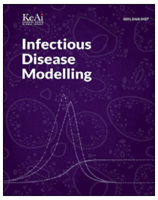
Infectious Disease Modelling 6 (2021) 805–819

Contents lists available at ScienceDirect

Infectious Disease Modelling

journal homepage: www.keaipublishing.com/idm



Edaphoclimatic seasonal trends and variations of the *Salmonella* spp. infection in Northwestern Mexico

Yasiri Mayeli Flores Monter [a], Andrea Chaves [b], Beatriz Arellano-Reynoso [a], Andrés Mauricio López-Pérez [c], Humberto Suzán-Azpiri [d], Gerardo Suzán [a, *]

[a] *Facultad de Medicina Veterinaria y Zootecnia, Universidad Nacional Autónoma de México, México City, 04510, Mexico*
[b] *Escuela de Biología, Universidad de Costa Rica, San José, 11501-2060, Costa Rica*
[c] *Department of Medicine and Epidemiology, School of Veterinary Medicine, University of California, Davis, CA, 95695, United States*
[d] *Laboratorio de Ecología, Universidad Autónoma de Querétaro, 76230, Mexico*

ARTICLE INFO

Article history:
Received 20 January 2021
Received in revised form 18 April 2021
Accepted 16 May 2021
Available online 10 June 2021
Handling editor: Dr. J Wu

Keywords:
Potential distribution
Soil
Temperature
Precipitation
Salmonella spp

ABSTRACT

Currently, *Salmonella* spp. is the bacterium causing the highest number of food-borne diseases (FADs) in the world. It is primarily associated with contaminated water used to that irrigates crops from intensive livestock farming. However, literature emphasizes that the reservoirs for *Salmonella* spp. remain in wildlife and there are unconventional sources or secondary reservoirs, such as soil. Human soil-borne diseases have not been modeled in spatial scenarios, and therefore it is necessary to consider soil and other climatic factors to anticipate the emergence of new strains or serotypes with potential threat to public and animal health. The objective of this research was to investigate whether edaphic and climatic factors are associated with the occurrence and prevalence of *Salmonella* spp. in Northwestern Mexico. We estimated the potential distribution of *Salmonella* spp. with an interpolation method of unsampled kriging areas for 15 environmental variables, considering that these factors have a seasonal dynamic of change during the year and modifications in longer periods. Subsequently, a database was generated with human salmonellosis cases reported in the epidemiological bulletins of the National System of Epidemiological Surveillance (SIVE). For the Northwest region, there were 30,595 human cases of paratyphoid and other salmonellosis reported have been reported in Baja California state, 71,462 in Chihuahua, and 16,247 in Sonora from 2002 to 2019. The highest prevalence was identified in areas with higher temperatures between 35 and 37 °C, and precipitation greater than 1000 mm. The edaphic variables limited the prevalence and geographical distribution of *Salmonella* spp., because the region is characterized by presenting a low percentage of organic matter ($\leq$4.3), and most of the territory is classified as aridic and xeric, which implies that the humidity comprises $\leq$ 180 days a year. Finally, the seasonal time series indicated that in the states of Baja California and Chihuahua the rainy quarter of the year is 18.7% and 17.01% above a typical quarter respectively, while for Sonora the warmest quarter is 23.3%. It is necessary to deepen the relationship between different soil characteristics and climate elements such as temperature and precipitation, which influence the distribution of different soil-transmitted diseases.

---

* Corresponding author.
E-mail address: gerardosuz@comunidad.unam.mx (G. Suzán).
Peer review under responsibility of KeAi Communications Co., Ltd.

https://doi.org/10.1016/j.idm.2021.05.002

1. Introduction

Salmonella spp. is one of the most complex groups of bacterial organisms of the Enterobacteriaceae family, and is classified into serovars based on lipopolysaccharides (O), flagellar proteins (H), and sometimes capsular antigens (Vi) (CFSPH, 2013). There are more than 2600 serovars described to date (Barreto et al., 2016; CDC, 2013; Contreras et al., 2019). According to the classification scheme used by the Centers for Disease Control and Prevention (CDC), the World Health Organization (WHO) and other studies (IICAB, 2005), there are currently only two species: *S. bongori* and *S. enterica* consisting of six subspecies *enterica*, *salamae*, *arizonae*, *diarizonae*, *houtenae*, and *indica* (Brenner et al., 2000). However, most of the serovars that cause disease in humans and other mammals belong to *S. enterica* subsp. *Enterica, including Salmonella* ser. Typhi, *Salmonella* ser. Paratyphi and *Salmonella* ser. Hirschfeldii which are human pathogens (Feasey et al., 2012). They are mainly transmitted from person to person and have no major animal reservoirs. The other serovars of *Salmonella* are sometimes designated as non-typhoidal *Salmonella*, and are zoonotic or potentially zoonotic (IICAB, 2005; Tennant et al., 2016).

In recent studies (Figueroa et al., 2005; Jara, 2017), salmonellosis could have unconventional sources or secondary reservoirs, such as well water, soil, rearing beds and carcasses where microorganisms survived for very long periods, but they do not multiply normally as they do in the digestive systems of animals. These bacteria can resist dehydration for a very long time, both in feces and in food for human or animal consumption (Acha & Szyfres, 2001; Pegues et al., 2002). Despite the fact that this bacterium predominantly resides in the gastrointestinal tract of warm- and cold-blooded animals, and it is ubiquitous in natural environments, where it deploys survival strategies. This allows it to prevail for prolonged periods in soils and sediments, adapting to stressful conditions of temperature, pH, desiccation, osmotic and nutritional stress, as well as predation, facilitating their survival, environmental dispersal and reaching new hosts (Donlan & Costerton, 2002; Tamagnini and Paraje, 2015).

The ability of the pathogenic strains of *Salmonella* spp. to survive in the environment depends on extrinsic and intrinsic factors: soil type, ambient temperature, humidity level, as well as bacterial resistance to external conditions (Klapecl et al., 2016). There are very few studies regarding the detection of *Salmonella* spp. in non-host sources such as soils (Winfield and Groisman 2003), which makes it practically impossible to estimate their real presence and distribution, thus it is unknown with scientific certainty, whether or not they represent a risk to the human and animal populations,. In spite of studies that consider contamination with *Salmonella enterica* could be due to contamination of soils (Jechalke et al., 2019). To understand this relationship, it is important to consider the influence of edaphic characteristics of *Salmonella* spp.: the distribution, the presence of other species that inhabit the soil, and the climatic factors driving the physicochemical, and microbiological characteristics of the soil. Barreto et al. (2016) and Contreras et al. (2019), have suggested implementing surveillance systems for *Salmonella* spp. in environmental samples, which identifies the effect of anthropogenic activity and anticipates the emergence of new strains or serotypes with potential public health impact. Few studies worldwide have associated these variables with *Salmonella* spp. outbreaks and in Mexico this relationship is practically unknown.

The need to identify distribution patterns of *Salmonella* spp. in Northwestern Mexico is important because of the high prevalence of *Salmonella* spp. in the three states of the region (Chihuahua, Sonora and Baja California) where edaphic and climatic factors are characterized by high temperatures. Also, this region stands out for occupying the fourth and fifth place in Mexico's food production (Chihuahua and Sonora, respectively) with extensive agricultural lands, while Baja California ranks second in the country in productive value per hectare harvested (INEGI, 2014a). For this reason, it is necessary to know how the predominant environmental factors in Northwestern Mexico regulate and influence the infection dynamics and distribution patterns of *Salmonella* spp. To understand dispersal dynamics of *Salmonella* spp. in the environmental studies and reconstruct the historical dispersion through time and space are required. To do so requires considering both geographic areas and sources of isolation studying the diversity profiles of populations of *Salmonella* spp. and establishing the specific role that each of the factors plays when *Salmonella* spp. switches from the environment to a new host. As these biological processes and interactions are recognized, the design and implementation of efficient strategies for prevention, diagnosis and control are needed, with the aim of preventing epizootic and epidemic outbreaks and minimizing the impact on public and animal health.

To understand the patterns of distribution and occurrence of species and infections, different models have been developed in the field of biogeography (Richardson and Whittaker, 2010). New techniques and tools have been developed in the last two decades to increase the predictive capacity to project the geographical-ecological space (Guisan & Thuiller, 2005), and niche amplitude estimation and prediction (Carrillo et al., 2016). In this way, habitat suitability consists of the mathematical or statistical relationship between the real known distribution and a set of independent environmental variables that are used as indicators (Wiens et al., 2010, Romero & Ramírez, 2016). One of the most widely applied local spatial interpolation techniques is the geostatistical or kriging method, which incorporates a mathematical model that describes the spatial variation of the data through a measure of the spatial autocorrelation between pairs of points, which describe the variance in a given distance (Hernández et al., 2011). Currently, spatial models include environmental, biological and anthropogenic variables, which makes it easier to decide on conservation priorities (Anderson et al., 2003; Sánchez et al., 2001). *Kriging* uses the degree of spatial autocorrelation between sampling sites to obtain estimates at unmeasured sites, considering the most appropriate Best Non-Biased Linear Predictor (MPLI) in the sense that minimizes the variance of the error in the prediction. It is based on the fact that natural variables are generally continuously distributed (Burrough & McDonell, 1998; Moral, 2004). One of its greatest advantages is that it provides a measure of the error or uncertainty of the estimated surface. Therefore, a theoretical distribution can be associated to each point of the estimated space, which also allows the possibility of carrying out probabilistic simulations and showing the result as the probability that each variable reaches a certain value (Cañada, 2004; Hernández et al., 2011; Moral, 2003).

Based on a geographical-ecological approach and using the kriging method the objective of this research was to define which edaphic and climatic factors influence the occurrence and prevalence of *Salmonella* spp. impacting public health in the Northwestern Mexico.

2. Material and methods

2.1. Study area

Northwestern Mexico includes three states: Baja California, Sonora and Chihuahua (Fig. 1). The state of Baja California is limited between 32° 43′07″, and 28° 00′00″ north latitude; and between 112° 45′54 ″ and 117° 07′27″ west longitude. Geologically, it comprises the physiographic Province of the Baja California Peninsula and the Sonoran Plains, composed mainly of crystalline rocks of the Cretaceous or pre-Cretaceous ages, and the height ranges from sea level to 3095 m asl (Peinado and Delgadillo, 1990).

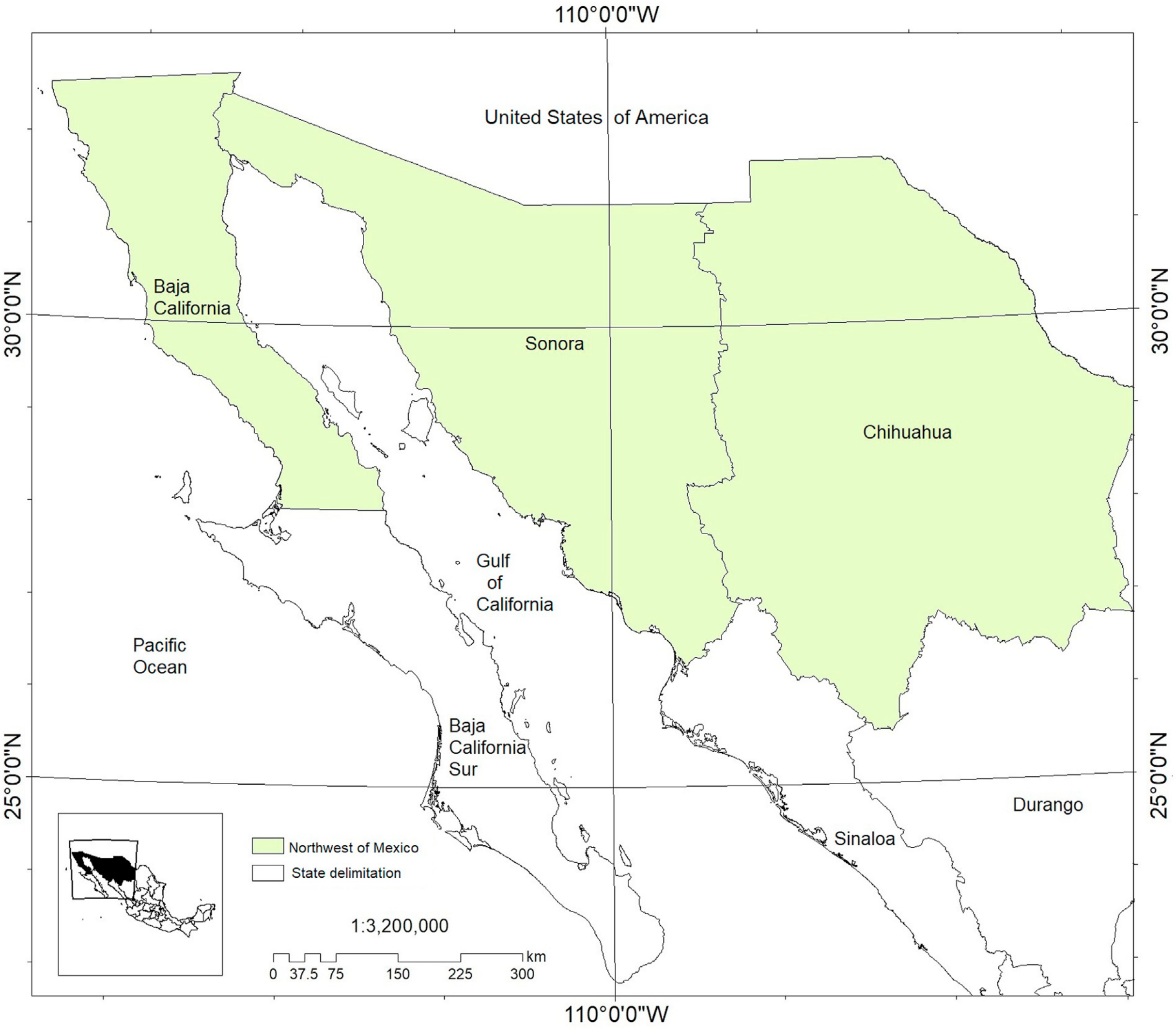


Fig. 1. Delimitation of the study area.

In the Baja California Peninsula, most of the soils are azonal and poorly developed. The taxonomic units that are around 60 cm deep constitute 73.88% of the surface and are of the regosol, lithosol and pheozem types. The peninsula is poor in water resources, the river currents are few and the volumes that run through them are small and ephemeral. It has an arid climate, considered as very dry in 69% of the state, dry in 24%, and temperate subhumid and semi-cold in (7%). The average annual temperature ranges between 18 and 19 °C with the highest temperatures, higher than 30 °C in the months of May to September and the lowest, around 5 °C in January. The average annual rainfall in the entity is 287 mm with a pluviometric amplitude that ranges between 60 and 500 mm. In most of the province, vegetation is characterized by various types of xerophytic scrubs, chaparrals, desert communities and sandy desert vegetation. It is characterized by a high degree of endemism, so its contribution to the national biological diversity is important (POEBC, 2014; Rosete et al., 2008).

The state of Sonora is located between 26° 17′ 49″ and 32° 29′38″ N, and between 108° 25′27 ″ and 115° 03′11″W. The landscape that is currently appreciated is the result of the intense volcanic orogenic activity that gave rise to the Sierra Madre Occidental. Its main rivers include Colorado, Sonora, Yaqui and Mayo. The most widely distributed soils are regosol that covers large areas of the plains and slopes in the western and central portions of the state, with the exception of the irrigation districts, where yermosols and xerosols dominate. Likewise, lithosols, shallow soils found in the mountains occupy a considerable surface (INEGI, 2000). The average annual temperatures throughout the year fluctuate between 10 and 30 °C, precipitation ranges from less than 100 to up to 900 mm in the middle and upper parts of the mountain system (INEGI, 1997). The state has 17 vegetation types, seven corresponding to the Sonoran Desert and one of transition to the Chihuahuan Desert, resulting in desert vegetation with a great diversity in structural forms. These bushes or shrubs, less than 4 m high, represent, together with halophilic vegetation and mangroves, the totality of the vegetation present in the desert region of the state. In the mountainous area different types of oak and coniferous forests are relevant, with tropical and subtropical vegetation in the mountain canyons. Vegetation, flora, fauna and the physical environment establish complex functional relationships at the ecosystem level that translate into great biological diversity (Martínez et al., 2010).

The state of Chihuahua extends between 31° 47′04″ and 25° 33′32″ north latitude, and between 103° 18′24 ″ and 109° 04′30″ west longitude. In terms of surface hydrology, it has the slopes of the Sierra Madre to the Pacific Ocean, the interior valleys of the Chihuahuan Desert, and the Río Bravo watershed that drains to the Gulf of Mexico. The predominant soils are regosols (26.88%), lithosols (22.74%), xerosols (20.04%) and feozems, (12.04%). Dry climates predominate in 73.53% of the state, located in the central-eastern part and in the plains, in systems of slopes and hills, as well as in the parallel mountain ranges. The remaining 23.24% of the surface have temperate and semi-cold climates characteristic of the high-altitude regions, and finally in 3.22% of the area climates are semi-warm ones in the area of ravines and canyons of the Sierra Madre Occidental. The average annual rainfall is 524.25 mm, ranging between 179.90 and 1208.90 mm. Vegetation comprises coniferous forest located in the Sierra Madre Occidental at altitudes from 2400 to 3000 m, with temperate humid climates, mean annual temperature of 11–17 °C, and with annual precipitation between 650 and 1000 mm. The oak forest develops on the slopes of the Sierra Madre Occidental, in an altitudinal range of 800 to 2000 m. The climate is dry temperate, with an annual average temperature of 14–16 °C and annual rainfall between 400 and 1000 mm. While the tropical deciduous and sub-deciduous forest is unique among canyons in the wooded part of the Pacific slope, between 400 and 900 m above sea level. The climate is humid and semi-warm, with an annual average temperature of 22–25 °C; annual rainfall of 600–800 mm, with six dry months (Royo et al., 2013). The entity has a great biological diversity, and without a doubt, the flora and fauna and the ecosystems that make up the Chihuahuan landscape and orography require its conservation (CONABIO, 2014).

2.2. Data collection and spatial analysis

This research comprises three phases: 1) data collection and calculation of bioclimatic profile variables, 2) generation of thematic cartography and 3) spatial analysis of data and study variables. For each phase geostatistical analysis tools of the ArcGIS program were used; the data corresponding to the edaphic variables were obtained from 170 samples of the data set of soil profiles at scale 1: 250,000, series II (Continuo Nacional) (INEGI, 2013) and from the soil erosion data set at scale 1: 250,000 series I (Continuo Nacional) (INEGI, 2014b): depth, pH, texture, percentage of organic matter and percentage of humidity.

The bioclimatic parameters were calculated for 48 meteorological stations in the three Northwestern Mexico states. Data obtained from the 1981–2010 monthly meteorological database of the National Meteorological Service, following the ANUCLIM methodology also used in Worldclim (Fernández et al., 2014) produced the 19 variables that make up the bioclimatic profile.

Subsequently, geographic records of *Salmonella* spp. from the Institute for Epidemiological Diagnosis and Reference (InDRE), the National Center for Diagnostic Services in Animal Health (CENASA), the International Regional Organization for Agricultural Health (OIRSA) and at the National Service for Agrifood Health, Safety and Quality (SENASICA) were obtained from the epidemiological bulletins of the National Epidemiological Surveillance System, and the Unique Information System for Epidemiological Surveillance (SUIVE). In addition, the Federal Commission for the Protection against Sanitary Risks (COFEPRIS) and SENASICA have reported through Whole Genome Sequencing (WGS) the geographic distribution of serotypes with the highest circulation in Baja California (Typhimurium, Infantis, Rissen), Sonora (Agona, Braenderup, Muenchen, Kentucky, Typhimurium, Schwarzengrund) and Chihuahua (Newport, Typhimurium, Enteritidis, Braenderu, Infantis, Molade and Thompson) (COFEPRIS, 2018).

From the records of the presence of *Salmonella* spp. topological superpositions were made to extract the values of each site in the form of a plot for the selected factors and the cartography corresponding to bodies of water, vegetation, land use, roads, human settlements, and Protected Natural Areas (ANP's). Subsequently, cartographic algebra was carried out, including a large set of operators or algorithms executable on one or more input raster layers to produce one or more output raster layers (Buzai & Baxendale, 2006). For this, the investigations of Thrusfield (2007) and Barreto et al. (2016), who report the behavior of the bacteria and its relationship with multiple factors, have been epidemiologically classified into three large groups according to their origin: factors of the biological agent itself, the environment, and the host (Fig. 2). The temporal and geographical interrelationship between these elements explains the natural history of the disease development (Table 1). Finally, seasonal time series were characterized, from the monthly records of *Salmonella* spp. in four periods (hot, rainy, dry and cold).

2.3. Theory and calculation

For the edaphic and climatic variables, an ordinary kriging interpolation was performed: producing reliable restructured surfaces considering the spatial structure using raw variables to minimize the variance of the errors, which it is considered the most conservative method to obtain comparable layers. The krigeaje is presented with a uniform resolution (Hartkamp et al., 1999; Lima et al., 2015; Varela et al., 2015). In this geostatistical design, an ordinary predictive kriging was performed, and a spherical model was fitted to the spatial structure, up to a distance above which the autocorrelation was zero, in this case, 15 m from any sample point. The biophysical profiles obtained synthesized the environmental conditions of the analyzed sites and represented the factors that make up the potential distribution of *Salmonella* spp.

The term “kriging” was originally used by Georges Matheron (Matheron, 1963) in honor of the South African mining engineer D.G. Krige, who carried out early work on this method (Krige, 1951). The ordinary kriging interpolator $\hat{Y}(x)$ is a linear interpolation, which meanings that it is defined by an equation. Kriging interpolation is based on the assumption of a probability model for $\hat{Y}(x)$, and is derived within that model with the objective of minimizing the variance of the interpolator $\hat{Y}(x)$ (Plant, 2019).

Given a set of position coordinate vectors {x1, x2, … xn}, where each coordinate vector xi has two components (horizontal x and vertical y), and given a set of values Y (x1), i = 1,2, … n measured at these locations, to compute an interpolation of the value Y(x) at a location x where the value of Y is not measured. Fig. 3 shows a schematic example in which n = 3; of course in real situations n will generally be larger than this (Plant, 2019).

An interpolator $\hat{Y}(x)$ is called a *linear interpolator* if for some set of coefficients ϕ_i, $i = 1\ 2, \ldots, n$,

$$\hat{Y}(x) = \sum_{i=1}^{n} \text{ø}iY(xi).$$

If the values Y (x1) are spatially uncorrelated, then their spatial location is irrelevant and the best interpolator is the mean $\hat{Y}(x) =$, independent of x. If, however, the values of Y (x1), are positively spatially autocorrelated, then we can expect that values of Y (x1) measured at locations close to x will be closer to the value of Y(x) than values that are farther away. For example, in Fig. 3, one would expect that the value of Y (x3) will be closer to that of Y(x) than will the value of Y (x1), with Y (x2) landing somewhere in between. Thus, one would expect that increasing the value of $\phi 3$ in relation to $\phi 1$ and $\phi 2$ in the equation would in this case produce a more accurate interpolation (Plant, 2019).

A derivation of the equations of the ordinary kriging estimator is given by Isaaks and Srivastava (1989). The error variance is given by

$$\text{var}\left\{\hat{Y}(x) - Y(x)\right\} = \text{var}\left\{\sum_{i=1}^{n} \text{ø}iY(xi) - Y(x).\right.$$

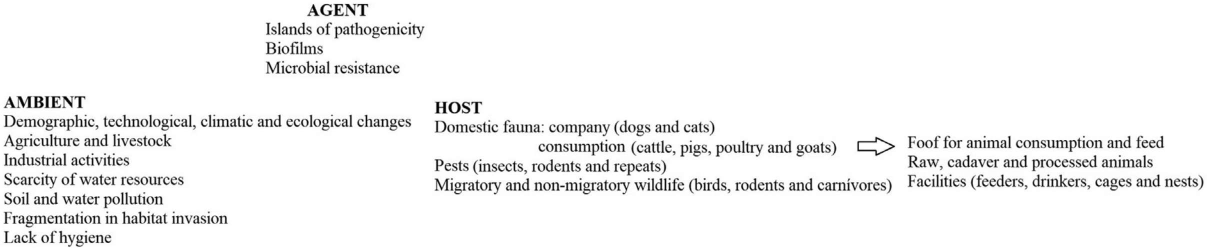


Fig. 2. Behavior of *Salmonella* spp. and its relationship with edaphic and climatic factors in three northwestern Mexican states. Own elaboration with information from Barreto et al. (2016).

Table 1
We designed this table with data from Costerton et al., 1999; Palacios et al., 1999; Gutiérrez et al., 2000; ESR, 2001; Donlan y Costerton, 2002; Winfield y Groisman, 2003; Martínez et al., 2004; FAO, 2005; Figueroa y Verdugo, 2005; Ledeboer y Jones, 2005; Constantin, 2009; Jensen et al., 2010; Silva et al., 2012; Steenackers et al., 2012; FSANZ, 2013; Barreto et al., 2016; WHO, 2016; Contreras et al., 2019; Godínez et al., 2019; Wang et al., 2020.

Own factors biological agent	Environmental factors	Host factors
Islands of biopathogenicity. This bacterium has 23 pathogenicity islands, of these, five are common to all serotypes: SPI-1, SPI-2, SPI-3, SPI-4 and SPI-5.	Soil characteristics: Type of agricultural soils especially when they are irrigated with treated water Clay texture, influences porosity and infiltration Depth 15—45 cm up to 120 cm Optimal pH (6.5—7.5) (5.5—7.4) range (3.8—9.5) Organic matter high concentration of nutrients, since it is a substrate and a means of propagation % humidity is capable of surviving from 13 to 10 days after irrigation and during the night, in the absence of radiation, and in a favorable humid environment they multiply Temperature persists in poorly composted bio-fertilizers due to its ability to tolerate a wide temperature range (7—49.5 C) and its ability to adhere to small soil particles	They are transmitted mainly by the fecal-oral route through direct contact with infected animals or through person-person contact. They are transported asymptomatically in the intestine or gallbladder of many animals and are excreted continuously or intermittently through the feces. They can also be transported latently in the mesenteric lymph nodes or tonsils; these bacteria are not excreted but rather reactivated after stress or immunosuppression.
Biofilms. Once the bacteria are released into the environment, they face non-host conditions that induce the bacteria to form bacterial associations surrounded by a polymeric matrix adhered to living or inert surfaces and can be formed in three interfaces: liquid-air, solid-air and solid-liquid.	Water bodies They can be natural or artificial, and are influenced by temperature, water chemistry and solar radiation for the survival and transport of the microorganism. Also, contamination with dead and decomposing animals, fecal material and garbage. It generally occurs where there is use of untreated groundwater along with inadequate treatment of collected groundwater and contamination of distribution systems.	Human beings. When they eat contaminated food of animal origin such as meat or eggs. They can also become infected by ingesting organisms present in animal feces, either directly or in contaminated food or water.
Microbial resistance. *Salmonella* has two categories of resistance: 1) the uptake of new genetic material or 2) mutations in the bacterial chromosome.	Seasonality. Increase in cases as of May, with a maximum peak in July and August and a decline as of September. It can also intensify in April and May reaching a peak in July, with a decrease in September and October. *S. enterica* cases show seasonal variation, with a higher number of cases reported in June and a lower number in December. Therefore, the highest season for the distribution of *Salmonella* is summer. Temperature. The optimum temperature for growth is between 35 and 37 °C, covering a range from a minimum of 7 °C, to a maximum of 49.5 °C. However, very low growth is reported at temperatures below 15 °C. There is some evidence of growth at 5.2 or 5.9 °C, for a specific serotype. Precipitation. Heavy rains or floods influence the frequency and level of contamination of drinking water.	Animals can be infected from contaminated food or water (including pastures) or from contact with an infected animal (including humans): Fomites and mechanical vectors (insects) can spread the bacteria. Vertical transmission occurs in birds, with contamination of the yolk membrane, albumen, and possibly egg yolk. They can be transmitted in utero to mammals: in particular, carnivores are also infected through meat, eggs, and other animal products that are not cooked properly.

From a theoretical perspective, there are two reasons to prefer kriging to simpler methods. First, if the correct model is used, the methods used in kriging have an advantage over other interpolation procedures in that the estimated values have a minimum error associated with them. This is why the method is sometimes called optimum interpolation. Second, this error is quantifiable. For every interpolated point an estimation variance can be calculated, which depends solely on the semivariogram model, the spatial pattern of the points, and the calculated weights. The estimation variance is given by the weighted sum of the semivariances of the distances from the control points to the location of the estimate (O'Sullivan and Unwin, 2010).

Geostatistical models consider the z (x) value of the regionalized variable at a site x in field D as a realization of a random variable Z (x). To distinguish deterministic variables from random ones, the former is denoted with a lowercase letter and the latter with a capital letter. Thus, the regionalized variable $z = \{z(x), x \in D\}$ is a realization of the random function Z. Contrary to the classical statistical model, the random variables thus defined are not independent and reflect the spatial continuity of the regionalized variable (Emery, 2013).

All kriging-type estimators are variants of the basic linear estimator $Z*(x)$, defined as: $Z*(x) - m(x) = \Sigma\omega(i)\,[Z(xi) - m(xi)]$ where, ωi are the weights assigned to the data z (xi), which are related to the magnitude and proximity of the samples and whose attributes are estimated in the semivariogram. The expected values of the random variables Z (x) and Z (xi) are m (x) and m (xi), respectively (Isaaks and Srivastava, 1989).

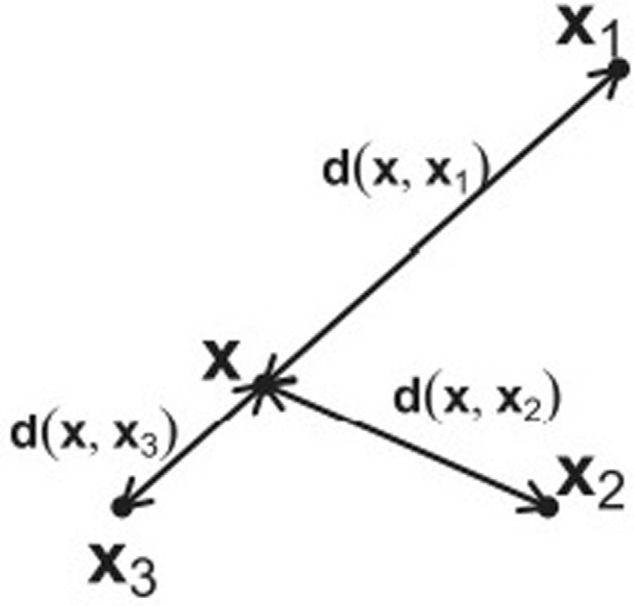


Fig. 3. Schematic representation of the location of three points x_1, x_2 and x_3 at which Y is measured, and a fourth location x, at which the value of Y is to be estimated (Plant, 2019).

3. Results

Considering the seasonality in the distribution of *Salmonella* spp. of the 19 variables that make up the bioclimatic profile, mean temperature (B1), temperature of the warmest month (B5), mean temperature of the wettest month (B8), mean temperature of the warmest quarter (B10), precipitation (B12), precipitation of the wettest month (B13), precipitation of the wettest month (B16) and precipitation of the warmest quarter (B18) were selected for the analysis (Fig. 4). Regarding the edaphic variables, maps were obtained by kriging interpolation of depth, pH, organic matter, texture and humidity (Fig. 5).

The weighting of the risk in high, medium and low is based on the intervals in which *Salmonella* spp. survive according to different authors (Table 2). The superposition of the thematic layers on the records of *Salmonella* spp. shows the differences in the environmental parameters and in their potential distribution, mainly in terms of the selected edaphic and bioclimatic variables. Based on this, we described the potential distribution in three categories: high, medium and low risk (Fig. 6).

Based on the epidemiological bulletins of the National Epidemiological Surveillance System, a total of 118,304 records of *Salmonella* spp. cases in humans were obtained: 30,595 from Baja California, 71,462 in Chihuahua and 16,247 in Sonora (DGE, 2002–2019) (Fig. 7). Where an increase in cases was observed from April to October, however, it is important to mention that the data are grouped in paratyphoid and other salmonellosis, only in the most recent years there is a separation between paratyphoid and other salmonellosis grouped in zoonotic diseases. To interpret the seasonality index, its equivalent in percentage was calculated; above 100% indicates the most outstanding season of the year and below 100% indicates the one with the least influence. Therefore the seasonal time series indicated that for the states of Baja California and Chihuahua the rainy quarter is 18.7% and 17.01% above a typical quarter respectively, and for the cold quarter 23.8% and 16.5% below the typical one. While in the state of Sonora the warm quarter is 23.3% above a typical quarter, and for the cold quarter 26.8% below the typical one (Table 3).

4. Discussion

According to the research consulted, *Salmonella* spp. have a survival interval, which was considered to estimate their potential distribution. However, due to the lack of the precise location of the cases of salmonellosis, it was not possible to correlate edaphoclimatic variables and actual cases. The high, medium and low risk of *Salmonella* spp. distribution is supported by an exhaustive review of previous research. To our knowledge this is the first study integrating edaphoclimatic seasonal trends and variations of the infection by *Salmonella* spp. in Northwestern Mexico. We identified the potential distribution areas of *Salmonella* spp. as well as an intermediate zone where human activities can contribute to the conservation of ecosystems, or increase the potential incidence of the bacteria due to the proximity to livestock areas and the use of contaminated water to irrigate crops. Although little is known in Mexico about the biogeography of the genus *Salmonella* spp. and its patterns of occurrence, some review studies have reported from January 1968 to March 2018 the presence of at least

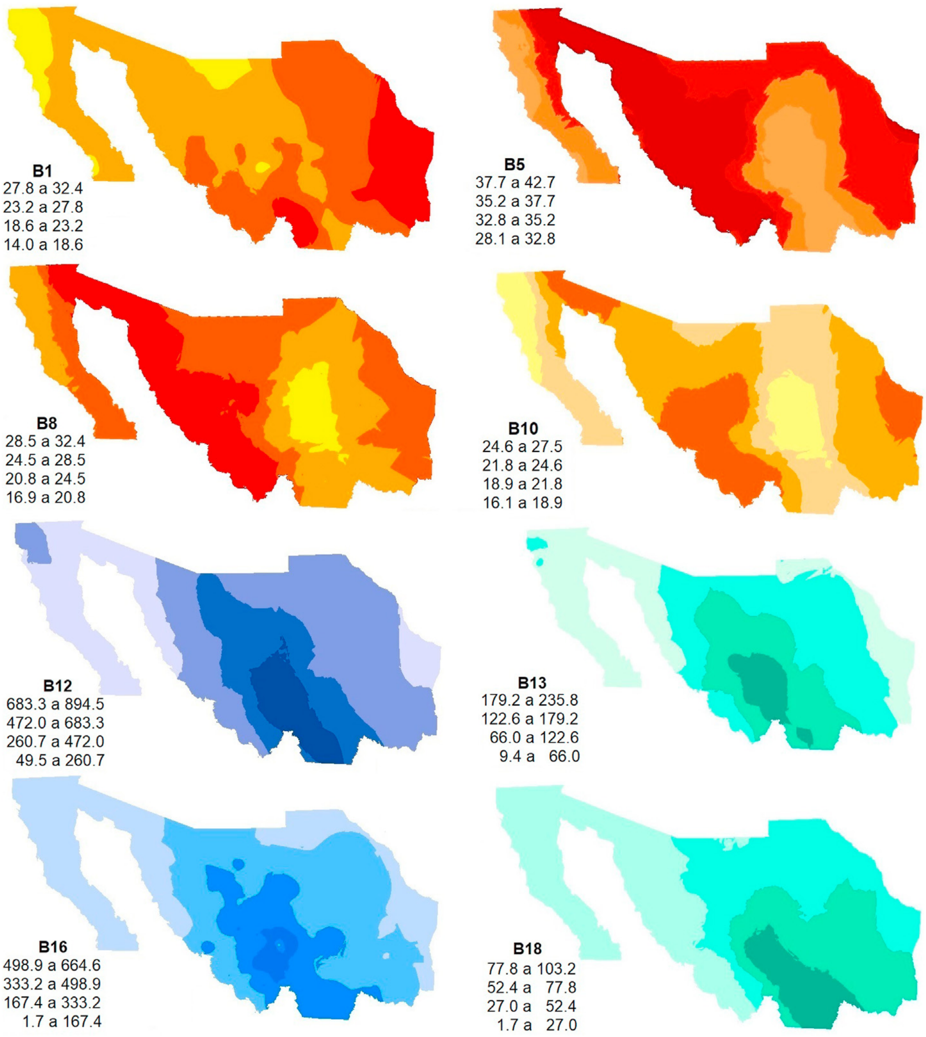


Fig. 4. Kriging geostatistical interpolation for the selected variables of the bioclimatic profile in Baja California, Sonora and Chihuahua. BIO1 average annual temperature, BIO5 maximum temperature of the warmest month, BIO8 average temperature of the wettest quarter, BIO10 average temperature of the warmest quarter, BIO12 annual precipitation, B13 precipitation of the wettest month, BIO16 precipitation of the wettest quarter and BIO18 precipitation of the warmest quarter.

216 different serotypes of *Salmonella enterica*, with Enteritidis, Typhimurium, Anatum, Agona and Meleagridis being the most prevalent (Contreras et al., 2019). They describe that those of animal origin are the main source of *Salmonella* spp. isolation (42.76%); and states located in ecoregions of hot-humid climates have the highest rates of non-typhoid salmonellosis in Mexico. However, although Mexico is located within this strip of tropical climate, its territory is divided by ecoregions, which are distinguished by unique environmental characteristics that can offer specific niches and represent a challenge to overcome for any microorganism during its life environmental phase.

In particular, *S. enterica* cases shown seasonal variation, with a higher number of cases reported in June (summer) and the lower number in December (winter). This trend coincides with reports from some European countries, Australia and the United States, where there is an increase in salmonellosis infections in the summer (Godínez et al., 2019). In Mexico, the most affected states have been Tabasco, Coahuila, Chiapas and Quintana Roo (Gutiérrez et al., 2000). From this study, the potential incidence of *Salmonella* spp. is mainly low in the states of Baja California, Sonora, and Chihuahua compared to these southern most states responding to edaphoclimatic conditions. According to the reports of the DGE (2002–2019), the state of Chihuahua presents the highest number of records (30,595), followed by Baja California (71,462) and Sonora (16,247); In general, there is a trend in the number of cases from the months of March to October, and the months of January and December have the lowest values. However, in some years there are exceptions.

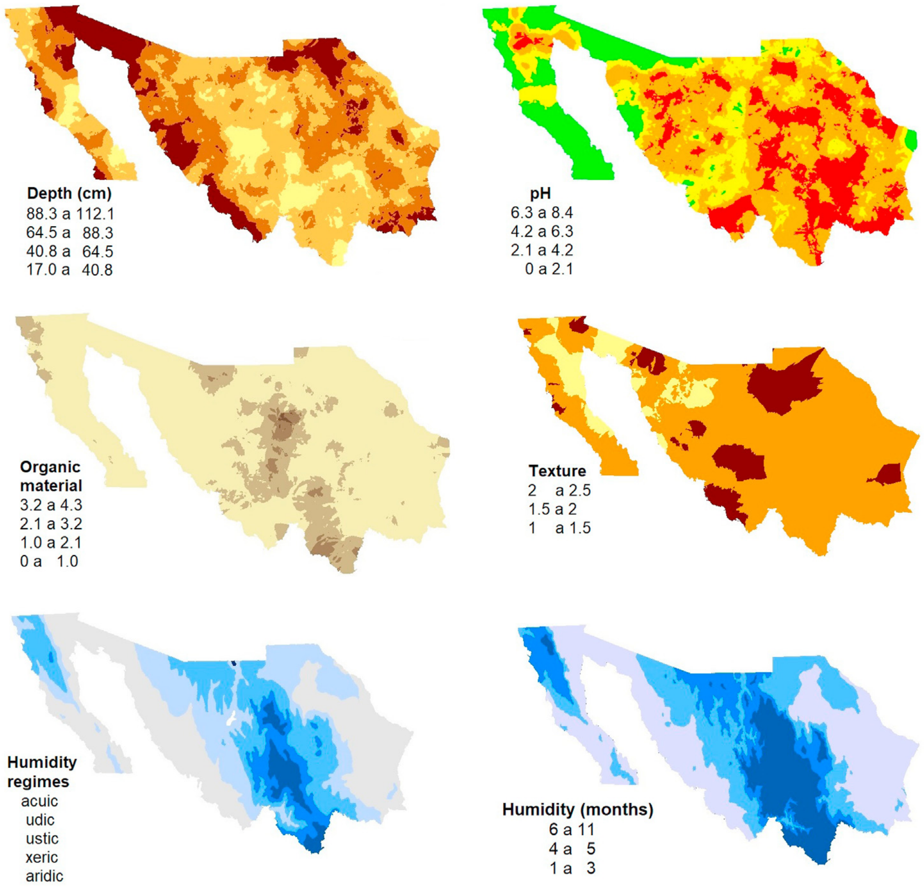


Fig. 5. Kriging geostatistical interpolation for the edaphic variables: depth, pH, material, texture and moisture, in Baja California, Sonora and Chihuahua.

4.1 Climatic variables

Regarding the climatic variables, several authors reported that *Salmonella* spp. proliferate during seasons characterized by high temperatures and rainfall, which can amplify bacterial replication and transmission to surface waters and food crops as possible sources of infection (Grjibovski et al., 2014; Haley et al., 2009; Kovats et al., 2004; Lal et al., 2002; Micallef et al., 2012; Simental and Martínez, 2008; Zhang et al., 2010). Akil et al. (2014) and Jiang et al. (2015) reported that this climatological dynamic has had a direct impact on some regions of the Mexican territory, since climatic events such as hurricanes are more frequent and more intense, and generate serious floods, especially in areas located near the Atlantic Ocean and the coastal part of the North of the country. In addition, extreme environmental conditions such as heat waves, high rainfall and intrinsic characteristics of the pathogen that include the formation of biofilms and antimicrobial resistance in *Salmonella* clones, generate a favorable condition for the establishment, persistence and dispersal of the bacteria in environmental niches (Akil et al., 2014; Angulo et al., 2004; Ledeboer and Jones, 2005).

In Northwestern Mexico, Chihuahua is the state with the highest mean annual rainfall (1184 mm) and in the rainiest (664.9 mm) and warmest (157.9 mm) quarters, which could be an explanation of why it had more cases compared to Baja California and Sonora. However, Baja California is characterized by the lower average annual rainfall (486.1 mm) and the number of cases reported in Baja California is higher with respect to Sonora. For this, Akil (2014), observed a seasonal trend in infections by *Salmonella* spp. and found a strong positive correlation between high temperature infections, while no correlation was also observed between the monthly average precipitation rate and infections. *Salmonella* spp. proliferates more rapidly at higher temperatures, and strong linear associations between temperature and salmonellosis reports have been observed in Europe and Australia. This could be an explanation for a greater number of cases of salmonellosis in Baja California due to a temperature of the warmest month up to 43.9 °C and in the wettest month of up to 33.6 °C, surpassing the

Table 2
Weighting of the edapho-climatic variables in the potential distribution of *Salmonella* spp. for the states that make up the Northwest of Mexico.

Variable	Weighting of the potential distribution
Depth	High: 15–45 cm Mean: 45–120 cm Low: ≥ 120 cm
pH	High: 6.5 to 7.5 which is mainly equivalent to neutral Mean. 5.5 to 6.5 which is slightly acidic Low. 3.8 to 5.5 and of 7.5–9.5 which is moderately acidic and slightly alkaline
Organic material	High: ≥ 6% Mean: 1.5 a 6% Low: 0–1.5%
Texture	High: Fine (clay) Mean: Mean (loamy-silty) Low: Coarse (sandy)
Humidity	High: Acuic with 365 days or its equivalent from six to 11 months Udic with 270–330 days Mean: Ustic 180–270 days or the equivalent of three to six months Xeric with 90–180 days Low: Aridic with 0 to ≤ 90 days or its equivalent from one to three months
Temperature	High: 30 to35 °C Mean: 15 to 34 °C and37 to 49.5 °C Low: 5.2 to 15 °C
Precipitation	High: Warm-wet 2000–4000 mm) Tempered-wet (2000–4000 mm) Warm-subhumid (1000–2000 mm) Mean: Tempered-subhumid (600–1000 mm) Low: Dry (300–600 mm) Very dry (100–300 mm)
Vegetation and use ground	High: Agricultural areas, human settlements and bodies of water Mean: Secondary vegetation Low: Forests, jungles, thickets, mesquite, mangrove, chaparral, tular, grasslands, gallery vegetation, halophyte and sandy deserts.

other two states. Annually, notifications of *Salmonella* spp. get a peak in summer and the notification rate has been shown to correlate positively and linearly with the average temperature of the previous month or week (Bambrick et al., 2008; Russell et al., 2010). It is important to consider that Akil (2014), also indicates that temperature can affect the transmission of infections by *Salmonella* spp. through various causal pathways, such as direct effects on bacterial growth and indirect effects on eating habits during hot days.

4.2 Edaphic variables

Furthermore, environmental factors can affect directly or indirectly microbial populations. The bacterium is capable of use organic matter as a substrate favoring propagation (Islam et al., 2004; Johannessen et al., 2005). Being this percentage the edaphic characteristic that limits the presence of *Salmonella* spp. on soil in Northwestern Mexico. The increase in *Salmonella* spp. in soil can be related to factors such as, nutrient concentration and the decrease associated with the degradation of organic matter carried out by the soil's own microorganisms, which compete with other bacteria species for nutrients and space. For example, the decrease in the concentration of nitrites, phosphates and organic matter are factors that contribute to the decrease of the organism (Holley et al., 2006). According to Palacios et al. (1999), agricultural soils present characteristics that could be suitable for these bacteria, especially when they are irrigated with purified water, given the high concentration of nutrients and the existing humidity and temperature values. Rodríguez et al. (2008) reported that *Salmonella* spp. persists in poorly composted bio-fertilizers due to its ability to tolerate a wide range of temperature (7–49.5 °C) and its ability to adhere to small soil particles (Wilkinson, 2007).

Another edaphic variable that limits the incidence of *Salmonella* spp. in the study area is the soil moisture content, because it influences the activity of microbial populations in different ways, since as the water dries, the films become thinner and affect the availability of the water and the osmotic ratios of cells. Bacteria (although many measured less than 1 μm o nm in diameter) have easy motility in films that are significantly thicker than 1 μm, regardless of whether they can grow at lower humidity (Julca et al., 2006). *Salmonella* spp. is able to survive in soil and plants for at least 13 to 10 days after irrigation with contaminated water. *Salmonella* spp. multiply in the absence of radiation, during the night and in a favorable humid environment (Palacios et al., 1999).

In Northwestern Mexico, arenosol (20.6%), leptosol (20.3%), regosol (14.1%), fluvisol (11.2%) and calcisol (11.1%) soils were distributed among others with less than 10%. Therefore, the texture in most of the territory is average. According to Natvig et al. (2002) and Franz et al. (2005), soils with clay textures favor the possibilities of colonization of *S.* Typhimurium due to particle size, aggregate formation, water retention and oxygen tension. These factors probably allowed the adherence of the

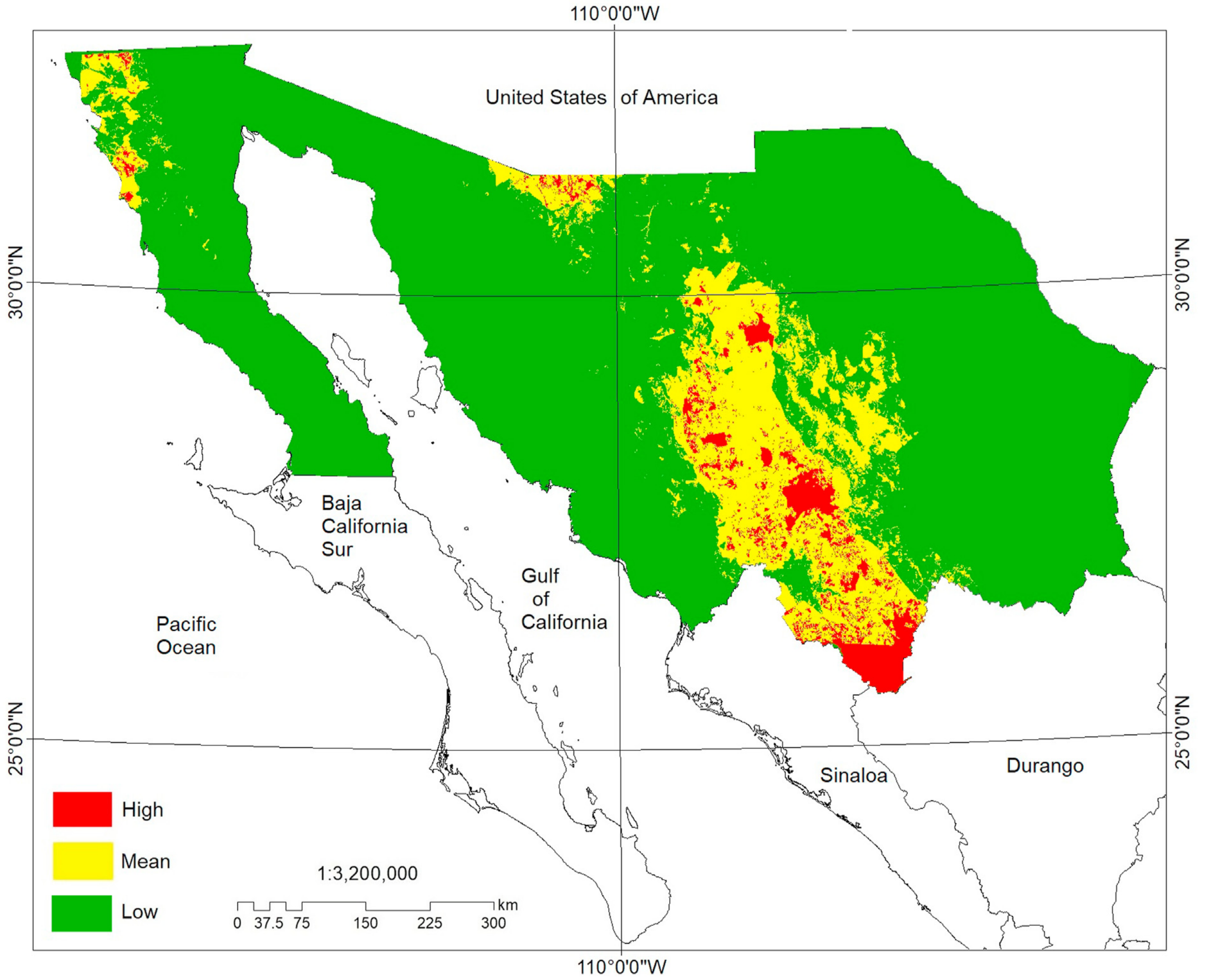
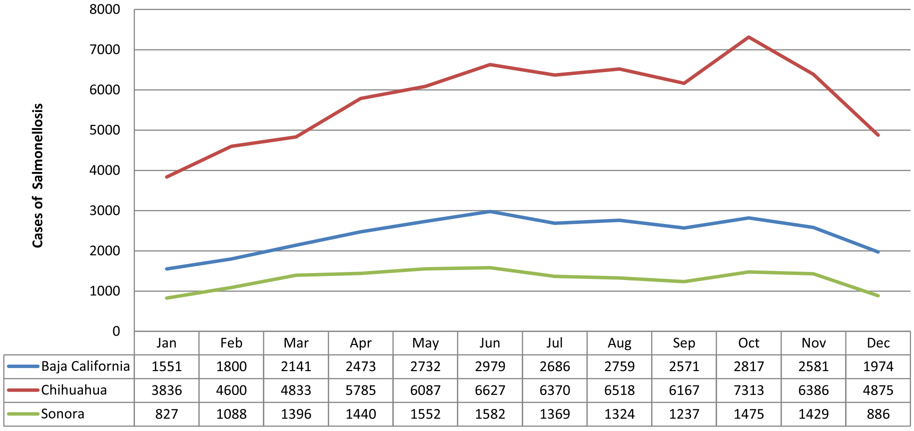


Fig. 6. Potential distribution of *Salmonella* spp. in Baja California, Sonora and Chihuahua considering the edaphic variables (humidity, depth, pH, organic matter content and texture), presence of bodies of water and vegetation and soil use.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Baja California	1551	1800	2141	2473	2732	2979	2686	2759	2571	2817	2581	1974
Chihuahua	3836	4600	4833	5785	6087	6627	6370	6518	6167	7313	6386	4875
Sonora	827	1088	1396	1440	1552	1582	1369	1324	1237	1475	1429	886

Fig. 7. Cases by state of Paratiphoid and other Salmonellosis in the period between 2002 and 2019.

microorganism and its maintenance during the eight weeks of culture. *S.* Typhimurium decreases its growth by one unit every 14 days if it is in a temperature of 4 °C and increases in temperatures close to 22 °C. Palacios et al. (1999) reported the presence

Table 3
Seasonal time series for the records of Paratyphoid and other Salmonellosis in the period between 2002 and 2019 in the warm, rainy, dry and cold quarters. The values indicate the average seasonal index and its equivalent in percentage.

Seasonality Baja California			Seasonality Chihuahua			Seasonality Sonora		
Warm	1.16709	116.83%	Warm	1.083483	109.49%	Warm	1.22841	**123.32%**
Rainy	1.186029	**118.72%**	Rainy	1.157858	**117.01%**	Rainy	1.02995	103.40%
Dry	0.882289	88.32%	Dry	0.88615	89.55%	Dry	0.99695	100.08%
Cold	0.760614	76.14%	Cold	0.830772	83.95%	Cold	0.72911	73.20%

of *Salmonella* spp. in the soils at the depth from 17 to 112 cm in Northwestern Mexico and also reported the presence of *Salmonella* spp. in soil samples at a depth of 15–45 cm, which were watered with and the bacteria added. These authors mention the concentration of *Salmonella* spp. was higher at the soil surface and decreased with depth, due to the filtering effect of the soil, which coincides with Al-Nakshabandi et al. (1997). On the other hand, Rosas et al. (1984) have shown the presence of a significant number of bacteria even at a depth of 120 cm, attributing it to the porosity of the soil and the infiltration of contaminated water.

Weissinger et al. (2000) indicate that the optimum pH for *Salmonella* spp. ranges between 5.5 and 7.4 and its increase is due to the acidic pH generated by the transformation of organic matter. In Northwestern Mexico, the pH in the three states ranges from very acidic to slightly alkaline. The minimum pH at which *Salmonella* spp. can grow is determined by temperature, salinity, and the type of acid present. Outside the pH range, the cells become inactivated, however, it is not immediate and *Salmonella* spp. have been shown to live long periods of time in acidic environments.

4.3 Vegetation the missing variable

Finally, the performance of the types of vegetation and land use in the study area indicates that the most susceptible areas are those associated with agricultural activities and the presence of human settlements. Secondary vegetation was considered a transition variable for conservation or with the possible incidence of *Salmonella* spp., because secondary vegetation is a community composed of a variable floristic composition depending on the time of abandonment (Castillo & Laborde, 2004) and which manifests itself after an ecosystem has been disturbed by factors such as: natural fires, falling trees due to strong winds, selective extraction of trees, agricultural activity, among others (Gómez & Vázquez, 1985). Other susceptible areas are territorial waters because they represent a common source of transmission, they receive agricultural drainage where *Salmonella* spp. can survive and reproduce. The detection of different serotypes and multiple isolates in water can be an expression of this contamination problem (Barreto et al., 2016).

5. Conclusions

We describe the potential distribution of *Salmonella* spp. with the kriging interpolation method for the 15 selected environmental variables and represent a novel way to estimate area of potential risk for soil-borne diseases. Areas with potential are those with temperatures between 35 and 37 °C and a precipitation greater than 1000 mm. We identified that edaphic variables limited the prevalence and geographical distribution of *Salmonella* spp., especially in this region, because it has a low percentage of organic matter ($\leq$4.3), and most of the territory is classified as arid and xeric, which implies that humidity comprises $\leq$ 180 days a year. Seasonal time series indicated that in the states of Baja California and Chihuahua the rainy quarter of the year is 18.7% and 17.01% above a typical quarter respectively, while for Sonora the warmest quarter occurred was 23.3%., These parameters may explain why 30,595 human cases of paratyphoid and other salmonellosis have been reported in Baja California state, 71,462 in Chihuahua and 16,247 in Sonora from 2002 to 2019.

Salmonella spp. is a bacterium that presents a complex transmission cycle that involves edaphoclimatic, hydrological, land use characteristics, as well as interactions with humans, domestic and wild fauna. Salmonellosis are grouped into Foodborne Diseases (ETA) and Acute Bacterial Diarrheal Diseases (EDAS), generating significant socioeconomic damage. They are considered one of the main microbiological risks for public health and food safety, because they are on the list of the main causes of morbidity in Mexico and indicate the lack of safety in food production. Understanding and preventing these zoonoses implies the development of research from an ecological approach that help to identify risk areas preventing animal and public health threats.

Although Mexico has the National Epidemiological Surveillance System, there is still much to investigate in terms of the geographical distribution of the different serotypes and the edaphoclimatic, hydrological, land use characteristics, as well as their interaction with humans, domestic and wild fauna. It is also important to promote research and the registry of other zoonotic salmonellosis, since they generally tend to be reported together with paratyphoid.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We want to thank the DGAPA postdoctoral program and the School of Veterinary Medicine from the National Autonomous University of Mexico (UNAM), and the CONACyT project “Fronteras de la Ciencia” 2016. No. 2016-01-1851.

References

Zoonosis y enfermedades transmisibles comunes al hombre y a los animalesAcha, P., & Szyfres, B. (Eds.). *Publicación Científica, 1*(580), (2001), 240–253.

Akil, L., Ahmad, A., & Reddy, R. (2014). Effects of climate change on *Salmonella* infections. *Foodborne Pathogens and Disease, 11*(12), 974–980.

Al-Nakshabandi, G., Saqqar, M., Shatanawi, M., Fayyad, M., & AlHorani, H. (1997). Some environmental problems associated with de use of treated wastewater for irrigation in Jordan. *Agricultural Water Management, 34*, 81–94.

Anderson, R. P., Lew, D., & Peterson, A. T. (2003). Evaluating predictive models of species distributions: Criteria for selecting optimal models. *Ecological Modelling, 162*, 211–232.

Angulo, F., Nargund, V., & Chiller, T. (2004). Evidence of an association between use of anti-microbial agents in food animals and antimicrobial resistance among bacteria isolated from humans and the human health consequences of such resistance. *Journal of Veterinary Medicine A, 51*, 374–379.

Bambrick, H., Dear, K., Woodruff, R., Hanigan, I., & McMichael, A. (2008). The impacts of climate change on three health outcomes: Temperature-related mortality and hospitalizations, salmonellosis and other bacterial gastroenteritis, and population at risk from dengue. *Garnaut Climate Change Rev*, 1–47.

Barreto, M., Castillo, M., & Retamal, P. (2016). *Salmonella enterica*: Una revisión de la trilogía agente, hospedero y ambiente, y su trascendencia en Chile. *Revista chilena de infectología, 33*(5), 547–557.

Brenner, F., Villar, R., Angulo, F., Tauxe, R., & Swaminathan, B. (2000). *Salmonella* nomenclature. *Journal of Clinical Microbiology, 38*, 2465–2467.

Burrough, A., & McDonell, A. (1998). *Principles of geographical information systems. Spatial information systems and geostatistics*. Oxford University Press.

Buzai, G., & Baxendale, C. (2006). *Análisis socioespacial con Sistemas de Información Geográfica*. Argentina: Lugar Editorial S.A.

Cañada, M. (2004). Aplicación de la geoestadística al estudio de la variabilidad espacial del ozono en los veranos de la comunidad de Madrid. In C. García, D. Liaño, F. Arróyabe, P. Garmendia, & D. Rasilla (Eds.), *El clima entre el mar y la montaña* (pp. 451–462). España: Asociación Española de Climatología y Universidad de Cantabria.

Carrillo, I., Suzán, H., Mandujano, M., Golubov, J., & Martínez, J. (2016). Niche breath and the implications of climate change in the conservation of the genus Astrophytum (Cactaceae). *Journal of Arid Environments, 124*(1), 310–317.

Castillo, G., & Laborde, D. (2004). La vegetación. In S. Guevara, J. Laborde, & G. Sánchez (Eds.), *Los tuxtlas. El paisaje de la Sierra* (pp. 231–265). Xalapa: Instituto de Ecología, A.C. y Unión Europea.

CDC (Center for Disease Control and Prevention). (2013). *Surveillance for foodborne disease outbreaks. United states (2009- 2010) morbidity and mortality weekly report (MMWR)* (Vol. 62, pp. 41–47).

CFSPH (The Center for Food Security and Public Health). (2013). *Salmonellosis .paratyphoid, nontyphoidal salmonellosis*. Estados Unidos: Iowa State University.

COFEPRIS (Comisión Federal para la Protección contra Riesgos Sanitarios). (2018). *Innovación en los Laboratorios. 5ta Reunión Nacional de Alimentos Mesa redonda 1: Sistema Nacional de Control de Alimentos*. México: Secretaría de Salud.

Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO). (2014). *La diversidad en Chihuahua estudio de estado*.

Constantin, O. (2009). Bacterial biofilm formation at air liquid interfaces. *Innovative Romanian Food Biotechnology, 5*, 18–22.

Contreras, M., Medrano, J., Ibarra, J., Martínez, J., Chaidez, Q., & Castro, N. (2019). The last 50 years of *Salmonella* in Mexico: Sources of isolation and factors that influence its prevalence and diversity. *Revista Biociencias, 6*(nesp). Inocuidad Alimentaria, e540.

Costerton, J., Stewart, P., & Greenberg, E. (1999). Bacterial biofilms: A common cause of persistent infections. *Science, 284*, 1318–1322.

DGE (Dirección General de Epidemiología). (2002-2019). *Boletín epidemiológico. Sistema nacional de Vigilancia epidemiológica. Sistema único de Información. México: Secretaría de Salud*.

Donlan, R. M., & Costerton, J. W. (2002). Biofilms: Survival mechanism of clinically relevant microorganisms. *Clinical Microbiology Reviews, 15*, 167–193.

Emery, X. (2013). *Geoestadística. Chile*. Facultad de Ciencias Físicas y Matemáticas, Universidad de Chile.

ESR. (2001). *Microbial pathogen data sheets: Non-typhoid salmonellae. New zealand food safethy authority (NZFSA)*. New Zealand Food Safethy Authority (NZFSA).

FAO. (2005). *Resistencia antimicrobiana a Salmonella*. Red Internacional de Autoridades de Inocuidad de Alimentos.

Feasey, N. A., Dougan, G., Kingsley, R. A., Heyderman, R. S., & Gordon, M. A. (2012). Invasive non-typhoidal *salmonella* disease: An emerging and neglected tropical disease in Africa. *Lancet, 379*, 2489–2499.

Fernández, A., Romero, R., & Zavala, J. (2014). Metodologías empleadas en el Atlas Climático Digital de México para la generación de mapas de alta resolución. *GEOACTA, 39*(1), 165–173.

Figueroa, G., González, M., Molina, A., Yáñez, R., Espinoza, J., Serna, M., & Carranza, J. (2005). Indentificación de *Salmonella* spp en agua, leones cantaloupe y heces fecales de iguana en una huerta melonera. *Medicina Interna de México, 21*(4), 255–258.

Figueroa, I., & Verdugo, A. (2005). Mecanismos moleculares de patogenicidad de *Salmonella sp. Microbiologia, 47*(1–2), 25–42.

Franz, E., Van Diepeningen, A., De Vos, O., & Van Bruggen, A. (2005). The effect of cattle feeding regime and soil management type on the fate of Escherichia coli O157:H7 and *Salmonella enterica* serovar Typhimurium in manure, manure-amended soil and lettuce. *Applied and Environmental Microbiology, 71*, 6165–6174.

FSANZ. (2013). *Agents of Foodborne illness* (2nd ed.). Canberra: Food Standards Australia New Zealand.

Godínez, A., Tamplin, M., Bowman, J., & Hernández, M. (2019). *Salmonella enterica* en Mexico 2000-2017: Epidemiología, Resistencia a los antimicrobianos y prevalencia en los alimentos. *Foodborne Pathogens and Disease, 17*(2), 98–118.

Gómez, A., & Vázquez, C. (1985). Estudios sobre la regeneración de selvas en regiones cálido-húmedas de México. In A. Gómez, & S. Del Amo (Eds.), *Investigaciones sobre la Regeneración de Selvas Altas en Veracruz, México (pp 1-25)*. México: Instituto Nacional de Investigaciones sobre los Recursos Bioticos y Editorial Alhambra Mexicana.

Grjibovski, A., Kosbayeva, A., & Menne, B. (2014). The effect of ambient air temperature and precipitation on monthly counts of salmonellosis in four regions of Kazakhstan, Central Asia, in 2000–2010. *Epidemiology and Infection, 142*, 608–615, 03.

Guisan, A., & Thuiller, W. (2005). Predicting species distribution: Offering more than simple habitat models. *Ecology Letters, 8*, 993–1009.

Gutiérrez, L., Montiel, E., Aguilera, P., & González, M. (2000). Serotipos de *Salmonella* identificados en los servicios de salud de México. *Salud Pública de México, 42*(6), 490–495.

Haley, B., Cole, D., & Lipp, E. (2009). Distribution, diversity, and seasonality of waterborne salmonellae in a rural watershed. *Applied and Environmental Microbiology, 75*(5), 1248–1255.

Hartkamp, A. D., De Beurs, K., Stein, A., & White, J. W. (1999). *Interpolation techniques for climate variables*. Mexico, D.F: CIMMYT. NRG-GIS Series 99-01.

Hernández, J., Delgado, M., & Espadas, C. (2011). Métodos de interpolación espacial y geoestadística. In F. Bautista (Ed.), *Técnicas de muestreo para manejadores de recursos naturales* (pp. 705–734). UNAM. 2ª Edición.

Holley, R., Arrus, K., Ominski, K., Tenuta, M., & Blank, G. (2006). *Salmonella* survival in manure-treated soils during simulated seasonal temperature exposure. *Journal of Environmental Quality, 35*, 1170–1180.

IICAB (Institut for International Cooperation Animal Biologics). (2005). *Characters Salmonella*.

INEGI (Instituto Nacional de Estadística, Geografía e Informática). (2000). *Síntesis de Información Geográfica del Estado de Sonora*. Geografía e Informática: Aguascalientes: Instituto Nacional de Estadística.

INEGI (Instituto Nacional de Estadística, Geografía e Informática). (2014a). *Conjunto de datos vectoriales de uso de suelo y vegetación, escala 1:250 000, serie V (capa unión) Aguascalientes*. Instituto Nacional de Estadística y Geografía.

INEGI (Instituto Nacional de Estadística, Geografía e Informática). (2014b). *Conjunto de datos de erosión de suelos, escala 1:250 000 serie I, continuo nacional. Elaboración de mapas: 2009-2013. Aguascalientes*. Geografía e Informática: Instituto Nacional de Estadística.

INEGI (Instituto Nacional de Estadística, Geografía e Informática. (1997). *La porcicultura en el estado de Sonora*. Geografía e Informática: Aguascalientes: Instituto Nacional de Estadística.

INEGI (Instituto Nacional de Estadística, Geografía e Informática). (2013). *Edafología, escala 1:250 000, serie II, continuo nacional*. Aguascalientes: Instituto Nacional de Estadística, Geografía e Informática.

Isaaks, E., & Srivastava, R. (1989). *An introduction to Applied geostatistics*. New York: Oxford University Press.

Islam, M., Doyle, P., Phataj, P., Millner, P., & Jiang, X. (2004). Persistence of enterohemorragic Escherichia coli O157:H7 in soil and on leaf lettuce and parsley grow in fields treated with contaminated manure compost or irrigation water. *Journal of Food Protection, 67*, 1365–1370.

Jara, C. (2017). *Detección y caracterización de Salmonella spp en muestras de hortalizas, suelo y agua obtenidas desde zonas rurales de la región Metropolitana*. Universidad de Chile.

Jechalke, S., Schierstaedt, J., Becker, M., Flemer, B., Grosch, R., Smalla, K., & Schikora. (2019). *Salmonella* establishment in agricultural soil and colonization of crop plants depend on soil type and plant species. *Frontiers in Microbiology, 10*, 1–17.

Jensen, P., Givskov, M., Bjarnsholt, T., & Moser, C. (2010). The immu ne system vs. Pseudomonas aeruginosa biofilms. *FEMS Immunology and Medical Microbiology, 59*(3), 292–305.

Jiang, C., Shaw, K., Upperman, C., Blythe, D., Mitchell, C., Murtugudde, R., & Sapkota, A. (2015). Climate change, extreme events and increased risk of salmonellosis in Maryland, USA: Evidence for coastal vulnerability. *Environment International, 83*, 58–62.

Johannessen, S., Bengston, G., Heier, B., Bredholt, S., Wasteson, Y., & Rorvik, L. (2005). Potential of Escherichia coli O157:H7 from organic manure into crisphead lettuce. *Applied and Environmental Microbiology, 71*(5), 221–2225.

Jones, B. D. (2005). *Salmonella* invasion gene regulation: A story of environmental awareness. *Journal of Microbiology, 43*, 110117.

Julca, A., Meneses, L., Blas, R., & Bello, S. (2006). La materia orgánica, importancia y experiencia de su uso en la agricultura. *Idesia, 24*(1), 49–61.

Klapecl, T., Wojcik-Fatlal, A., Cholewa, A., Cholewa, G., & Dutkiewiczl, J. (2016). Microbiological characterization of vegetables and their rhizosphere soil in Eastern Poland. *Anales de Medicina Agrícola y Ambiental, 23*(4), 559–565.

Kovats, R., Edwards, S., Hajat, S., Armstrong, B., & Ebi, K. (2004). MenneThe effect of temperature on food poisoning: A time-series analysis of salmonellosis in ten European countries. *Epidemiology and Infection, 132*(3), 443–453.

Krige, D. G. (1951). *A statistical approach to some mine valuations and allied problems at the Witwatersrand*. Master's thesis. Witwatersrand, South Africa: University of Witwatersrand.

Lal, A. T., Ikeda, T., French, N., Baker, M., & Hales, S. (2002). Climate variability, weather and enteric disease incidence in New Zealand: Time series analysis. *PloS One, 8*(12), Article e83484.

Ledeboer, N., & Jones, B. (2005). Exopolysaccharide sugars contribute to biofilm formation by *Salmonella enterica* serovar Typhimurium on HEp-2 cells and chicken intestinal epithelium. *Journal of Bacteriology, 187*, 3214–3226.

Lima, S., Varela, S., González, J., Oliveira, G., Diniz, J., & Terribile, C. (2015). EcoClimate: A database of climate data from multiple models for past, present, and future for macroecologists and biogeographers. *Biodiversity Informatics, 10*, 1–21.

Martínez, A., Carámbula, B., & Algorta, G. (2010). Origen y distribución de serotipos de Salmonella 2003-2009, Centro Nacional de Salmonella, Montevideo, Uruguay. In *XX congreso latinoamericano de Microbiología, montevideo*.

Martínez, J., Liebana, E., Garcia, L., Perez, P., & Saco, M. (2004). Characterization of *Salmonella enterica* serovar Typhimurium from marine environments in coastal waters of Galicia (Spain). *Applied and Environmental Microbiology, 70*, 4030–4034.

Matheron, G. (1963). Principles of geostatistics. *Economic Geology, 58*, 1246–1266.

Micallef, S., Rosenberg, R., George, A., Kleinfelter, L., Boyer, M., McLaughlin, C., Estrin, A., Ewing, L., Jean, J., Hanes, D., Kothary, M., Tall, B., Razeq, J., Joseph, S., & Sapkota, A. (2012). Occurrence and antibiotic resistance of multiple *Salmonella* serotypes recovered from water, sediment and soil on mid-Atlantic tomato farms. *Environmental Research, 114*, 31–39.

Moral, F. (2003). *La representación gráfica de las variables regionalizadas. Geoestadística lineal*. Badajoz, España: Servicio de Publicaciones de la Universidad de Extremadura.

Moral, F. (2004). *Aplicación de la geoestadística en las ciencias ambientales*. Ecosistemas. http://www.aeet.org/ecosistemas/041/revision3.htm.

Natvig, E., Ingham, S., Ingham, H., Cooperband, L., & Roper, T. (2002). *Salmonella enterica* serovar Typhimurium and Escherichia coli contamination of root and leaf vegetables grown in soil with incorporated bovine manure. *Applied and Environmental Microbiology, 68*, 2737–2744.

O'Sullivan, D., & Unwin, D. (2010). *Geographic information analysis*. Canadá: John Wiley & Sons, Inc.

Palacios, M., Lupiola, P., Del Nero, E., Pardo, A., Rodriguez, F., Pita, M., & Tejedor, M. (1999). Primeros resultados del estudio de la persistencia de *Salmonella* en la zona no saturada del suelo agrícola. In R. Muñoz, & A. R.y C. Tascón (Eds.), *Estudio de la zona no saturada del suelo*.

Pegues, D. A., Ohl, M. E., & Miller, S. I. (2002). *Salmonella*, including *Salmonella typhi* (p. 669-697. In M. J. Blaser, P. D. Smith, J. I. Ravdin, H. B. Greenberg, & R. L. Guerran (Eds.), *Infections of the gastrointestinal tract*. Philadelphia: Lippincott Williams & Wilkins.

Peinado, M., & Delgadillo, J. (1990). Introducción Al conocimiento fito-topográfico de Baja California (Mexico). *Stvdia Botánica, 9*, 25–39.

Plant, R. (2019). *Spatial data analysis in ecology and agriculture using R*. Florida: CRC Press.

POEBC (Programa de Ordenamiento Ecológico del Estado de Baja California). (2014). *Periódico Oficial del Estado de Baja California del 3 de julio de 2014, Tomo CXXI, No 34*. Número especial.

Richardson, D. M., & Whittaker, R. J. (2010). Conservation biogeography foundations, concepts and challenges. *Diversity and Distributions, 16*, 313–320.

Rodríguez, D., Torres, F., Gutiérrez, E., López, M., Martínez, M., & Carrascal, A. (2008). Determinación de *Salmonella* Typhimurium en compost inoculado artificialmente empleado en un cultivo de lechuga. *Acta Biológica Colombiana, 13*(3), 61–74.

Romero, U., & Ramírez, A. (2016). Revisión de las técnicas para el modelado de la distribución de especies. *Revista Biológico Agropecuaria Tuxpan, 5*(7), 1514–1525.

Rosas, I., Báez, A., & Coutiño, M. (1984). Bacteriological quality of crops irrigated with wastewater in the xochimilco plots, Mexico city, Mexico. *Applied and Environmental Microbiology, 47*, 1074–1079.

Rosete, F. A., Pérez, D., & Bocco, G. (2008). *Cambio de uso del suelo y vegetación en la Península de Baja California, México. Investigaciones Geográficas* (Vol. 67, pp. 39–58). Boletín del Instituto de Geografía.

Royo, M. H., Melgoza, A., & Sierra, J. S. (2013). Flora medicinal del estado de Chihuahua medicinal plants of Chihuahua state. *Revista Mexicana de Ciencias Farmacéuticas, 4*(18), 58–69.

Russell, R., Paterson, M., & Lima, N. (2010). How will climate change affect mycotoxins in food? *Food Research International, 43*, 1902–1914.

Sánchez, V., Peterson, A., & Escalante, P. (2001). El modelado de la distribución de especies y la conservación de la diversidad biológica. In H. Hernández, A. García, A. Álvarez, M. y Ulloa, & Comps (Eds.), *Enfoque contemporáneos para el estudio de la biodiversidad* (pp. 359–379). México: Universidad Nacional Autónoma de México.

Silva, G., López, H., Ortiz, V., Juárez, F., & López, M. (2012). Excreción fecal de *Salmonella albany*, su aislamiento en la ración alimenticia y repercusión en el estado de salud de un ocelote (*Leopardus pardalis*) en cautiverio. *Veterinaria México, 43*(1), 59–69.

Simental, L., & Martínez, J. (2008). Climate patterns governing the presence and permanence of salmonellae in coastal areas of bahia de Todos santos, méxico. *Applied and Enviromental Microbiology, 74*, 5918–5924.

Steenackers, H., Hermans, K., Vanderleyden, J., & De Keersmaecker, S. (2012). *Salmonella* biofilms: An overview on occurrence, structure, regulation and eradication. *Food Research International, 45*, 502–531.

Tamagnini, L., & Paraje, M. (2015). ¿Qué son las bacterias viables no cultivables? *Revista de la Facultad de Ciencias Exactas Fisicas y Naturales, 2*(2), 99–102.

Tennant, S. M., MacLennan, C. A., Simon, R., Martin, L. B., & Khan, M. I. (2016). Nontyphoidal *Salmonella* disease: Current status of vaccine research and development. *Vaccine, 34*, 2907–2910.

Thrusfield, M. (2007). *Veterinary epidemiology*. Orxford: Wiley-Blackwell.

Varela, S., Lima, M., & Terribile, L. (2015). A short guide to the climatic variables of the last glacial maximum for biogeographers. *PloS One, 10*, Article e0129037.

Wang, M., Qazi, I. H., Wang, L., Zhou, G., & Han, H. (2020). *Salmonella* virulence and immune escape. *Microorganisms, 8*, 407.

Weissinger, W., Chantarapanony, L., & Beuchat, R. (2000). Survival and growth of *Salmonella* baildon in shredded lettuce and diced tomatoes, and effectiveness of chlorinated water as a sanitizer. *J Food Microbiol, 62*, 123–131.

WHO (World Health Organization). (2016). *Antimicrobial resistance - World health organization*.

Wiens, J., Ackerly, D., Allen, A., Anacker, B., Buckley, L., Cornell, H., Damschen, E., Davies, T., Grytnes, J., & Harrison, S. (2010). Niche conservatism as an emerging principle in ecology and conservation biology. *Ecology Letters, 13*, 1310–1324.

Wilkinson, K. (2007). The biosecurity of on-farm mortality composting. *Journal of Applied Microbiology, 102*, 609–618.

Winfield, M. D., & Groisman, E. A. (2003). Role of nonhost environments in the lifestyles of *Salmonella* and Escherichia coli. *Applied and Environmental Microbiology, 69*, 3687–3694.

Zhang, Y., Bi, P., & Hiller, J. (2010). Climate variations and *Salmonella* infection in Australian subtropical and tropical regions. *The Science of the Total Environment, 408*, 524–530.