata (1999) stated that pelagic fish prey such as el dorado (C. hippurus) are composed of epipelagic species, although there are also records of mesopelagic species distributed at medium depths. Zuñiga et al. (2009) and Farrel et al. (2014) suggested that surface and mean sea temperature plays a key role in the reproductive cycle of this fish, as they point out that the reproductive activity of el dorado (*C. hippurus*) occurs in a temperature range from 21 °C to 30 °C, with maximum activity in females and reproductive males at 25 °C and above, which intensifies as the temperature rises. This is confirmed by García-Melgar (1995), who pointed out that the coast of Baja California Norte and Baja California Sur corresponds to an important breeding, refuge, and feeding area for el dorado (*C. hippurus*). Along the entire Mexican Pacific coast, average sea surface temperatures range from 19 °C to temperatures greater than 28 °C, thus possessing optimal temperatures for feeding and reproduction of this species (López, 2018).

Regarding the presence of nitrates (the third predictive variable of the potential distribution model of el dorado), it is important to note that the spatiotemporal distribution of this compound is key for food webs in the oceans, it is a basic and fundamental nutrient for the functioning of these marine ecosystems (Paparazzo et al., 2013). Nitrate is a compound that is naturally present in the environment as a consequence of the nitrogen cycle (Moreno et al., 2015); and in aquatic environments, the nitrogen uptake process is mainly exerted by phytoplankton and bacterioplankton (primary producers) in the euphotic layer, so the conversion of inorganic to organic nitrogen is one of the most relevant biogeochemical processes in the environment associated with these groups (Cabrita et al., 1999). Being a top predatory fish in its ecosystem, el dorado (*C. hippurus*) feeds mainly on herbivorous fish (Briones et al., 2017), which in turn feed on that phytoplankton, so the existence of nitrate on the Mexican Pacific coast is an excellent indicator that the food web, of which the el dorado (C. hippurus) belongs to, works well, i.e., there are not only primary producers, but the preys of el dorado (*C. hippurus*) and, therefore, is an excellent indicator of the potential distribution of this fish.

Thus, the present study determines for the first time the current potential distribution of el dorado (*C. hippurus*) on the Mexican Pacific coast, which is of great relevance not only because it is a species of great ecological importance (Varghese et al., 2003), but also because it is reserved for sport fishing in Mexico (DOF, 1995). This information will provide data to establish priority conservation areas (sustainable management) and protocols for monitoring their populations and predictive variables of their potential distribution along the Mexican coast.

CONCLUSIONS

The entire Mexican Pacific coast, from Baja California Norte to Chiapas, has suitable environmental conditions for the current potential distribution of el dorado (C. hippurus). The three variables that contributed most to explaining the potential distribution pattern of el dorado (C. hippurus) were Maximum Temperature at Minimum Depth, Minimum Temperature at Medium Depth, and Nitrate with a Range at Maximum Depth. These environmental variables are excellent indicators of suitable conditions for the feeding and reproduction of this fish and, therefore, are determinants of its potential distribution.

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