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# Potential effects of climate change on the distribution of invasive bullfrogs *Lithobates catesbeianus* in China

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**Abstract.** Climate plays important roles in determining the geographical distribution of species, including the invasion area of alien species. Little is known, however, about the influence of climate change on the distribution area of invasive amphibian species in China. We adopted a maximum entropy model to predict the potential suitable invasive range of invasive bullfrogs *Lithobates catesbeianus* in China under two future climate scenarios in 2050 and 2070. Our results reveal that bullfrogs were mainly distributed in East and Central China at present, and the suitable area for the species may decrease in future. This suggests that climate change may negatively impact this alien-invasive species.

**Keywords.** Bullfrog, climate change, environmental limitations, invasive species, potential distribution, species distribution model.

## INTRODUCTION

Biological invasion of alien invasive species is considered to be the second leading cause of global biodiversity loss and habitat degradation (Pimentel et al., 2000; Bellard et al., 2012; Runyon et al., 2012), seriously threatening the health of ecosystems (Hobbs and Huenneke, 1992; D'Antonio et al., 2004; Vilà et al., 2011; Espíndola et al., 2012; Sorte et al., 2013) and causing significant economic losses (Pimentel et al., 2000). The proliferation and outbreak of invasive species are becoming more and more serious (Pyšek and Hulme, 2010). The acceleration of globalization has affected the distribution of invasive species and almost no ecosystem is immune to the impact of alien species (Weber and Li, 2008; Catford et al., 2012). China is a large country encompassing many different climatic regions, where many invasive species can find suitable habitats where to establish. Investigating the potential distribution of invasive species could help to address the conservation efforts to eliminate or reduce the negative effects of biological invasions on local wildlife and ecosystems (Xie et al., 2001).

As in the rest of the world, climate change is affecting also China's ecosystems (Hu et al., 2012). Climate change has shown enormous influence on species distribution (Erasmus et al., 2002; Walther et al., 2002; Root et al., 2003; Hari et al., 2006; Guralnick, 2007). For example, climate change in the 20th century has changed the distribution of butterflies (Parmesan et al., 1999), birds (Thoms and Lennon, 1999), amphibians (Araújo et al., 2006) and mammals (Hersteinsson and Macdonald, 1992). Climate change has attracted wide attention of governments and scientists because of its enormous influences on ecosystem functions and global environmental quality (Thomas et al., 2004; Kiritani, 2011).

The bullfrog *Lithobates catesbeianus* is native to eastern North America, but has been introduced throughout the world during the past two centuries (Lever, 2003).

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The species is considered as one of the most harmful and threatening invasive species, since it is relatively large and negatively affects native amphibians through competition (Zhou et al., 2005), predation (Kiesecker and Blaustein, 1998; Lowe et al., 2000) and disease transmission (Hanselmann et al., 2004). Knowledge of the patterns of bullfrog invasion is, therefore, extremely important for planning conservation strategies aiming to understand and reduce the impacts of their invasion. Bullfrogs were introduced into China in 1959 via the aquaculture and aquarium trades (Han, 1991). The species successfully established wild populations, and it is spreading locally (Li and Xie, 2004; Wu et al., 2004). Once established it is extremely difficult to eradicate (Li and Xie, 2004). Although the distribution of the species has been simulated at a global scale (Ficetola et al., 2007) to predict areas susceptible to invasion, little is known about its potential distribution in China and how future climate scenarios will influence its distribution. We therefore modeled the potential distribution of bullfrog based on current climatic models and projected the results onto future climate scenarios (2050 and 2070) under two emissions scenarios, RCP4.5 (a radiative forcing of 4.5 W/m$^2$ at the end of 2100) and RCP8.5 (a radiative forcing of 8.5 W/m$^2$ at the end of 2100). Our main aims were to describe the current potential distribution of the bullfrogs in China and to model its distribution under future climate change scenarios.

## MATERIALS AND METHODS

We collected individual records of bullfrogs in China from: 1) the relevant literature (n = 83 records); 2) the Global Biodiversity Information Facility database (GBIF, http://data.gbif.org, n = 6 records); and 3) our own field investigations (n = 6 records). We used Arcgis 10.2, combined with Google Earth, to extract the longitude and latitude coordinates and discard duplicate records (Warren and Seifert, 2011). All the distribution points with a spatial resolution of 30 arc-sec are buffered in GIS to ensure that only one point exists within the range of 30 arc-seconds (approximately 1 km × 1 km). Totally, we achieved 95 individual records of bullfrogs in China.

We downloaded climate data with a spatial resolution of 30 arc-sec from the Worldclim database (http//www.worldclim.org/bioclim). We used Arcgis 10.2 to unify all the factors into the same coordinate system and extent (Tang and Yang, 2006). As our base map, we used a 1: 4,000,000 map of China as original map from the national basic geographic information system (http://nfgis.nsdi.gov.cn).

We prepared a total of 22 layers of variables (19 environmental variables and 3 topography variables), that mainly reflect seasonal variation in temperature and precipitation (Hijmans et al., 2005), and topography factors (elevation, aspect and slope). We extracted their values at each distribution point and we calculated the pairwise Pearson product-moment correlation coefficients. In the cases where two variables were inter-correlated to a high degree ($r > 0.75$, Nori et al., 2011a, b), we selected the most important biologically factors (Bourke et al., 2018). We selected 6 final bioclimatic variables and 3 topography variables that did not show high correlation with other variables ($r < 0.75$) (Nori et al., 2011a, b). The final variable set included "Annual Mean Temperature" (bio1), "Mean diurnal range of temperature" (bio2; the mean of monthly maximum temperatures minus the monthly minimum temperatures), "Isothermality" (bio3, Mean Diurnal Range/(Max Temperature of Warmest Month-Min Temperature of Coldest Month)×100), "Mean Temperature of Wettest Quarter" (bio8), "Annual Precipitation" (bio12), and "Precipitation Seasonality" (bio15, Coefficient of Variation), elevation, aspect and slope. To estimate the influence of global climate change on the potential distribution of the species, we modeled the distribution for three different time slices: present, 2050 and 2070. The climate data was available from the Worldclim data (http//www.worldclim.org/bioclim). Due to the large effect of different Atmosphere Global Circulation Models (AGCMs) in species range projections (Diniz-Filho et al., 2009), we selected three different AGCMs (BCC-CSM1-1, ACCESS1-0 and IPSL_CM4) for each time slice with each climate models involving two future emissions scenarios developed by IPCC's Fifth Assessment Report (RCP4.5 and RCP8.5) (http//www.worldclim.org/bioclim). The selected AGCMs have different equilibrium climate sensitivity values ranging from 0.9 °C to 4.8 °C.

Maximum Entropy Modeling (Maxent) is a useful method to simulate the potential habitat redistribution under climate change, due to high predictive accuracy and strong stability (Phillips et al., 2006; Steven et al., 2006; Wisz et al., 2008). We used a maximum entropy approach to model climatically suitable areas of bullfrogs in China using Maxent 3.3.3e (www.cs.princeton.edu/~shapire/maxent), and we validated the model using a cross-fold approach (Hijmans, 2012). We randomly selected 75% of bullfrog records for model training (Bourke et al., 2017) and the remaining 25% for model testing, with a logistic output format ranging from 0 (unsuitable environmental conditions) to 1 (optimal) (values near 0.5 representative of average habitat quality; Phillips and Dudík, 2008). Jackknife tests were run to measure variable importance (Phillips et al., 2006). In addition, a bias file was included in the run to represent sampling effort to reduce the sampling bias and increasing speed (Young et al., 2011).

The accuracy of the model was evaluated by using the area under the receiver operating characteristic curve called AUC (Swets, 1988), commonly recognized as the optimal model prediction since it is unaffected by the threshold value and insensitive to incidence of species (Fielding and Bell, 1997). AUC scores quantify the SDM's ability to differentiate between random prediction (AUC = 0.5) and perfect identification of suitable grid cells (AUC = 1.0) (Hanley and McNeil, 1982; Phillips et al., 2006; Wang et al., 2007). After converting the Maxent output avg.asc into raster format, we reclassified the results of Maxent with thresholds in ArcGIS (Lu et al., 2012) and divided the suit bal environmental conditions into 4 levels based on the fitness index size (Wang et al., 2007; Zhai and Li, 2012) with low potential (< 0.2), moderate potential (0.2-0.4), good potential (0.4-0.6), high potential (> 0.6) (Yang et al., 2013).

To test for possible differences of the predicted distribution under different climate scenarios, each out of the twelve maps was compared to the current distribution map using Map Comparison Kit software (version 3.2.3; MCK, 2017) and an overall similarity index was computed between a map pair. We applied the "fuzzy numerical" algorithm as these maps were numerical (Visser and de Nijs, 2006; Falaschi et al., 2018).

## RESULTS

We obtained a good SDM performance with an average test AUC value of 0.867, which indicated that the prediction has high credibility. Analysis of variable contributions revealed that the "Annual Precipitation" had the highest explanative power, explaining 34.7% of the variation, followed by "Mean Diurnal Range" (33.9%), "Elevation" (20.4%) and "Annual Mean Temperature" (3.1%), suggesting that the geographical distribution of bullfrog was most affected by these four factors.

The results from Maxent analysis showed at present there were many areas unsuitable for habitation by bullfrogs: Inner Mongolia, Gansu, Qinghai and Tibet. Overall, mainly the center, east, southeast and the southwest of China were suitable area of bullfrog survival, with a small number of suitable areas in Xinjiang, Ningxia, Jilin, Liaoning and Heilongjiang (Fig. 1).

The AUC values were above 0.8 in all of the models, indicating that the prediction results have high credibility. Generally, climatically suitable areas may become narrower as the invasion begins to retract in the southeast coastal the north of the north China plain, Sichuan basin and the middle and lower reaches of the Yangtze River (Fig. 2; Table 1). Only minor differences were observed in model projection onto climate change scenarios derived from BCC-CSM1-1, ACCESS1-0 and IPSL_CM4 (Fig. 3; Table 1), and these differences and similarities were also confirmed by the fuzzy numerical comparison performed in MCK: similarity maps (Fig. 4) showed only slight differences between current distribution map and these future distribution maps with the similarity index rose from 0.552 to 0.773.

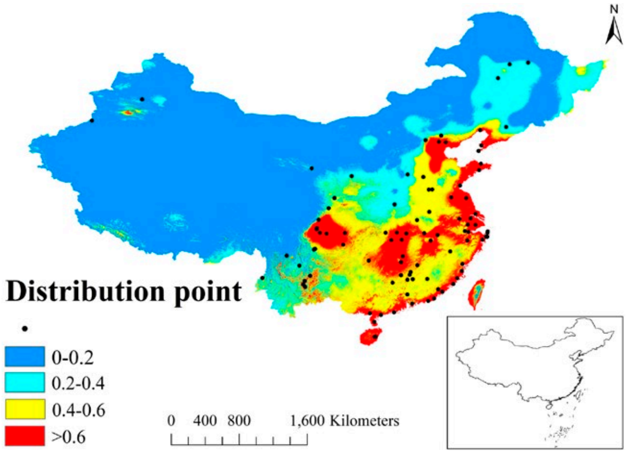

**Fig. 1.** Map of the suitable distribution of bullfrog in China (Present).

## DISCUSSION

We investigated the current potential and future distribution for bullfrogs under different climate change scenarios. The results show that under the current climatic conditions, bullfrogs have a wide range of potential distribution in China, located in the center, east, southeast and southwest China, with only a small number of suitable areas in north China including Xinjiang, Ningxia, Liaoning, Jilin and Helongjiang. Generally, our models also revealed that global climate change is likely to shrink slightly the extent of suitable habitat under future scenarios.

Compared to Ficetola et al. (2007), who found that bullfrogs are mainly distributed in eastern China, our study results extend its distribution area to central China, with a few locations in the west and northeast China, which may represent new invasion areas. This can be explained by the facts that some new invasion sites have been found in China recently (Fei et al., 2012).

The current distribution pattern of bull frogs in China can mainly be explained by precipitation and temperatures. Previous study also showed that bullfrog presence seems to be positively related to precipitation (Ficetola et al., 2007). The availability of water (including the presence of permanent wetlands) for breeding are commonly recorded important environmental features needed for the presence of bullfrogs (Maret et al., 2006) and their tadpoles' growth, development and metamorphosis (Govindarajulu et al., 2006). In addition, Mean Diurnal Range also influences the distribution of bullfrogs. This is also similar to the results from Ficetola et al. (2007) and, indeed, Bullfrog is a 'warm-adapted species' (Bachmann, 1969; Harding, 1997). Besides, previous studies showed that the current distribution of bullfrogs in China is also explained by 1) the proximity to the frogfarms, from where bullfrogs can escape: most of the bullfrog farming in China is surrounded by highly suitable habitats, and the frogs can establish wild population there (Wu et al., 2004; Li and Xie, 2004); 2) the abandonment/release of bullfrogs mainly by religious groups, which also led to the establishment of new wild population, e.g., in Yunnan

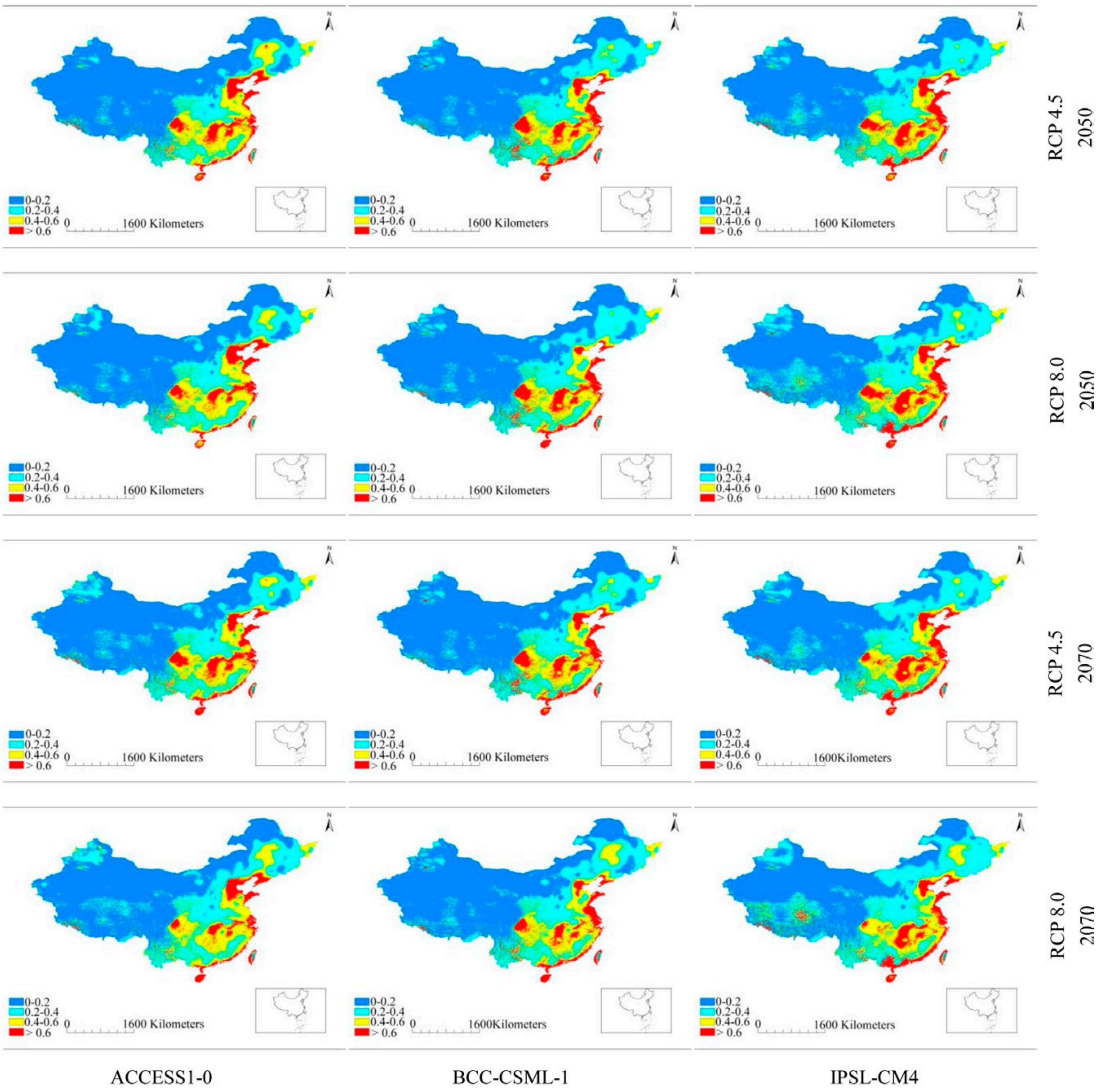

**Fig. 2.** Maps of the potential suitable distribution of bullfrog in China in 2050 and 2070.

and Sichuan (Wu et al., 2004; Li and Xie, 2004).

As shown by the fuzzy numerical comparison performed in MCK, slight differences between current and future distribution maps have been observed. Also, projecting bullfrogs' climatically suitable areas on future climate change scenarios (RCP4.5 and RCP8.0) indicated that climatically suitable areas will become narrower in China. The potential habitats of bullfrogs in China will retreat to the most suitable area including the north of the north China plain, Sichuan basin and the middle and lower reaches of the Yangtze River (Fig. 2), where bullfrog farming is particularly common (Fei et al., 2012).

Biological invasions are complex and the potential habitat distribution is determined by a variety of factors (Li et al., 2009). In this study, we only considered the effect of the climate and terrain, but we did not consider the effect of the other factors including the vegetation cover, biotic interactions with other species, species

**Table 1.** Changes in the potential distribution area under climate change in 2050 and 2070.

| Climate scenarios | Atmosphere Global Circulation Models (AGCMs) | Area of the most suitable zone (the red part of the map)/ Million square kilometers | Percentage (%) |
|---|---|---|---|
| Present | | **82.27201** | **9.19%** |
| 2050RCP4.5 | ACCESS1-0 | 66.06528 | 6.88% |
| | BCC-CSML-1 | 68.44306 | 7.12% |
| | IPSL-CM$ | 80.92153 | 8.42% |
| 2050RCP8.0 | ACCESS1-0 | 59.2675 | 6.18% |
| | BCC-CSML-1 | 69.33708 | 7.22% |
| | IPSL-CM$ | 89.20736 | 9.28% |
| 2070RCP4.5 | ACCESS1-0 | 67.75792 | 7.05% |
| | BCC-CSML-1 | 72.75847 | 7.57% |
| | IPSL-CM$ | 78.15097 | 8.13% |
| 2070RCP8.0 | ACCESS1-0 | 55.53778 | 5.78% |
| | BCC-CSML-1 | 60.97194 | 6.35% |
| | IPSL-CM$ | 78.69361 | 8.19% |

migration capacity, species evolutionary adaptations, and human exploitation of wild populations, on the potential distribution of the bullfrog. If these factors were fully considered, the predicted results could have been more closely related to the current distribution of species (Graham and Hijmans, 2006).

To effectively prevent further invasions of bullfrogs in China, management policies should be more pragmatic, preventing new introductions within suitable habitats and eradicating populations when possible. Based on the predictions on bullfrog potential habitats from SDMs, the authorities should consider the model results to focus the management strategies on these potentially sensitive regions. In addition, authorities should tighten control of bullfrog farming to prevent their escape. In addition, frog factories could be moved to areas which are surrounded by unsuitable habitats of bullfrogs, which would reduce a lot the possibility of survival of escaped captive individuals.

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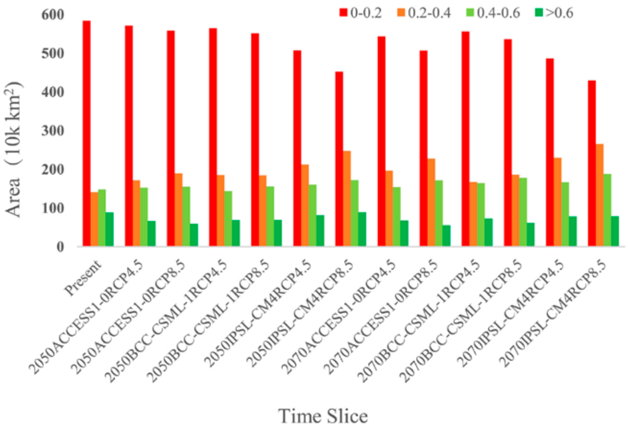

**Fig. 3.** Comparison of potential suitable distribution of bullfrog at present, in 2050 and in 2070 under future climatic conditions with low potential (< 0.2), moderate potential (0.2-0.4), good potential (0.4 – 0.6), high potential (> 0.6).

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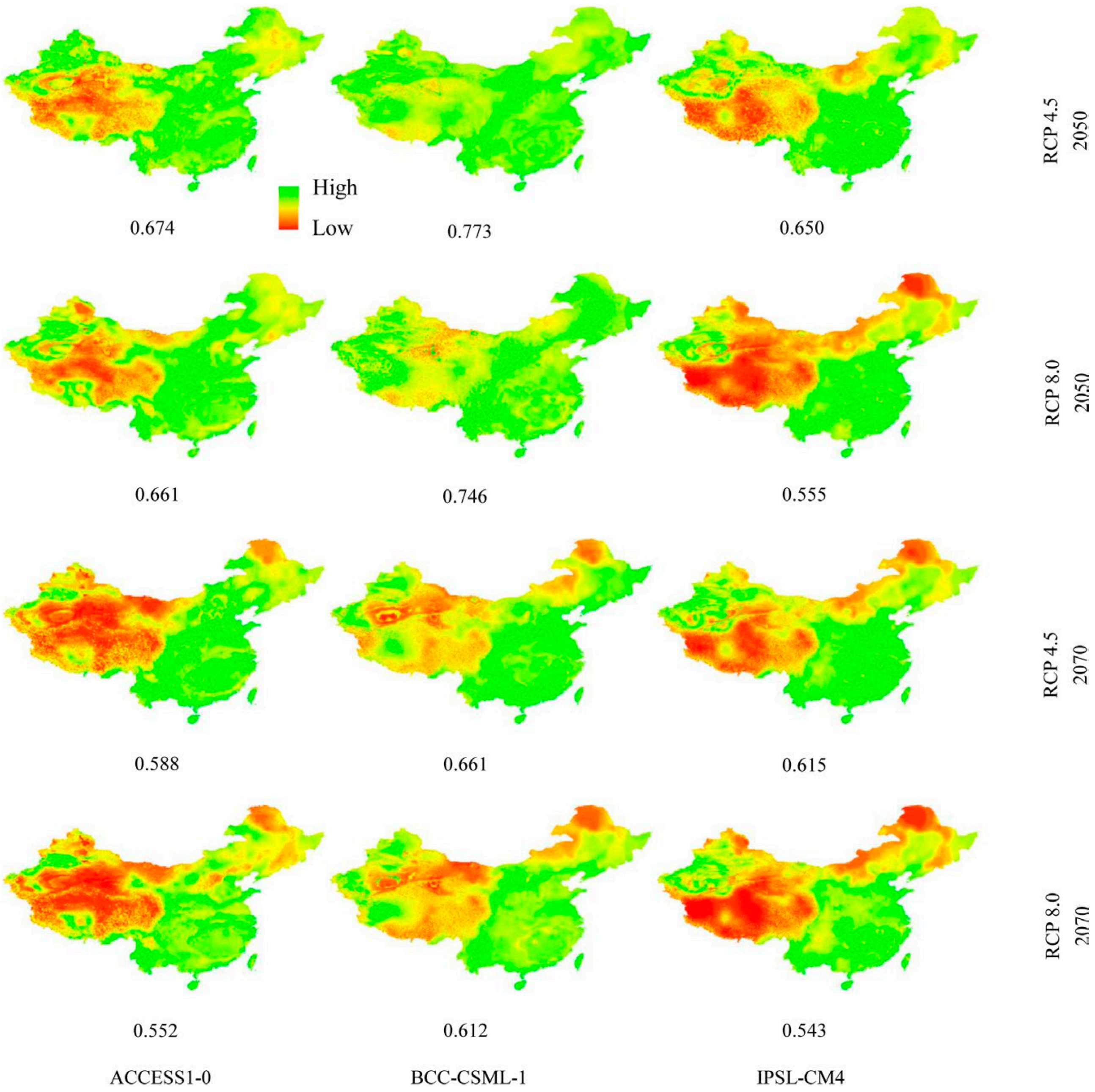

**Fig. 4.** Similarity maps of the fuzzy numerical comparison between current distribution map and future potential distribution maps under future climatic conditions performed in MCK with similarity index of each map

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