



Monitoring spatiotemporal impacts of changes in land surface temperature on near eastern fire salamander (*Salamandra infraimmaculata*) in the Middle East

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ARTICLE INFO

Keywords:

Salamandra infraimmaculata

Land surface temperature

Changing trends

MODIS

Habitat patches

ABSTRACT

Persistence and coexistence of many pond-breeding amphibians depend on seasonality. Temperature, as a seasonal climate component, affects numerous physical and biological processes of pond-breeding amphibians. Satellite-derived land surface temperature (LST) is the radiative skin temperature of the land surface, which has received less attention in spatiotemporal seasonal habitat monitoring. The present study aims to evaluate the increasing and decreasing effects of LST trends at two levels: (1) habitat suitability and connectivity; (2) individual population sites and their longitudinal distribution (with increasing longitude).

Habitat suitability modeling was conducted based on an ensemble species distribution model (eSDM). Using electrical circuit theory, the connectivity of interior and intact habitat cores was investigated. An average seasonal LST was prepared separately for each season from 2003 to 2021 and entered into Mann-Kendall (MK) analysis to determine the spatiotemporal effects of LST changes using the Z-Score (ZMK) at two confidence levels of 95 and 99%. Based on the results, in winter, 28.12% and 70.70% of the suitable habitat were affected by an increasing trend of LST at 95% and 99% confidence levels, respectively. The highest spatial overlap of the decreasing trend of LST with the suitable habitat occurred in summer and was 6.4% at the 95% confidence level and 4.2% at the 99% confidence level. Considering population site at 95% confidence interval, the increasing trend of LST was calculated to be 20.2%, 9.5%, 4.2%, and 6.3% of localities in winter, spring, summer, and autumn, respectively. At the 99% confidence level, these percentages reduced to 8.5%, 3.1%, 1%, and 1%, respectively. During winter and summer, based on the results of the longitudinal trend, an increasing trend of LST was observed in sites. Localities of Hatay and Ilica village in Turkey experienced seasonally asynchronous climate change regimes. The approach used in this study allowed us to create a link between the life cycle and seasonal changes on a micro-scale (breeding sites) and macro-scale (distribution and connectivity). Findings of this paper can be effectively used by conservation managers to preserve *S. infraimmaculata*'s metapopulation.

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<https://doi.org/10.1016/j.heliyon.2023.e17241>

Received 13 September 2022; Received in revised form 9 June 2023; Accepted 12 June 2023

Available online 14 June 2023

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1. Introduction

Ecological systems are hierarchically structured systems in which processes and patterns operate on distinct spatial and temporal scales [1]. Temporal scales can include monthly, seasonal and annual as well as short-term and long-term scales. Seasonal variations, also referred to as seasonality, are regular and periodic changes in the environmental and climatic conditions of the annual timescale [2]. Repeatability of seasonal acclimation appears to be important in energy metabolism and locomotor activity, which are essential characteristics of mobile organisms [3]. These characteristics in turn influence growth, reproduction, and survival [4]. The projected changes in global climate might vary seasonally [5], which can impact vital processes such as breeding. Reproductive seasonality is defined as seasonal patterns in reproduction to capitalize on resource availability and favorable conditions to ensure the survival of offspring and parents, often the female [6]. However, the importance of the repeatability of acclimation with respect to adaptation strongly depends on the context [3].

Important environmental variables such as rainfall and temperature exhibit seasonal patterns, which affect amphibians [7]. Temperature affects biochemical reactions and all physiological processes such as growth, metabolism, locomotion and digestion and can impact the efficiency of individuals [8], especially ectotherms [9], reproductive period, and population dynamics [10]. Ectotherms adapt to the heterogeneity of thermal environments through complex responses which include thermoregulatory behavior, thermal acclimation, thermal sensitivity of performance, and life-history traits [11]. The special characteristics of amphibians (such as permeable skin) make them more dependent on abiotic parameters (e.g., temperature and humidity) than other vertebrates [12]. The annual migration of pond breeding amphibians between breeding pools, terrestrial feeding habitats, and hibernation sites makes them highly dependent on landscape connectivity [13]. Seasonality affects habitat temperature, connectivity and life cycle of pond-breeding amphibians. To cope with seasonal changes, many species migrate [14]. Also, to keep their body temperature low compared to average environmental temperature, land-dwelling amphibians search for microenvironments created as a result of heterogeneity within the habitat [15].

Changes in seasonal temperature patterns are among the predicted outcomes of climate change [16]. Given the increased pace of climate change, adaptation could prove challenging [17]. Climate change is expected to influence plant phenology and temperature seasonality [18], jeopardizing the availability of resources necessary for vital biological processes such as feeding and reproduction [19]. In contrast to spatially asynchronous dynamics which support meta population persistence, climate change can impact seasonal cycles which expose regions to both warming and cooling in different seasons, a process which is referred to as seasonal asynchrony [20]. Due to its variations over time, asynchronous climate change can exert selection pressure on species in contrasting directions, which limits how a population could respond to changes [20].

Salamanders have summer aestivation and leave the sites with autumn and winter rains [21]. During the aestivation period, parts of the habitat for amphibians can serve as climatic shelters [22]. Considering the effect of asynchronous climate change, the efficiency of the evolutionary adaptation of salamanders in using these areas in response to local variations in environmental temperature may be compromised. Despite the importance of examining changes in seasonal variables, ecologists have neglected the use of seasonal data, which could be due to the need to their collection over many years [23]. Broad-scale coverage, along with the ability of satellite remote sensing (SRS) to use ecological indicators [24] as a time series with the purpose of description and explanation has provided the possibility of spatiotemporal monitoring of many habitats. Thus, it is essential to monitor lake information over a time period in areas which lack a ground-based monitoring program [25]. SRS data has great value for studies on amphibians with characteristics such as limited dispersal abilities, strong site fidelity and spatially disjunct breeding habitats [26] as it allows to simultaneously analyze metamorphosis with geographical distance based on environmental conditions. Using time series data to detect late frost periods, abnormal hot summers and growing degree days can be determined [24].

As the determining factor in the exchange of IR radiation and turbulent heat flows at the intersection of the surface and the atmosphere, LST is one of the key parameters of physical processes in surface energy and water balance at both local and global scales [27]. Knowledge of LST spatial changes offers various practical uses such as assessing evaporation and transpiration [28], analyzing land use changes [29], monitoring vegetation [30], determining insect distribution ranges [31] and evaluating urban climate [32]; however, so far, little attention has been given to the use of LST seasonal monitoring of habitats. Integration of long-term LST with species distribution data can lead to the analysis of the possible effects of trends on species, which could be achieved with SDMs. In summary, SDMs are tools to identify the habitat and vital needs of species which are developed based on investigating the relationship between species and various environmental variables [33,34].

S. infraimmaculata has been distributed in many parts of Europe and Asia over the past 13 million years [35]. Over time, this species has been isolated from *S. salamandra* and distributed across a narrow band in the Middle East and Asia Minor [36]. According to the IUCN, it is classified as a Near Threatened (NT) species. *S. infraimmaculata* is among the species present in surface and deep waters [37], and its larval growth process lasts for two months [38,39]. The temperature of breeding ponds of this species is estimated to be between 1.5 and 24 °C [40]. Determining whether changes in habitat characteristics such as temperature influence distribution range and landscape connectivity for pond-breeding amphibians can clarify the conservation status of these species, guide monitoring programs, and shape conservation policy and management [41].

Various studies have been conducted to investigate the habitat suitability of *S. infraimmaculata*. In a study by Ref. [42]; the response of *S. infraimmaculata* to climate change scenarios was investigated. Their results showed that habitat loss would be more apparent at the margins of the distribution range and low elevations. In another study by Ref. [21]; the relationship between population size and breeding site characteristics of *S. infraimmaculata* was investigated. The results revealed that permanent breeding sites hosted more populations than temporary sites. At the site scale, water depth and hillshade, and at the regional scale, elevation and proximity to other breeding sites played significant roles [43]. studied the distribution of *S. infraimmaculata* in Syria. The findings showed that the

precipitation of the coldest quarter with a contribution of 92.9% in the model greatly shaped the distribution of this species. The supposed scarcity of the species in northwestern Syria could be attributed to the shortage of suitable surface water. Review of the research literature showed that there are few studies on the relationship between habitat suitability and connectivity, and LST analysis has been carried out on small scales such as at the city [44] or at the wetland scales [45]. The present study aims to investigate the impact of increasing and decreasing trends of LST on habitat suitability and connectivity. Also, the authors attempt to assess the impact of LST fluctuations on site populations and their longitudinal distribution.

2. Materials and methods

2.1. Study area and presence points

The boundary of the study area has been determined in accordance with the distribution of presence points. The study area covers parts of the Middle East including Iran, Iraq, Armenia, Azerbaijan, Turkey, Syria, Lebanon, and Israel (Fig. 1) and it is estimated to be 1081067.34 km². The area encompasses Mount Lebanon mountain range in Lebanon, Taurus Mountains in the Anatolian Plateau in Turkey and parts of the Zagros Mountains in Iran and Iraq. A total of 124 presence points were adopted from Refs. [42,46]; which are shown in green in Fig. 1. 119 of 124 points were obtained from the study of [42]; which included observations of the species collected during field visits, daily observations of larvae in streams, as well as observations from breeding sites. Also, five points were obtained from the study of [46] collected during field visits in the north of Kermanshah province and south of Kurdistan province in western Iran from late winter to spring and summer of 2017–2019. Table S1 provides additional information about the used points in the modeling. Spatial autocorrelation reduction was done by applying the 1000-m filter (spatial resolution of the study) using SDMtoolbox [47] and 30 presence points were excluded. Finally, 94 localities remained, 17 were located in Iran, 2 in Iraq, 42 in Israel, 5 in Lebanon, 8 in Syria, and 20 in Turkey. Fig. 1 depicts the presence points and their elevation fluctuations.

2.2. Distribution modeling of *S. inframaculata*

According to the ecological features and relevant studies on *S. inframaculata* [21,42,43,48], the bioclimatic, topographic, vegetation, and land use/cover variables of the study were selected. The bioclimatic variables were obtained from the Chelsa database (<https://chelsa-climate.org>) with a spatial resolution of 30 s. The elevation variable was downloaded from the WorldClim database (www.worldclim.org) with the same spatial resolution. The topo-climate variables including Compound Topographic Index (CTI) and Cluster Hillshade were prepared from the elevation variable. Studies show that CTI has a strong relationship with soil characteristics including depth, texture, organic content, and moisture [49,50]. In general, valley bottoms and basins have the largest CTI values, and the smallest values belong to ridges [51]. The CTI was prepared in QGIS 3.16.3. The Cluster Hillshade was attained using the Terrain Mapping toolbox in ArcGIS 10.4.1. Given the important role of vegetation cover on amphibians, the NDVI index was prepared as an 11-year average from 2010 to 2021 using the MODIS/006/MYD13A2 product of the MODIS satellite in the Google Earth Engine (GEE) [52]. The land use/land cover was prepared with a spatial resolution of 300 × 300 m from the Copernicus Climate Change Service (C3S). C3S offers global land cover (LC) maps for the period from 2016 to 2019. These productions are consistent with the annual

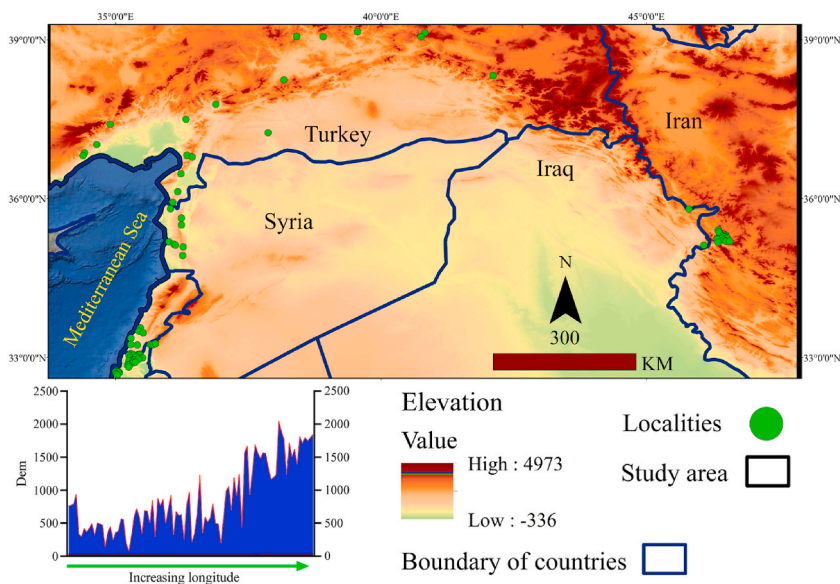


Fig. 1. Boundary of the study area, presence points of *S. inframaculata* (green points) and altitude changes of samples against increasing longitudes

global LC maps available from 1992 to 2015 prepared by the European Space Agency Climate Change Initiative LC project [53]. The variables of distance from agricultural land and distance from mosaic natural vegetation including tree, shrub and herbaceous cover (>50%) and also cropland (<50%) were obtained from the land use/cover map. Then, to assess the effect of landscape fragmentation on the habitat, the fragmentation index was calculated with a 3×3 pixel window (size of the area) for different classes of the land use/land cover in TerrSet. A correlation was established between all the variables and those with a correlation greater than 0.75 were excluded from the analysis. The eSDM was prepared in R 4.3.1 from the models of maximum entropy (MAXENT), classification tree analysis (CTA), multivariate adaptive regression splines (MARS), generalized linear model (GLM), generalized boosting models (GBM), generalized additive models (GAM), artificial neural networks (ANN), and random forests (RF) in SSDM package [54]. A total of 1000 pseudo absence points were created randomly across the entire study area [55]. 70% of the data were allocated to training and 30% to testing. The models had 10 replications. TSS (True Skill Statistic) was the criterion used for calculating the threshold of the binary map. The metric maximizes the sensitivity and specificity sum [56]. Those models with kappa power greater than 0.75 were combined to form eSDM. The models were validated using TSS, Kappa, sensitivity, specificity, and Percentage of correctly classified (PCC) criteria. The importance of habitat variables in modeling was calculated using the Area Under the Curve (AUC) criterion. The outputs included a habitat suitability probability map and a binary map (suitable/unsuitable habitat).

2.3. Habitat connectivity

Due to the importance of habitat fragmentation [43], the nodes were identified in such a manner to maintain the continuity of the habitat patches. This was done using the multi-scale fragmentation analysis in Guidos Toolbox. The eSDM binary map was entered into Foreground Area Density (FAD) analysis. This method is implemented using moving windows and five different sizes of neighboring pixels including 7, 13, 27, 81, and 243 [57]. Finally, the method classifies the patches based on density percentage. The patches that were in the interior and intact classes were considered to be nodes. To identify corridors, electric circuit theory was used in Circuitscape software. This method is based on the random walk theory and uses electric circuit theory, in which the current (species) moves between focal nodes (habitat patch or presence points), taking into account the voltage (probability of movement or travel of the species) and resistance (permeability of the habitat) [58,59]. In this method, the current between habitat patches can be calculated based on the ampere unit. The landscape resistance map in this study was obtained by inverting the habitat suitability probability map [60]. The connectivity between the habitat cores was established in a pairwise method (iterate across all pairs in the focal node file). The cumulative current map generated by establishing a current between population pairs in the resistance map represents the movement probability of a random walker by each pixel in a landscape. To quantitatively assess the effect of LST trends on the current, the current map was divided into five categories, including very low (0–0.2), low (0.2–0.4), medium (0.4–0.6), high (0.6–0.8), and very high (more than 0.8). Then, the effects of increasing and decreasing LST trends on the current were investigated.

2.4. LST preparation and trend analysis

The LST data was prepared daily and by season using the MYD11A1 product in GEE [52]. The Moderate-resolution Imaging Spectroradiometer (MODIS) LST product, due to its daily global coverage, is used widely in regional and global research. As *S. infraimmaculata* is a prolonged breeder, it is prone to drying up in summer [61]. Therefore, in order to analyze the vulnerability of climatic refuges and breeding sites to the effects of climate change on seasonal temperature cycles, LST changes were examined in all seasons. Thus, for each season of each year (from 2003 to 2021), only one image was adopted from GEE as the average of that season. As LST (MODIS) is calculated only under clear sky observations, it is biased towards cloudless days [62]. To take this bias into account, the seasonal average of LST [62] was calculated in terms of the Kelvin scale in GEE with a scale factor of 0.02 [52]. The use of mean values will reduce the random errors in the images [63].

The MK nonparametric test [64,65] is typically used to detect trends in time series. The null hypothesis of this outlier-robust test determines whether a time series does not have a monotonic trend (uneven or clear trend), while the alternative hypothesis confirms a significant monotonic trend (p-value <0.05). The LSTs were converted into raster time series and then, MK test was performed in TreeSET. This analysis has different outputs, from which z-score (or ZMK) and Mann-Kendall (MK-Tau) were used in this study to analyze the results. The MK-Tau option estimates the correlation coefficient and ranges from -1 to $+1$, where 1 means a continuously increasing trend, -1 continuously decreasing trend, and 0 no trend. The ZMK with a mean of 0 and a variance of 1 follows the standard normal distribution. Its positive values show uptrends in a time series and the negative values show downtrends. The ZMK values for the significance levels of 10%, 5%, and 1% are 1.645, 1.960, and 2.576, respectively [66]. In this study, ZMK values were investigated at the significance levels of 95% and 99%. For each significance level, a binary map was prepared, where the value of 1 showed the areas with trends and 0 the areas with no trends. Its overlaying with the binary eSDM allows for investigating the effect of increasing and decreasing LST trends on habitat suitability. Prior to performing the MK test, some analysis are usually performed to reduce serial autocorrelation, a process known as pre-whitening [67]. showed that the use of different pre-whitening methods leads to changes in the results, and for large data (such as the data used in the present study), serial autocorrelation is not a concern [68,69]. In addition, original Mann-Kendall is recommended for the analysis of images [70]. After calculating the trend of changes at the significance levels of 99% and 95%, the intersect analysis was used in ArcGIS to evaluate the spatial displacements of areas with decreasing and increasing trends during all seasons.

2.5. LST analysis at the sites

The investigation of the characteristics of sites may be regarded as a surrogate for investigating the species status [71]. Therefore, in this study, each presence point was considered as a site, and in addition to habitat analysis, site analysis was also conducted. The effect of temperature changes on sites was investigated using two approaches. The first approach was to examine changes in the distribution sites of the species. Therefore, the localities were sorted based on increasing longitude, and then the LST values were extracted for each site using the Extract Value to Point command in ArcGIS. The modified MK was used at two confidence levels of 99% and 95% for trend analysis. By choosing longitude, the increase in altitude was also involved in the trend analysis since eastern localities have higher elevations compared to western localities (Fig. 1). The lack of correlation between input data is the basic assumption for trend analysis by the MK test; therefore [72], autocorrelation test was used to remove any serial autocorrelation. Using sen's slope, the direction and size of the changing trends were checked. In the second approach, the changing trends were investigated in the location of the presence points to analyze the effects on the sites. In this regard, ZMK values were extracted as per presence point. Finally, localities that experienced increasing and decreasing trends at the 95% and 99% significance levels were detected using ArcGIS.

3. Results

3.1. Model validation and the importance of habitat variables

The GLM model was able to identify 94% of the presence points of the species (sensitivity), while this value was 0.9 (specificity) for pseudo-absence points (Table 1). Among the models, only the ANN performed poorly compared to the other models. The threshold applied by the final model was 0.4 and the Kappa value was 0.9, which indicates the power of the ensemble models. The suitability of *S. infraimmaculata* habitat is influenced by annual precipitation (Bio12), NDVI and average daily temperature range (Bio2), respectively (Fig. S1).

3.2. Habitat suitability and seasonal temperature trends

The results of eSDM suggest that the suitable habitat of *S. infraimmaculata* comprises a narrow strip from the west to the east of the Middle East. Habitat quality is higher in western parts and in areas adjacent to the Mediterranean Sea than central and eastern parts (Fig. 2). MK-TAU showed that most of the study area and the majority of the sites showed an increasing LST trend in winter. In spring, the decreasing trend of LST mostly occurred in the south of the study area, far from the distribution range of the species. In summer, the decreasing trend differed from spring, and the northern and higher parts of the study area showed a decreasing trend.

The habitat patches encompassed an area of 103,979.52 km². Patches in the west, east and center of the study area were studied. The proximity of the patches to each other is higher in the eastern and western parts than in the central part. The effectiveness of habitat patches in areas with increasing and decreasing trends at different levels of significance is shown in Table 2. The increase in LST at the two significance levels (95% and 99%) was higher in winter than in the other seasons (28.1% and 7.1%, respectively). In winter, there was no decrease in LST with overlapping habitat patches (Table 2). In summer, the habitat spots showed both increasing and decreasing trends in LST (at two significance levels). In autumn, the increase in LST had far less impact on habitat patches. The intersect analysis of increasing temperature trends at the significance level of 99% among all seasons showed that an area equal to 110.50 km² of the habitat had an increasing trend in all seasons. This area is 19.9 km² at the 95% level. At the significance level of -99% and -95%, none of the regions with a decreasing trend had spatial overlap.

3.3. Effect of LST on the cumulative current

Habitat patches are compatible with high quality habitats and the cumulative current between them decreases with increasing distance (Fig. 3). In summer, the influence pattern of the decreasing temperature trend on the cumulative current was different. In the eastern parts of the distribution range (Iran and Iraq), the decrease in temperature occurred mostly at the edge of water sources and cities (as thermal islands), while in the western parts, the pattern was different and the main decrease in temperature was in high elevations facing the coastal cities. These areas have dense vegetation cover in the form of forests and highlands facing the Mediterranean Sea. The eastern heights of Tripoli and Tartus in Syria, the northeastern heights of Bental nature reserve on the edge of Jabal

Table 1
Validation results of the single models based on different metrics.

Models	AUC	Sensitivity	Specificity	PCC	Kappa
GLM	0.94	0.94	0.94	0.94	0.88
MARS	0.94	0.89	0.99	0.94	0.89
GBM	0.93	0.91	0.95	0.93	0.86
CTA	0.90	0.90	0.90	0.90	0.80
RF	0.95	0.94	0.97	0.95	0.91
MaxEnt	0.95	0.97	0.94	0.95	0.91
ANN	0.88	0.82	0.93	0.88	0.75
SVM	0.93	0.94	0.93	0.93	0.86

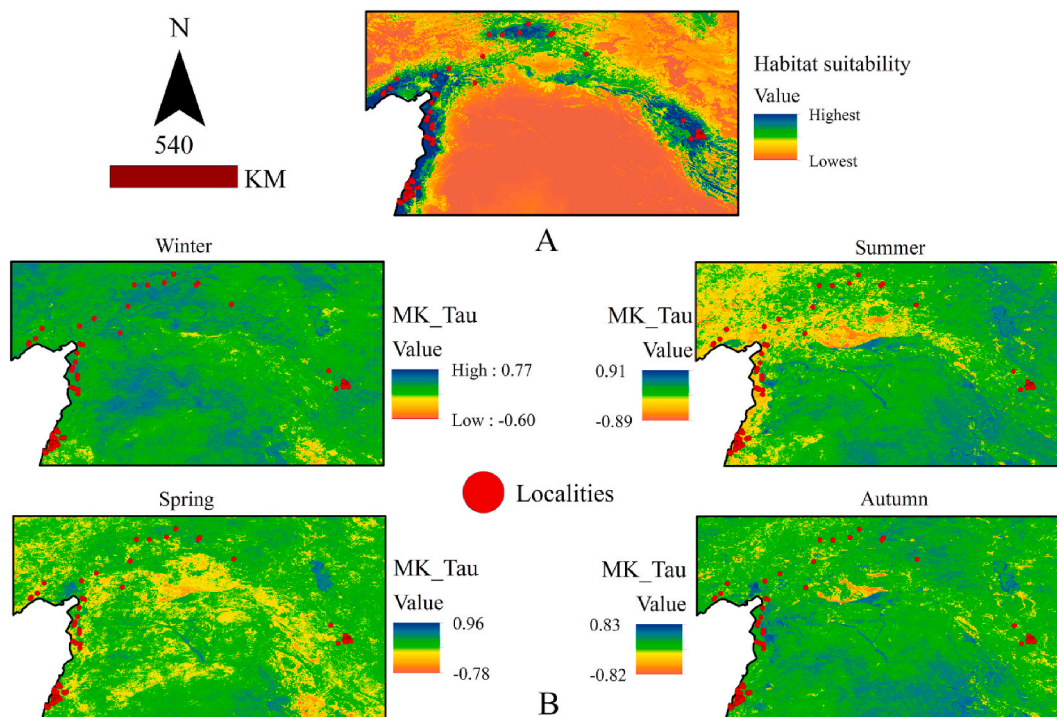


Fig. 2. A: habitat suitability and B: LST trends according to MK_Tau in the study area for each season.

Table 2

Relationship between LST trends (at 99% and 95% significance levels) and suitable habitat in different seasons.

	Incremental Trend			Decreasing Trend		
Season	Sig Level	Area (km ²)	%	Sig Level	Area (km ²)	%
Winter	99	8013.90	7.70	99	0	0
Spring	99	2475.22	2.38	99	34.74	0.03
Summer	99	5311.16	5.10	99	4395.64	4.22
Autumn	99	2399.45	2.30	99	50.34	0.04
	Incremental Trend			Decreasing Trend		
Season	Sig Level	Area (km ²)	%	Sig Level	Area (km ²)	%
Winter	95	29319.77	28.12	95	0	0
Spring	95	5993.87	5.76	95	243.61	0.23
Summer	95	7617.29	7.32	95	6733.20	6.47
Autumn	95	4121.29	3.96	95	82.89	0.07

Moussa Biosphere reserve in Lebanon, northern and northeastern heights of the city of İskenderun in Hatay province and northern heights of the city of Silifke in Mersin province, southern Turkey, and Mount Meron and Nahal Kziv reserve in Israel are some examples.

Different qualities of the cumulative current are not equally affected by increasing and decreasing trends.

very low, low, medium, high, and very high currents in the study area occupied an area of 1162823.9 km², 78066.9 km², 7520.36 km², 929.8 km², and 176.8 km², respectively (Table 3). Accordingly, in the decreasing trend (99% level) of summer, 80.1% of the high current intensity occurred in the area under the influence of the decreasing temperature trend. At the significance level of 99%, in summer, 17.5% of the high current intensity was affected by the increasing trend and most of these increases occurred in the eastern habitats, i.e. in Iran and Iraq.

3.4. Effect of LST trends at the sites

At the significance level of 95%, 20.2%, 9.5%, 4.2%, and 6.3% of the localities experienced an increasing trend in winter, spring, summer, and autumn, respectively (Table 4). These values were 8.5%, 3.1%, 1%, and 1% at the significance level of 99%, respectively. For instance, in Iran, seven localities experienced a significant temperature increase in winter at the significance level of 95%. Localities affected by increasing or decreasing trend of LST (at the 95% and 99% significance levels) are shown in Fig. S2 and Fig. S3, respectively.

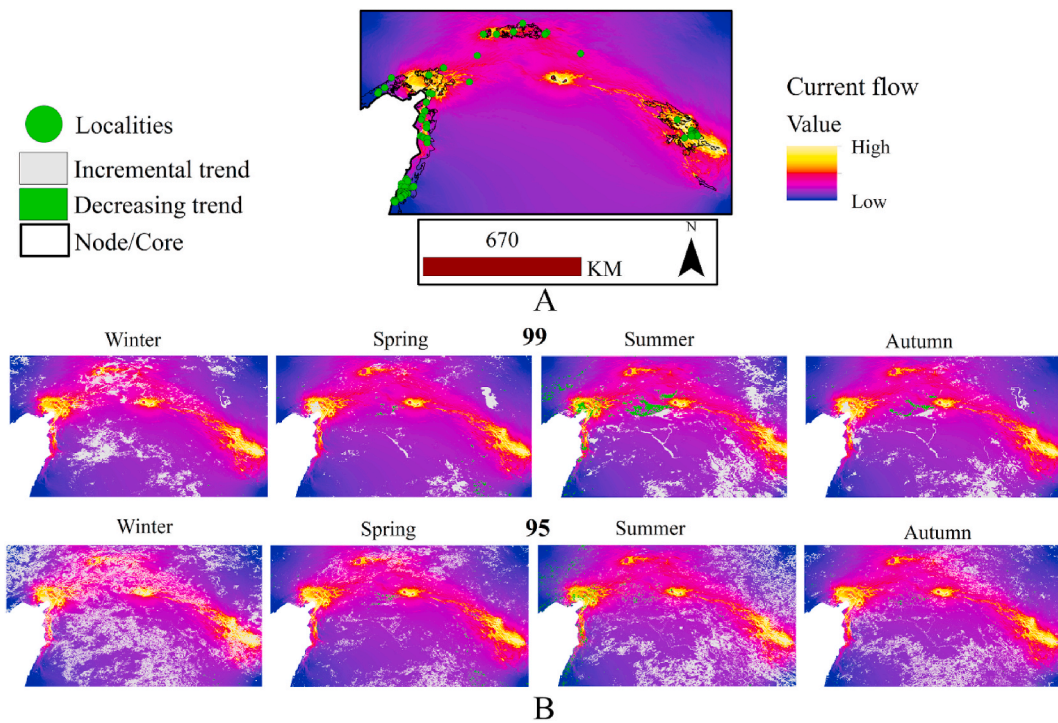


Fig. 3. A: current flow between the habitat patches and B: Effectiveness of increasing and decreasing LST trends (at 99% and 95% significance levels).

Table 3
Effects of increasing and decreasing temperature spots on quality of current flow classes.

		Influence of LST trends on current flow in km ²									
Sig	Season	Very low	%	Low	%	Average	%	High	%	Very high	%
-99	Winter	108.78	0	0.00	0	0.00	0	0.00	0	0.00	0
	Spring	4431.24	0.3	6.60	0	0.00	0	0.00	0	0.00	0
	Summer	24028.34	2.06	3224.18	4.13	707.87	9.41	76.16	80.19	0.00	0
	Autumn	6511.41	0.5	92.30	0.11	5.15	0.06	0.00	0	0.00	0
+99	Winter	109234.04	9.39	7294.79	9.34	501.36	6.66	116.97	12.57	0.00	0
	Spring	38624.04	3.32	3435.78	4.40	611.08	8.12	59.57	6.40	5.93	3.35
	Summer	133698.82	11.49	2186.52	2.80	379.48	5.04	84.75	9.11	31.02	17.53
	Autumn	73899.41	6.35	2615.59	3.35	351.20	4.66	14.95	1.60	0.00	0
-95	Winter	241.23	0.02	0.00	0	0.00	0	0.00	0	0.00	0
	Spring	4930.34	0.42	88.07	0.11	1.75	0.02	0.00	0	0.00	0
	Summer	14827.02	1.27	2678.90	3.43	408.22	5.42	44.84	4.82	6.83	3.86
	Autumn	3104.94	0.26	76.46	0.09	13.75	0.18	1.16	0.12	0.00	0
+95	Winter	281567.91	24.21	25697.39	32.91	2454.13	32.63	276.02	29.68	37.82	21.38
	Spring	77285.95	6.64	2805.13	3.59	226.29	3	63.04	6.77	11.01	6.22
	Summer	177991.64	15.30	4769.22	6.10	782.37	10.40	217.01	23.33	32.86	18.57
	Autumn	126910.75	10.91	1518.20	1.94	188.57	2.50	10.57	1.13	0.59	0.33

Based on the results of the longitudinal trend (Table S2), LST changes in winter were increasing and significant in all years. The Sen's slope estimator ranged from -0.1 in 2003 to -0.0 in 2021, thus the LST difference of the localities from west to east in winter is decreasing. Fifteen localities from Iran and Turkey experienced an increase in temperature at the 95% significance level. After winter, the trend of increasing temperature based on longitude in summer was also quite evident; therefore, the Sen's slope estimator increased from 0.1 in 2003 to 0.13 in 2021.

4. Discussion

Despite the numerous studies conducted on the conservation of amphibians, only few address the issue of long-term seasonal time-series in their distribution ranges [10]. In this study, seasonal LST was used in the period of 2003–2021 to evaluate the possible effects of temperature changes on *S. infraimmaculata*. MK analysis findings were combined with the eSDM output to investigate the

Table 4

Localities with increasing and decreasing LST trends at the 95% and 99% significance levels.

Incremental trend				
Sig	Seasons	country	number	Localities
+95	Winter	Iran	7	Hanjme, Hazarhkani, Goshkhani, Barquru, Mazibenm, Zhiwar, Shaho
		Israel	1	Kziv Stream
		Syria	3	Arrawda, Roman well, Sharre
		Turkey	8	Sütluce/Tunceli, Derinçay village, Alatepe village, Bitlis, Aslantepe and Gündüzbey Villages, Mezitli, Mersin, Iskenderun-Hatay, Harbiye and Antakya
+99		Iran	5	Barquru, Langarez, Maziben, Buryar, shaho
		Turkey	3	Tađar Stream-Çemipgezek Tunceli, İica Village, Eskihalfeti/Sanlıfurfa
+95	Spring	Israel	5	Shomera, Maalot, Alon Spring, Mt. Carmel, Hek Spring,
		Syria	1	Arrawda
		Turkey	3	Yuva and Salihli Villages, Alatepe village, Aslantepe and Gündüzbey Villages
		Israel	1	Secher
+99		Turkey	2	Gelinodalarý-Pülümür Tunceli, Derinçay village
		Iran	3	Hanjme, Zhiwar, Harsin
+95	Summer	Israel	1	Alon Spring
		Iran	1	Chor
+95	Autumn	Israel	4	Secher, Ein Nesher, Mt. Carmel, Hek Spring
		Syria	1	Sharre
		Turkey	1	Bitlis
		Israel	1	Alon Spring
Decreasing trend				
-95	Winter	-	-	-
-99		-	-	-
-95	Spring	-	-	-
		-	-	-
-95	Summer	Turkey	3	İica Village, Altinboga Village, Gözne-Mersin
		Syria	2	Ain Asharkia, Ain Al Thahab
		Lebanon	2	Biskinta, Hasbayya
		Israel	9	Even Menachem, Fara, Sasa, Humema, Kser, Michmanim, Eshhar, Manof, Atzmon
		Israel	2	Segev, Kaukab
-99		Syria	1	Ain Ghadran
		Turkey	1	Hassa, Hatay
		-	-	-
-95	Autumn	-	-	-
-99		-	-	-

effectiveness of the distribution range and possible corridors with respect to temperature changes. The trend of LST for individual sites and longitudinal trends of all sites were also investigated. As a result, the sensitivity of sites to each other could be determined. Seasonal LSTs were obtained from GEE. GEE with cloud computing platform has provided a suitable platform for studying large study areas in long-term time scales with time-consuming complexity owing to the possibility of choosing different time scales. In this study, broad-scale MODIS data allowed us to simultaneously examine all Mediterranean populations of *S. infraimmaculata* (without gaps) in a seasonal time scale. LST is different from air temperature and in some cases, the difference is $K \pm 1$ [73,74]. Due to this small difference, LST can be a useful tool to investigate temperature dynamics from fine to coarse scales.

According to eSDM, the potential distribution range of *S. infraimmaculata* can reach areas in the west of Iran (Kurdistan, Kermanshah, İlam and Lorestan provinces) where the species is not currently present. These areas were not mentioned in the studies previously conducted on this species [42,75]. This could be due to the use of variables that are affected by altitude as well as the continuity of favorable conditions such as rainfall and vegetation cover caused by the Zagros Mountains [76]. Bio12 had the greatest impact on the distribution of *S. infraimmaculata*, followed by NDVI and Bio2. The direct relationship of *S. infraimmaculata* in Syria with rainfall has been previously acknowledged [43]. In a study by Ref. [36] in Turkey, precipitation was identified as an important parameter, which is in line with the findings of this study. *S. infraimmaculata* prefers mountain habitats with high humidity and forest cover for life [77]. Vegetation cover can have different roles, such as providing shelter and shade and creating microclimates which protect the animal against solar radiation [78]. This explains why it is absent in many areas such as southern Iraq, Syria, and Lebanon as hot areas serve as an obstacle to the distribution of this species [75].

Small parts of the habitat have an increasing trend of LST (at levels 95% and 99%) in all seasons (190.50 and 15 km², respectively). Therefore, a large part of the potential habitat of *S. infraimmaculata* has heterogeneity in LST (Table 2), which can be due to the diversity of reflectance and roughness of the land surface [79]. A significant area of the habitat lacks the potential to increase LST (Table 2). However, in the decreasing trend, the decrease is greater in summer than in other seasons. A large part of this decreasing trend is due to the existence of different vegetation types including forests along the coasts of the Mediterranean Sea as well as agricultural lands in the central parts of the distribution range (Diyarbakir province in Turkey). The cooling effect of vegetation is directly related to evapotranspiration, especially in summer [80]. Vegetation can change surface energy flux through evaporation and transpiration [30]. By selective absorption and reflection of solar radiation and regulation of latent and sensible heat exchange, vegetation cover can affect LST [81]. *S. infraimmaculata* is mostly present along the borders of permanent and temporary water sources, which is due to its dependence on specific features such as seasonal rock pools and springs within its home range [82]. Therefore, in

response to increasing temperatures, *S. infraimmaculata* sites play a more crucial role than potential habitats and require continuous monitoring.

The longitudinal trend of LST sites indicates a significant and continuous increase in LST in both winter and summer. As this trend is associated with an increase in altitude from west to east, it could be postulated that altitude has not been able to play an effective role in reducing LST. The distribution of *S. infraimmaculata*, even in the highest mountain ranges of the Middle East, has not prevented the species from being affected by the trend of increasing LST and global warming. This is while many studies highlight the role of highlands (i.e. the Zagros Mountains) as climatic refuges for *N. derjugini* and *N. kaiseri* [83,84]. The increase in LST at high altitudes in areas where *S. infraimmaculata* is present could be due to the decrease in albedo following snow melt [85] as well as due to deforestation and land use changes in *S. infraimmaculata* habitats. With the increase in temperature in winter and the decrease in precipitation and increase in evaporation and transpiration [86], the hydroperiod of pools, wetlands and streams will change. Hydroperiod of wetlands and ponds is one of the most important parameters for estimating population growth for organisms with water-developing larvae [87]. A long hydroperiod affects the survival of larvae [88]. Decreased precipitation also affects deep ponds. In a study by Ref. [21] on *S. infraimmaculata*, increasing pond depth was found to be a significant factor in turning ponds into breeding sites. Ponds and reservoirs that experience an increasing trend of LST are under threat. Ephemeral aquatic habitats that dry up during the warm seasons of the year face severe selective pressure due to limitations of food, oxygen, desiccation and metamorphosis prior to drying [39,89].

Temperature regimes of embryos depend mainly on spawning sites selected by reproductive adults [90]. Also, salamanders tend to return to their place of birth in xeric habitats [91]. The same goes for *S. infraimmaculata* [61]. Amphibians are known to have higher growth rates at moderate temperature ranges. Amphibian eggs and larvae are also more likely to survive in habitats with moderate temperature ranges [92,93]. Temperature affects the developmental rates of larvae, as previously noted in a study on *Neurergus derjugini* [94]. After metamorphosis, *S. infraimmaculata* remains in terrestrial habitats [95]. With the increase in temperature and acceleration in the developmental rates of larvae, they leave the ponds and because temperatures increase in summer, there is a possibility of desiccation of larvae [96]. There are reports on the effect of increasing temperature on the reduction of dissolved oxygen in water as well as increasing the possibility of cannibalism in *S. infraimmaculata* due to competition for resources [39]. Thus, increasing trends of LST in sites can influence the reproductive success of *S. infraimmaculata* adults.

Different sites of species presence did not experience the same trends of LST increase. No sites in Iraq and Lebanon experienced an increasing trend of LST (Table 4). Iran, Turkey, Israel, and Syria had increasing trends, despite the proximity of sites in Iraq to sites in Iran. There are also some sites that experienced both increasing and decreasing trends. Such variations in trends could be regarded as seasonally asynchronous climate change regimes. The sites of Hatay and Lica village in Turkey belong to this category. Such extreme fluctuations might compromise the species ability to adapt. Asynchronous climate change regimes often disrupt population dynamics by creating phenological inconsistencies [20]. If this asynchrony affects reproduction, it can lead to reproductive isolation [97], a process that also occurs in birds [98].

Studies have shown that the genetic distance of *S. infraimmaculata* is lower along ephemeral stream channels [99]. In a large spatial extent, dispersal limitation could lead to a decrease in distribution. Therefore, the movement ability of *S. infraimmaculata* (1300-1100 m) within adjacent sites would be of higher quality. As the distance between the cores increases, the cumulative flows between the cores decrease (Fig. 3); hence, why the genetic distance of *S. infraimmaculata* is correlated with the Euclidian distance [100]. Similarly, the different qualities of cumulative current flow in winter and summer are influenced by the increasing trend of LST, and movement in these seasons is more likely to be influenced. Changes in temperature lead to changes in other environmental parameters, and in response to such changes, species undergo movements such as breeding migration. Temperature can cause various metabolic costs on movement that affect the quality of habitat patches and cause non-random movement among them [101]. In a study by Ref. [102] on *Ambystoma maculatum*, the results revealed that breeding migration began earlier during warmer winters. Altered migration timing can affect the decoupling of community dynamics [103] and asynchrony in the arrival time of sexes [104]. In a study by Ref. [7] on two species, *T. cristatus* and *L. vulgaris*, the results showed that increasing temperatures caused premature breeding migrations. Reducing the area of ponds can also be effective in the spread of species and migration between breeding habitats as pond density is a basic criterion for success in landscape connectivity [105].

S. infraimmaculata has acquired adaptations against increasing temperatures. For instance, larvae can feel dryness and change their developmental rates, yet this accelerated development can also damage larvae [21]. In addition, *S. infraimmaculata* can adapt to summers with low rainfall [106]. Moreover, evidence has shown that the presence of species in waterways and valleys, as a type of riparian ecosystems, can play an effective role in regulating temperature [107]. There are also reports on the positive effects of increased temperatures. Higher air and body temperatures after hibernation are vital for ectotherms to reproduce, move and escape from predators in their habitat [108]. In a study by Ref. [109] on *Bufo bufo* under laboratory conditions, it was found that shorter winters and more moderate temperatures during hibernation had a positive effect on the survival of toads and body mass changes. The positive effect of mild and shorter winters has also been reported in other studies [110,111]. Great seasonal variations in immunity of ectotherms usually occur with maximal immune responses during the summer season [112]. Studies on amphibians showed that in cold seasons, the possibility of spreading diseases increases [113,114]. In another study by Ref. [115] on the relationship between species habitat and environmental conditions, the results indicated that in areas with increased canopy cover and colder water temperature, the probability of bacteria outbreak increases. The results of the study by Ref. [116] showed that in a bioclimatic gradient, the bacterial composition of the skin of amphibians changes in a way that bacterial richness decreases for each host towards warmer and more stable thermal conditions. In another study by Ref. [7] on *T. cristatus* and *L. vulgaris*, increasing temperature was found to be beneficial to recruitment and juvenile survival [7]. If this is also true for *S. infraimmaculata* juveniles, considering that juveniles disperse to new places more frequently than adults [7], the increase in temperature in breeding ponds could facilitate survival

[21].

Regarding the positive and negative effects of increased temperatures, it is evident that evaluation of such effects on *S. infraimmaculata* across its distribution range requires more comprehensive experimental investigations, particularly in its eastern habitats. If field investigations of sites show increasing trends and confirm the effects on the survival and reproduction of salamanders, holes can be dug near the localities to maintain their survival through metapopulations [117,118].

5. Conclusion

Although species distribution modeling using climate change scenarios can offer valuable insights into species' conservation, it fails to provide information about recent trends. Such information about past processes is crucial for present-day decision makings. If it is aimed to examine past changes in a temporal-spatial manner to determine time scales, it is possible to address questions in ecology in the context of seasonality. Temperature is one of these components whose monitoring in time series can help to identify seasonally asynchronous climate change regimes. If LSTs are combined with field measurements, many of the species' responses, including responses which could not be studied before, can be investigated in the form of phenology. Across its narrow distribution range, *S. infraimmaculata* has suitable conditions in terms of distribution and sensitivity to increasing temperatures. However, LST changes in the presence points are quite evident. The higher altitude of the eastern localities could not protect them from the increase in LST. For a more accurate evaluation, it is essential to conduct this study on a fine scale along with more comprehensive field investigations. Changing the scale of the findings will reveal the sensitivity of the species to the environment in further details.

Author contribution statement

- 1 - Conceived and designed the experiments Peyman Karami.
- 2 - Performed the experiments Peyman Karami, Sajad Tavakoli, Mina Esmaeili.
- 3 - Analyzed and interpreted the data Peyman Karami.
- 4 - Contributed reagents, materials, analysis tools or data Peyman Karami, Sajad Tavakoli, Mina Esmaeili.
- 5 - Wrote the paper Peyman Karami, Sajad Tavakoli, Mina Esmaeili.

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.

Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.heliyon.2023.e17241>.

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