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ORIGINAL ARTICLE

Impact of climate-driven temperature increase on inland aquaculture: Application to land-based production of common carp (*Cyprinus carpio* L.)

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Abstract

Climate change will expose the food-producing sector to a range of challenges. Inland aquaculture farms are particularly vulnerable, due to the difficulty in changing their location, and therefore require specific tools to predict the influence of direct and indirect effects on production, environment and economic feasibility. The objective of our study was to apply a simple set of models to produce a set of growth, risk and suitability maps for stakeholders within the common carp sector in Poland, to assist decision-making under two different scenarios of climate change: a moderate situation (RCP 4.5) and an extreme situation (RCP 8.5). We used present (2000–2019) and future projections (2080–2099) for water surface temperature based on land surface temperature data from regionally downscaled climate models to draw maps to: (i) show optimal temperature conditions for carp growth, (ii) assess risk of disease outbreak caused by three important common carp pathogens: Cyprinid herpesvirus 3 (CyHV-3), carp oedema virus (CEV) and spring viremia of carp (SVCV) and (iii) predict potential suitability changes of carp farming in Poland. The study identified areas with the most and least favourable temperature conditions for carp growth, as well as those areas with the highest/lowest number of days with suitable temperatures for virus infection. These suitability maps showed the combined effect of direct and indirect effects of climate change projections under RCP 8.5 and RCP 4.5 scenarios. The approach applied herein will be of use worldwide for analysing the risks of temperature increase to land-based aquaculture, and the results presented are important for carp farmers in Poland and elsewhere, industry in general, and government stakeholders, to understand the direct and indirect effects of climate change on the triple bottom line of people, planet, and profit.

KEYWORDS

aquaculture sites, CEV, CyHV-3, freshwater aquaculture, pond farming, risk maps, suitability maps, SVCV

1 | INTRODUCTION

In May 2013, world aquaculture production overtook capture fisheries for human consumption, and in 2018, 82.1 million tonnes of fish were farmed, representing 46% of total aquatic production (FAO, 2020). In the Western World, aquaculture predominantly takes place in estuarine and coastal systems (Smaal et al., 2019); for instance, in Europe only 16.5% of production occurs in inland waters. However, on a worldwide scale, 62.5% of aquaculture occurs in land-based systems such as lakes, reservoirs, ponds, and rivers (FAO, 2020). Moreover, 86.5% of finfish and 38.9% of crustaceans cultivated worldwide are grown in inland waters – together these correspond to a combined volume of over 50 million tonnes per year (Table 1). This contrasts sharply with wild capture, where only 12.4% of fisheries takes place in freshwater systems (recalculated from FAO, 2020).

Fisheries and aquaculture are sensitive to climate change due to direct effects, such as (i) temperature-related perturbations in metabolism or reproduction or (ii) higher mortality or morbidity due to increased dissolved oxygen stress and indirect effects, such as (i) changes in host susceptibility to pathogens due to shifts in overlapping optimal temperature windows, (ii) increased storminess, which increases the risk of escapees and introgression or (iii) changes in temperature-related distribution of harmful algal bloom (HAB) species (Townhill et al., 2018). Whereas in capture fisheries issues are more closely linked to shifts in species distribution, leading to the loss of fishing grounds but also to the emergence of new ones, the consequences for aquaculture are quite different. Organisms are cultivated at specific farm locations in water bodies by means of structures such as cages, rafts, longlines, trestles or as often occurs in inland waters, constructed earthen ponds or raceways, which themselves constitute the water body. This occurs not just due to environmental and ecological considerations but due to licensing and regulatory constraints (Corner et al., 2018). Furthermore, inland aquaculture in Europe takes place at sites where connectivity is generally weak; cages deployed in a lake or impoundment are at a fixed position and cannot easily be moved to a different water body, and the same applies to artificial structures such as earthen or concrete ponds.

In addition, business mobility is a challenge: land-based aquaculture is typically a small-scale activity – often a farmer will live in the vicinity of the farm, just as in agricultural smallholdings; moreover,

TABLE 1 Relevance of land-based aquaculture at a global scale (adapted from FAO, 2020)

Category	Africa	Americas	Asia	Europe	Oceania	World
Inland aquaculture						
Finfish	1893	1139	43,406	508	5	46,951
Crustacea	0	73	3579	0	0	3653
Molluscs			207			207
Other aquatic animals		1	528	0		528
Subtotal (10^3 tonnes y^{-1})	1893	1213	47,719	508	6	51,339
Marine and coastal aquaculture						
Finfish	291	1059	3995	1892	92	7328
Crustacea	6	888	4834	0	6	5734
Molluscs	6	640	15,876	680	102	17,304
Other aquatic animals	0		387	3	0	390
Subtotal (10^3 tonnes y^{-1})	302	2587	25,093	2575	200	30,756
All aquaculture						
Finfish	2184	2197	47,400	2399	97	54,279
Crustacea	6	961	8414	0	6	9387
Molluscs	6	640	16,083	680	102	17,511
Other aquatic animals	0	1	915	3	0	919
Total (10^3 tonnes y^{-1})	2196	3799	72,812	3083	205	82,095
Per cent inland						
Finfish	81.7	51.8	91.6	21.2	5.2	86.5
Crustacea	0.0	7.6	42.5	–	0.0	38.9
Molluscs	0.0	0.0	1.3	0.0	0.0	1.2
Other aquatic animals	–	100.0	57.7	0.0	–	42.4
Aggregate (%)	86.2	31.9	65.5	16.5	2.9	62.5
Per cent world production by continent (%)	2.7	4.6	88.6	3.8	0.3	100

a farmer will often cultivate both in water and on land, and in SE Asia and China ponds are commonly used for multi-trophic cultivation (Ferreira et al., 2014). For aquaculture, these constraints, together with (i) the expected changes in freshwater availability due to climate change and (ii) the much lower volume of water when compared to the ocean, which increases the coupling between air, land, and water and therefore the susceptibility of inland systems; mean that such systems may well be more sensitive to climate change effects than marine systems. This is a worldwide problem, since it will affect the livelihood of farmers and food security of populations that rely on production of carp (e.g. Eastern Europe, China), tilapia (SE Asia and China, Brazil, Central America, Africa), catfish (North America, SE Asia) and shrimp (SE Asia and China, Central and South America).

Modelling tools are a useful approach to identify and assess risks in aquaculture, but in order to be widely applicable, including in parts of the world such as SE Asia, Africa and South America, such models must be of a generic nature, simple and flexible enough to be applied in areas that are not data-rich. Different types of models were identified as the most relevant for evaluating risks associated with climate change for inland aquaculture. Geographic Information System (GIS) models have been used as practical decision-making tools worldwide to improve inland and marine aquaculture sustainability and efficiency (Ross et al., 2013). Models that explore the effects of climate change on selected host-pathogen systems exist mostly for marine species (Ben-Horin et al., 2013; Groner et al., 2016; Ferreira et al., 2021) rather than for freshwater species (Macnab & Barber, 2012). GIS-based statistical models provide opportunities to evaluate spatially-distributed determinants of aquatic health and disease (Thrush et al., 2011) and this 'risk mapping' approach was first proposed by Thrush and Peeler (2013). The authors used satellite remote-sensing, measured environmental data and epidemiological studies to draw risk maps for the whole United Kingdom (Thrush & Peeler, 2013), enabling the identification of common carp populations susceptible to koi herpesvirus (KHV) and spring viremia of carp virus (SVCV), which broadly overlap the areas with the highest number of days per year where the temperature is optimal for the establishment of these diseases. Moreover, the output of the work may be directly applied to identify areas where diseases can be managed in farmed populations, for example, proliferative kidney disease (PKD) outbreaks in farmed rainbow trout (*Oncorhynchus mykiss*). However, except of disease modelling based on risk maps aquaculture sector expect information that will indicate areas with the best and least suitable conditions for fish farming in the future. Therefore, next generation of maps should combine information both on risk of diseases and optimal growth conditions for a specific species. To the best of our knowledge, such maps were not developed and are currently not available for the carp sector in Europe. Therefore, the aims of our work were: (i) to produce both risk and suitability maps assessing direct, indirect and combined effects of temperature increase on carp aquaculture in Central Europe and (ii) to indicate how the maps may be used by farmers, policymakers and other stakeholders to mitigate risk and optimize sustainable production, food security, and employment in a changing climate.

2 | METHODS

2.1 | Study area

The study area covered the area of Poland (divided into 10 × 10 km cells) where 7081 water bodies (larger than 1 ha) with a total area of 280,977 ha of which approximately 65,000 ha are used for common carp aquaculture (Figure 1). Farming of common carp is decentralized and traditional, with farms scattered across whole country. Carps are typically cultured in earthen ponds in extensive or semi-extensive production systems with dietary supplementation of locally available grains. Production cycle is 3 years long (approx. 33 months) and most of the time fish are stocked in different ponds (fingerling, stock, grow out) depending on production stage. Ponds are relatively shallow (maximum 1.5 m deep) and the water flow is usually low. The area of production ponds varies between small and large farms and ranges from 1 ha up to 300 ha. Considering the characteristics of the ponds, they are susceptible to temperature changes. In Poland, main pathogens that threaten the production of common carp are viruses. Three viruses were previously reported on farms across country (i) spring viremia of carp virus (SVCV), which affects fingerlings in the spring; (ii) carp oedema virus (CEV) an emerging disease, causing high mortality and (iii) cyprinid herpesvirus 3 (CyHV-3) causing fatal disease in common carp. Therefore, in the study, we focused on temperatures suitable for abovementioned virus development.

2.2 | Calculation of water surface temperatures

Land Surface Temperature (LST) values for the total area of Poland, including conservative representative concentration pathways (RCP 4.5) and non-mitigation business as usual (RCP 8.5) scenarios for each of the two time slices, that is present-day (2000–2019) and long-term (2080–2099), were provided by Plymouth Marine Laboratory (PML). Based on the methodology developed in Thrush and Peeler (2013), water surface temperatures (WST) were calculated using LST. The initial algorithm was calibrated using empirical water temperatures recorded in carp ponds in 2012–2014 and provided by courtesy of the Institute of Ichthyobiology and Aquaculture (Polish Academy of Science in Gołysz). Based on calculated WST and recorded water temperatures in carp ponds datasets, the regression algorithm (Supplementary Fig. S1) was built using STATISTICA 13.1 (TIBCO Software Inc., USA):

$$WST = 0.95LST + 5.29, \tag{1}$$

where *WST* is the temperature of water (°C) recorded in carp ponds and *LST* is the temperature of air (°C).

2.3 | Quantification maps for optimal growth and virus infection

First, the number of days with WST 20°C–34°C, and within two ranges 10°C–17°C and 15°C–28°C were calculated for the two time slices

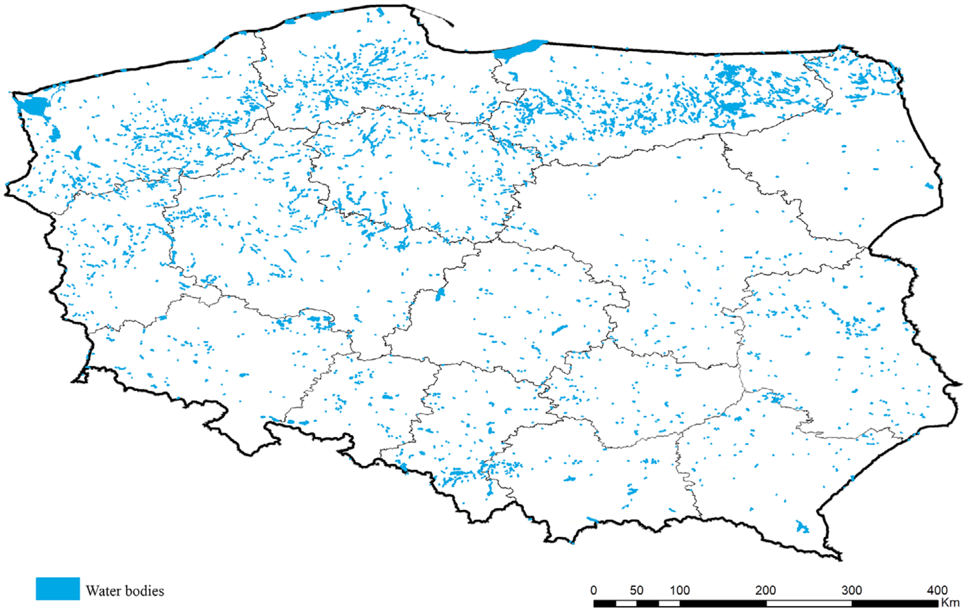

FIGURE 1 Study area

2000–2019 and 2080–2099 in each cell (10 × 10 km) using MATLAB software (MathWorks, USA). Water temperatures 20°C–34°C are optimal for common carp growth (Backiel, 1964; Song-bo et al., 2012; Stegman, 1960), whereas temperatures between 10°C and 17°C are optimal for successful replication and infection of SVCV (Ahne et al., 2002) and between 15°C and 28°C for two warm-water viruses, that is, CyHV-3 and CEV (Iida & Sano, 2005; Way et al., 2017; Yuasa et al., 2008; Zhang et al., 2017).

For each cell, the number of days was calculated using following formula:

$$C = \frac{1}{n}\sum_{Y_0}^{Y_n} d_0, \tag{2}$$

where C is the number of days of overlap window; n is the number of years of individual time slices; Y_n is the closing year of time slice; Y_0 is the starting year of time slice; d_0 is the number of days in the year with the water temperature within the assumed threshold.

Next, based on the calculated number of days for each cell, maps showing a percentage change in the number of days with WST 20°C–34°C, 10°C–17°C and 15°C–28°C between the two time slices, that is, 2000–2019 and 2080–2099, were produced. For each cell, the value of change (%) of average days per year was calculated using Equations (3)–(5), accordingly.

$$C_{20-34} = \frac{1}{n_0}(n_n - n_0) \times 100\%, \tag{3}$$

where C_{20-34} is the change of average days per year with WST 20°C–34°C; n_n is the average annual number of days 20°C–34°C for years 2080–2099; n_0 is the average annual number of days 20°C–34°C for years 2000–2019.

$$C_{10-17} = \frac{1}{n_0}(n_n - n_0) \times 100\%, \tag{4}$$

where C_{10-17} is the change of average days per year with WST 10°C–17°C; n_n is the average annual number of days with water temperature 10°C–17°C for years 2080–2099; n_0 is the average annual number of days with water temperature 10°C–17°C for years 2000–2019.

$$C_{15-28} = \frac{1}{n_0}(n_n - n_0) \times 100\%, \tag{5}$$

where C_{15-28} is the change of average days per year with WST 15°C–28°C; n_n is the average annual number of days with water temperature 15°C–28°C for years 2080–2099; n_0 is the average annual number of days with water temperature 15°C–28°C for years 2000–2019.

All calculations were performed with ArcGIS 10.5. Maps were made using polygon reference fields by means of the choropleth method. A continuous scale was adopted for data presentation.

2.4 | Suitability maps for common carp farming

Four suitability maps were made for time slices 2000–2019 and 2080–2099 under RCP 4.5 and RCP 8.5 scenarios using data from maps showing number of days with each of three temperature ranges. In details, the scoring system used to rate the suitability of the area for common carp farming was created by combining the number of days with water temperature within the range of 20°C–34°C and the number of days with water temperature suitable for SVCV (10°C–17°C), and CyHV-3 and CEV development (15°C–28°C). Components used to create suitability maps were considered separately without weighing each of them (for details see discussion). The results were assigned to ten classes divided by the method of equal intervals, scoring from 1 to 10 (Supplementary Table S1). It was assumed that increased number of days with water temperature 20°C–34°C resulted in more points assigned, since it creates more favourable conditions for carp growth. Conversely, increased number of days with water temperature between 10°C–17°C and 15°C–28°C caused less points assigned due to increased disease development, which threatens carp farming. The number of points in each cell was calculated using Equation (6):

$$C_S = N_{S20-34} + N_{S10-17} + N_{S15-28}, \tag{6}$$

where C_S is the number of points in each cell (calculated for time slices 2000–2019 and 2080–2099 under RCP 4.5 and RCP 8.5 scenarios); N_{S20-34} is the suitability score of number of days per year with water temperatures 20°C–34°C (number of scores 1–10); N_{S10-17} is the suitability score of number of days per year with water temperatures 10°C–17°C (number of scores 1–10); N_{S15-28} is the suitability score of number of days per year with water temperatures 15°C–28°C (number of scores 1–10).

Next, two maps were made to show change in suitability of geographical regions for carp farming between present-day (2000–2019) and long-term (2080–2099) under RCP 4.5 and RCP 8.5 scenarios following Equation (7):

$$C_{SF} = C_{S2080-2099} - C_{S2000-2019}, \tag{7}$$

where C_{SF} is the number of points in each cell (calculated for RCP 4.5 and RCP 8.5 scenarios); $C_{S2080-2099}$ is the number of points in each cell for time slice 2080–2099; $C_{S2000-2019}$ is the number of points in each cell for time slice 2000–2019.

Depending on the points assigned, the cells were reclassified (equal intervals) to five suitability classes: high (25–29 pts), medium-high (20–24 pts), medium (15–19 pts), medium-low (10–14 pts) and low (5–9 pts) for simplified interpretation. Moreover, an additional suitability map was made to show difference between carp aquaculture under RCP 4.5 and RCP 8.5 models on the occasion if the latter scenario named 'business as usual' unfortunately will be more likely, following Equation (8):

$$C_{VS} = C_{SF8.5} - C_{SF4.5}, \tag{8}$$

where C_{VS} is the number of points in each cell; $C_{SF8.5}$ is the number of points in each cell for RCP 8.5 scenario; $C_{SF4.5}$ is the number of points in each cell for RCP 4.5 scenario.

Suitability maps were built using ArcGIS 10.5 and a continuous scale has been adopted for data presentation.

3 | RESULTS

3.1 | Direct effect of temperature increase on *C. carpio* growth

Our results showed that the average number of days with water temperature beneficial for carp growth will increase by 28.5% and 53.5% in 2080–2099 according to RCP 4.5 and 8.5 scenarios, respectively. Additionally, the change in the number of days with water temperature 20°C–34°C in Poland ranged from 17% to 135% and from 35% to 203% for RCP 4.5 and 8.5, respectively (Supplementary Figs. S2a and b, S3a and b and S4a and b). Regardless of the scenario, climate warming is expected to stimulate growth performance of common carp since days with WST exceeding 30°C were rarely found even in the RCP 8.5 scenario for 2080–2099. The highest change in number of days with water temperature 20°C–34°C is forecasted for northern and southern regions (Figure 2a and b).

3.2 | Quantification of indirect effects of temperature increase on carp health

This study showed that mean number of days with water temperature suitable for CyHV-3 and CEV to induce diseases will increase by 4.4% and 17% in 2080–2099 under RCP 4.5 and 8.5, respectively. Moreover, the increase in number of days with water temperature between 15°C and 28°C in Poland ranged from 1% to 32% and from 12% to 61% for RCP 4.5 and 8.5, respectively (Supplementary Figs. S2c and d, S3c and d and S5a and b). The KHV and CEV temperature maps likewise display an optimal growth forecast, showing a greater increase of days with water temperature between 15°C and 28°C in the north of Poland and in the mountainous regions on the south (Figure 2c and d). Regions in the south where most of the carp farms are located will be more vulnerable to KHVD and CEVD under the RCP 8.5 scenario when compared to RCP 4.5.

In terms of SVCV, the mean number of days with water temperature 10°C–17°C will increase by 1.8% and 17.1% in 2080–2099 under RCP 4.5 and 8.5, respectively. Additionally, we noted that the number of days with water temperatures suitable for SVCV for RCP 4.5 ranged from a 12% decrease to a 9% increase depending on the area, whereas for RCP 8.5 an increase between 3% and 22% will be noted across the country (Supplementary Figs. S2e and f, S3e and f and S6a and b). The reduction of conditions suitable for SVC development reported with RCP 4.5 will be visible in the more mountainous southernmost areas and in north, while the central part of Poland will note a limited increment (Figure 2e). However, an increase according to RCP 8.5 will be significant for the whole country, with the exception of mountainous areas, where changes will be limited (Figure 2f). Thus, farms located at the foot of mountains will experience beneficial conditions compared to the rest of the country.

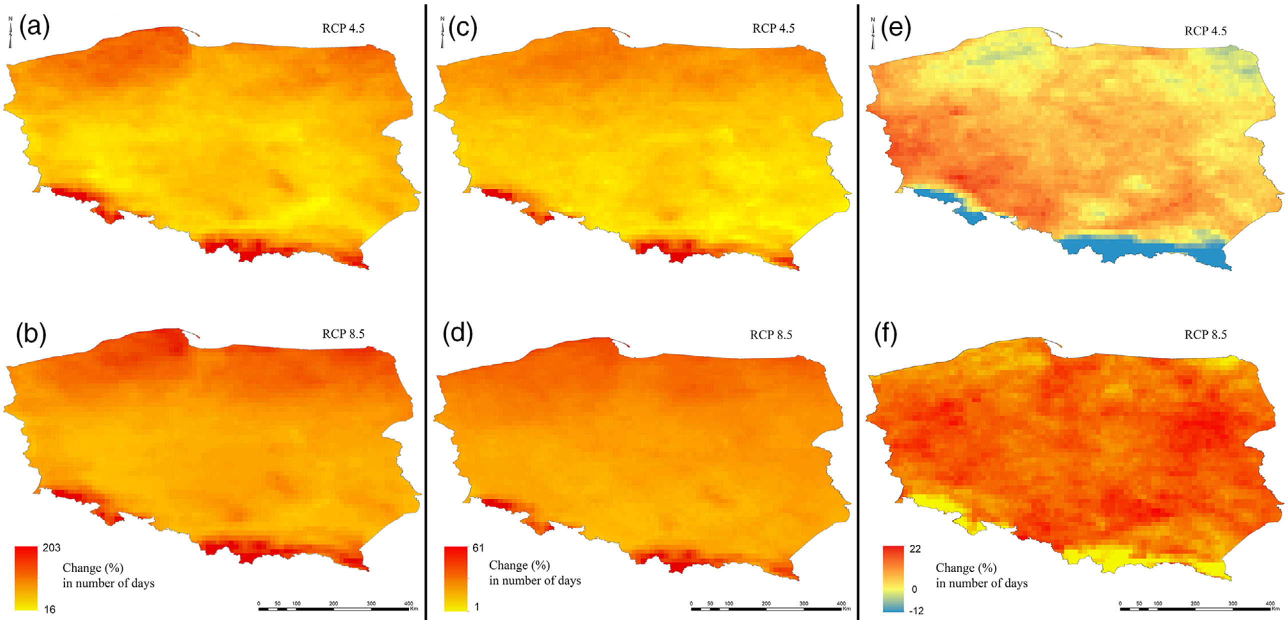

FIGURE 2 Change (%) in number of days between 2000–2019 and 2080–2099 periods with water temperature suitable for carp growth (a and b), Cyprinid herpesvirus 3 and carp oedema virus (c and d), and Spring Viremia of Carp virus infections (e and f): WST 20°C–34°C for RCP 4.5 (a), 20°C–34°C for RCP 8.5 (b), 15°C–28°C for RCP 4.5 (c), 15°C–28°C for RCP 8.5 (d), 10°C–17°C for RCP 4.5 (e) and 10°C–17°C for RCP 8.5 (f)

3.3 | Suitability maps for carp farming

The suitability maps considering both direct and indirect effects showed that in present-day (2000–2019) time slice most of the areas had medium suitability under RCP 4.5 and RCP 8.5 (76.3% and 84.0% respectively) (Figure 3a and b). Suitability of the rest of the country was medium-low, accounting for 23.3% and 15.6% under RCP 4.5 and RCP 8.5, and less than 1% of low class in case of both RCPs. For long-term (2080–2099) period under RCP 4.5 (Figure 3c), most areas will have medium (80.7%) or medium-high (14.9%) suitability for carp farming. Whereas under RCP 8.5 scenario (Figure 3d) medium-high and high will consist of 45.3% and 51.9% of areas in Poland, respectively. Additionally, none (0%) of the country area will be low suitable for carp farming under both RCP scenarios. The suitability change maps between present-day (2000–2019) and long-term (2080–2099) period showed that under RCP 4.5 scenario 65.7% of the country area will keep the same class, and for 34.3% of the area, class will be one higher (Figure 4a). While under RCP 8.5, 34.9% of the area will be one class higher and 65.1% of the area two classes higher in long-term compared to present-day time slice (Figure 4b). Suitability change map that compared RCP 8.5 and RCP 4.5 scenarios at the end of the century showed no change for 0.04% (one cell), one class higher for 61.4% and two classes higher for 38.5% of the country area (Figure 4c).

4 | DISCUSSION

4.1 | Direct effect of temperature increase on *C. carpio* growth

Common carp is highly resistant to environmental conditions (temperature fluctuations, supersaturation, hypoxia, pH changes) and is considered a thermophilic species; to maintain effective growth, the average daily temperature should exceed 20°C for at least 100 days per year (Backiel, 1964; Stegman, 1960). Previous studies on common carp farming in cages in water reaching 30°C (Eljasik et al., 2020; Panicz et al., data unpublished) showed no negative impact on growth rate of 2nd and 3rd year fish. Moreover, as showed in Song-bo et al. (2012), intake of feed by common carp was significantly reduced when water temperature exceeded 34°C. Goolish and Adelman (1984) showed that growth rate of juvenile common carp was higher in temperatures above those proposed in FAO (2018) as optimal (18°C–25°C). Farms located in the north (10% of total number of farms; Hryszko et al., 2018) will mainly benefit from the extended culture season since southernmost areas marked with the darkest colours are mountainous and thus to some extend not physiographically suitable for farm siting. In terms of direct effects, a water temperature rise will thus positively affect production and yield. However, carp ponds are water bodies with relatively low (or no) water flow and higher water temperatures can potentially increase fish oxygen uptake and lead to hypoxic conditions, significantly increasing mortality rate even in partially resistant species like common carp (Wojda, 2004; Zhou et al., 2000). Moreover, other factors associated with temperature rise such as water shortages (already being observed in sector) may additionally affect carp production.

4.2 | Quantification of indirect effects of temperature increase on carp health

CyHV-3 is the most threatening virus, with a carp mortality rate of 100% (Rakus et al., 2013), while CEV may account for an 80% mortality rate (Oyamatsu et al., 1997), and both viruses may co-infect fish (Kim et al., 2020) and temperatures for infection mostly overlap with

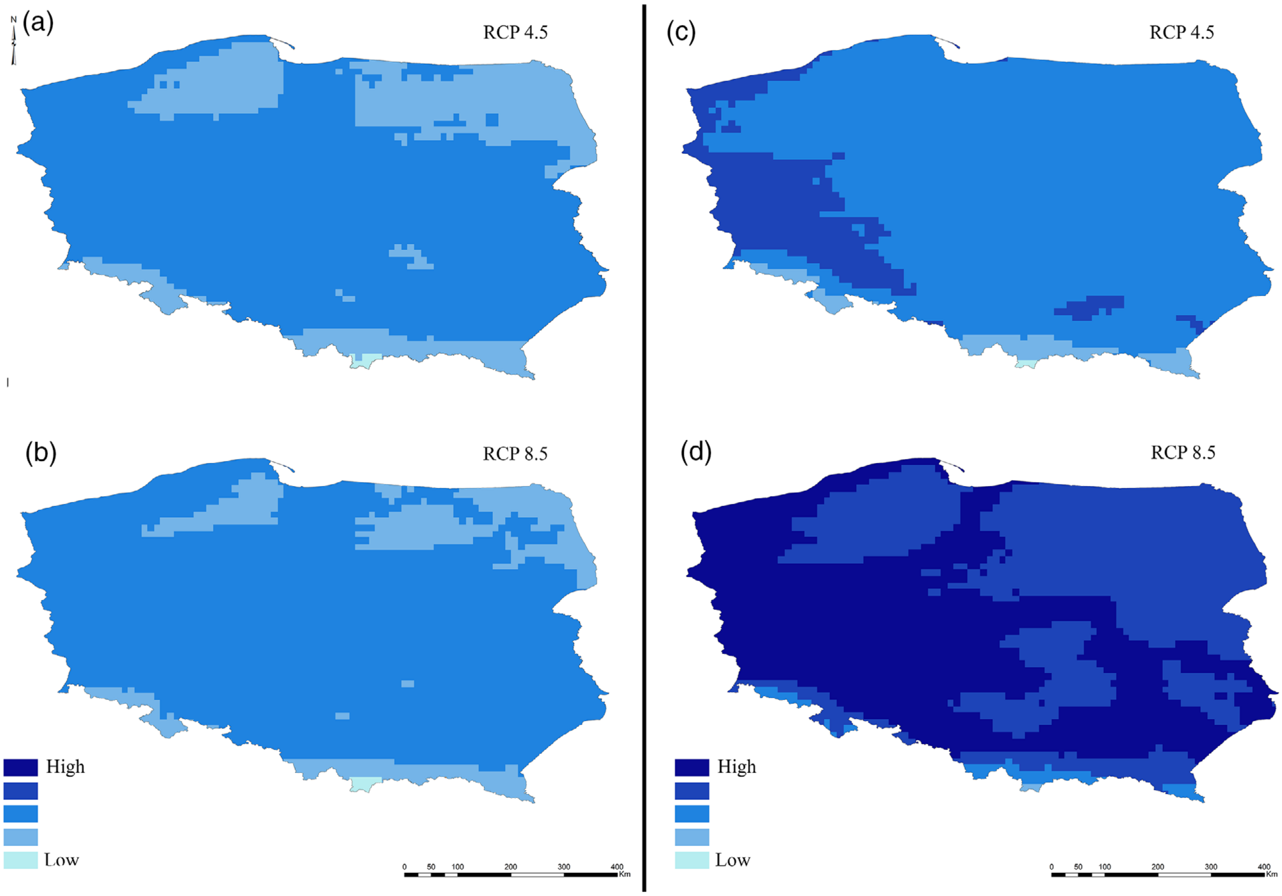

FIGURE 3 Suitability maps for carp farming, considering direct and indirect effects in present-day (2000–2019) period under RCP 4.5 (a) and RCP 8.5 (b), and long-term (2080–2099) period under RCP 4.5 (c) and RCP 8.5 (d)

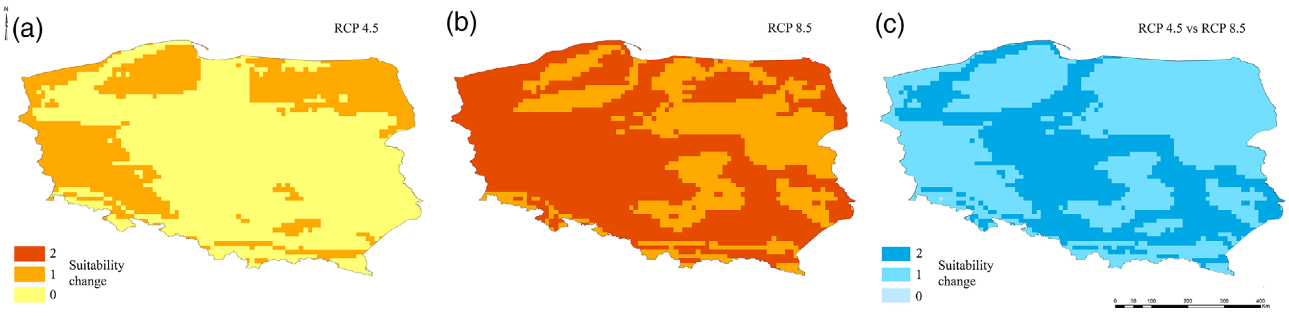

FIGURE 4 Suitability change maps for carp aquaculture in period 2080–2099 for RCP 4.5 (a), RCP 8.5 (b) and change in carp culture suitability in scenarios RCP4.5 vs. RCP 8.5 (c)

the temperature optimum for carp growth. Recent General Veterinary Inspectorate (2020) records showed that most of the KHVD outbreaks between 2014 and 2020 were identified in the carp farms located in the south of Poland. Similarly, in the same region, Matras et al. (2017) confirmed the highest number of CEV cases in the 2013–2015 period. The discrepancy in the number of confirmed cases between northern and southern farms stems from the higher density of farm sites in the south (Hryszko et al., 2018) but also from favourable thermal conditions for disease development in this region. Therefore, carp farms in northern Poland should consider mitigation measures to avoid spread of CyHV-3 and CEV (e.g. certified disease-free fry, fry from own hatchery, homozygosity level monitoring), since the risk of infections will increase with climate change.

According to the General Veterinary Inspectorate (2020), SVCV is under control, due to enhanced knowledge in the inland aquaculture sector. Despite the overall rise of outbreak risk of SVCV in Poland and confirmed presence of the virus in the environment, outbreaks are relatively rare and occasional (Maj-Paluch et al., 2019). Moreover, cultured carps were previously found to be less susceptible to SVCV than wild carps (Woo & Cipriano, 2017 and references therein). Therefore, maps showing increasing risk of SVCV should be taken as reminder that the virus is still threatening the carp sector and can cause significant mortalities (up to 70%), especially in juvenile fish exhausted after the wintering period (Ahne et al., 2002). Additionally, viral diseases are difficult to remove from the environment. For instance, in farms with CyHV-3 history (Bergmann et al., 2006) viruses remain active and cause significant carp loses (Panicz et al., 2020). Moreover, other organisms co-existing in pond culture, such as invertebrates, can accumulate virus particles and act as infection reservoirs (Kielpinski et al., 2010; Panicz et al., 2020). To envisage the combined effects of direct and indirect factors of climate change on carp farming in the future, the results from both quantification maps were ranked and merged into a suitability map.

4.3 | Suitability maps for carp farming

Changes in Polish freshwater aquaculture caused by climate warming are already tangible and, based on our results, the whole country may experience them to a greater or lesser extent, depending on the RCP scenario. In our study, the initial idea of risk mapping created in Thrush and Peeler (2013) has been further developed to a suitability mapping that provides information on establishment of pathogens and additionally considers future hydrochemical farming conditions. To our knowledge, resulting maps for the first time assessed the degree of site suitability for farming of common carp in Poland under two RCP scenarios for each of the two time slices, that is, present-day (2000–2019) and long-term (2080–2099). The results showed that higher emissions (RCP 8.5) will increase the number of sites that are suitable for carp farming mainly due to higher number of days per year that estimated daily average pond surface temperatures satisfy optimum criteria for common carp growth. Our results are in line with findings obtained in Varga et al. (2020), where carp sector in Hungary is expected to increase production of carp over the next decades. Authors showed that regardless of the RCP scenario (4.5 and 8.5), the result of higher anabolic activity and appetite of carp, and for this reason, feed utilization will be more efficient. However, as underlined by authors model did not consider the effects of climate change on fish diseases and the risk of diseases will increase, specifically due to the increase in water temperature and extreme weather events (Marcos López et al., 2010). In our study, all components (growth, CyHV-3/CEV and SVCV) were considered separately as independent factors with different characteristics, that is, temperature range and impact in relation to temperature increase. Fish growth is directly dependent on water temperature, but dependence has a non-linear character as fish allocate some part of energy to gonad development and reproductive behaviour (Wootton et al., 2022). Therefore, in our paper, we did not want to overestimate the impact of the increased number of days with water temperatures suitable for carp growth. Diseases were frequently excluded from various assessments of climate impact on aquaculture (Lorentzen, 2008; Froehlich et al., 2022; Varga et al., 2020). Mainly due to problematic quantification of their impact on aquaculture in relation to other components (low-oxygen hazard, flooding risk, etc.) (Callaway et al., 2012). In our paper, CyHV-3/CEV and SVCV were considered as separate components used to make suitability maps due to following reasons: (i) temperature range for development of the pathogens overlap only to a minor extent (12°C–17°C vs. 15°C–28°C); (ii) co-infection has not been described for these pathogens (but frequent for CyHV-3 and CEV) (Kim et al., 2020) and (iii) according to numerous findings, the risk of known and emerging diseases will increase with further temperature rise, but also with other drivers of change (Handisyde et al., 2017; Kennedy et al., 2016; Reid et al., 2019). Despite increasing number of days permissive for diseases development, suitability maps made in our study showed that towards the end of the century, most of the Poland area will have increasing number of areas suitable for common carp farming. Therefore, climate change may intensify common carp production but also may lead to species diversification and increase of biomass yield from earthen ponds ecosystems.

In assumptions, the suitability maps have been designed as an 'open' and adaptable tool to assist both assessment and selection of aquaculture sites for other aquaculture species whose farming depend on different species-specific array of direct and indirect climate change factors. For example, suitability maps developed for freshwater aquaculture of rainbow trout could include data related to temperatures and additionally information on projections of changes in velocity and the volume of water in rivers that subsequently flows through the farm as well as information on likeliness of heavy-rainfall events in future. Such information is crucial for the farmers as increasing sediment load can reduce or arrest the filtration rate of aquatic organisms and lead to contamination (Brinkmann et al., 2013; Reid et al., 2019). In case of marine aquaculture, suitability maps may support site selection procedure as projections related to various environmental variables (i.e., significant wave height) are now accessible for evaluating which areas have higher probability of being affected by storms (Porporato et al., 2020). As highlighted by our results, the application on suitability maps for assessment and selection of aquaculture sites in terms of climate change could be both tested in other areas and extended to different species, not only aquatic.

5 | CONCLUSIONS

Inland aquaculture in Central Europe is currently at a turning point, and carp farmers seek new solutions and tools to produce common carp and offer customers convenient (processed) carp products widely available through the year. Our study provides carp farmers, stakeholders and decision-makers involved in inland aquaculture with suitability maps that show both opportunities and threats. Farms located in regions predicted with higher number of days with favourable culture conditions for carp growth (water temperature 20°C–34°C) will be able to shorten production cycle and increase production yield. However, at the same time, risk-maps made for SVCV, CyHV-3 and CEV, three main pathogens responsible for carp mortalities, showed regions that will experience an increase in the number of days with permissive water temperatures for virus infection. As the carp farming business is a stationary with respect to location, the set of suitability maps developed in this work serves as a predictive tool that allows farmers to plan and execute steps needed to prepare mitigation and adaptation actions in response to climate change. The approach presented in our paper may be transferred and applied in various aquaculture sectors involved in finfish and invertebrate farming, both in freshwater and in marine conditions.

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CONFLICT OF 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.

ETHICS STATEMENT

The authors confirm that the ethical policies of the journal, as noted on the journal's author guidelines page, have been adhered to. No ethical approval was required as this is an article using temperature data.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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