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Invasion meltdown and burgeoning threats of invasive fish species in inland waters of India in the era of climate change

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Cyprinus carpio, Oreochromis niloticus *and* Clarias gariepinus *are the most abundantly captured invasive fish species in the mid-stretch of the Ganga river. Fish yield and biomass data based on mean abundance by weight was calculated using algorithms and spatio-temporal population dynamics model for future prediction of these invasive fish species. Temporal biomass forecast based on mean abundance by wieght for the period from 2020 to 2029 was determined. The findings of this study predicted fish yield of 176 ±16.33 kg km^{-1} day^{-1}* C. carpio *and 55.43 ± 6.4 kg km^{-1} day^{-1} O.* niloticus *during 2029 which might result into 117.87% and 116.9% rise in temporal biomass of Common Carp and Tilapia respectively in a decade's time while 139.2% rise in temporal biomass was predicted for the invasive African catfish. The yield of invasive Common Carp, Tilapia and African Catfish was correlated with rainfall and temperature data using ANOVA and we found that variance was $F=1.36$; $p=0.263$ for* C. carpio*; $F=1.60$; $p=0.326$ for* O. niloticus *and $F=1.63$; $p=0.101$ for* C. gariepinus*, indicating that variance was very close for Tilapia and African Catfish. The observed values of variance indicated that climatic changes had more impact to these two species than to the Common Carp. The concrete and forecast values were calculated considering 95% lower and upper level of confidence, which was significant ($p<0.05$) and the annual regression was found to be $p<0.464$, $p<0.419$ and $p<0.499$ for* C. carpio, O. niloticus and C. gariepinus*, respectively. Further, interactive performance of invaded* C. carpio, O. niloticus and C. gariepinus *was also assessed for understanding invasion meltdown. The results of mean abundance by weight based yield forecast of invaded Tilapia, Common Carp and African Catfish for the period of 2020 to 2029 suggest a stable production in the Ganga River in years to come. It also manifests a positive pattern of invasion in the times of climate change displaying invasion meltdown. This suggests increased pressures of fish invasions on temporal and spatial scales, and imposing new management challenges for freshwater ecosystems.*

Keywords: Ganga river, climatic factors, temporal biomass

Introduction

Freshwater fish form a key component of invasive alien fauna in many countries around the world including India, and several regions have fish communities with high proportions of non-native species (Leprieur et al. 2008; Singh and Lakra, 2011; Singh et al., 2013). In the Ganga river, many invasive fish species have been reported and are contributing to the fishery (Singh et al., 2013). Introduced fish invasions in the time of climate change have been reported to represent key threats

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to global biodiversity (Galil et al., 2008; Rolls et al., 2017). Invasion of introduced fish species and their effects on habitats has emerged as a major threat to ecosystems around the globe in general and in India in particular (Singh and Lakra, 2011; Singh et al., 2013; Fletcher et al., 2016). Although invasive species possess many attributes that can explain its ability to spread and survive even in new habitats and harsh environments, no study has identified processes that might explain its restricted pattern of superabundance. A few researchers have tried to estimate invasive species biomass and abundance on the basis of the mean abundance by weight (Dominguez et al., 2020; Singh and Srivastava, 2020). Several models estimating spatial and temporal variation in population density are increasingly used to track shifts in population distribution subject to environmental and climatic changes (Harsch et al. 2014; Thorson et al., 2017).

In recent times, increased global temperatures have been reported to help invasive species establish themselves in newer aquatic ecosystems (Arnaud et al., 2021). Rivers and streams have been reported to get warmed during the past few decades, and stream and water temperatures were projected to increase further in future as warmer climates. Climate not only has an impact on physical characteristics on surface waters, but also is a master variable for ecologically important chemical processes (Galil et al., 2008; Auffhammer *et al* 2012; Jayaraman and Murari, 2014). Invasive species might cause habitat modification, extinctions of endemic species, affect human health, and therefore endanger enormous economic costs (Singh and Lakra, 2011; Singh et al., 2013; Singh et al., 2014; Hanley and Michaela, 2019). In current time, unsustainable harvesting of natural stock of fishes especially from inland waters owing to invasion of introduced fish species led habitat degradation of riverine ecosystem and emerging conservation issues in the tropics, which has resulted in the stock decline of important local fish species, (Singh et al. 2013; Panlasigui et al., 2018; Mondal and Bhat 2020). Climate variables, namely temperature, precipitation, and humidity may have significant long-term implications on water quality and fisheries with special reference to fish invasions (Auffhammer *et al* 2012; Jayaraman and Murari, 2014).

In this study, we investigated how invasive fish species will flourish on temporal scale under the influence of climate change in future. By extrapolating the ten years data (2010-2019) on the yield and biomass for three invasive fish namely the common carp, tilapia and African catfish from the mid-stream of the Ganga river, we attempted to forecast temporal biomass changes for the next decade i.e., from 2020 to 2029 using spatio-temporal population dynamics model for future prediction. Further, we also tested the invasion meltdown hypotheses that the presence of a second invading species enhanced the abundance and potential for further invasion by another non-native species causing aggravated detrimental impacts to indigenous species in terms of their abundance.

Materials and Methods

Fish catch data and biomass

Data on the catch of non-native species the common carp, tilapia and African catfish was collected from the mid-stretch of the Ganga river through regular fishing exercise made by fishermen at different fish landing areas of bridge area in Kanpur, Mehdi ghat in Kannauj, Shuklaganj in Unnao, Daraganj in Prayagraj, Adalhat in Mirzapur, Saraimohana in Varanasi, Dadri ghat in Ghazipur and Ganga ghat in Ballia districts of Uttar Pradesh state of India by using mostly boats, gillnets, cast nets and occasionally drag net (Figure 1). The catch data for three invasive fish namely the *Cyprinus carpio, Oreochromis niloticus and Clarias gariepinus* were collected from different locations on monthly basis for the study period from 2010 to 2019. Catch per unit effort (CPUE) was calculated for each study location following the method described by Bucol *et al.* (2017).

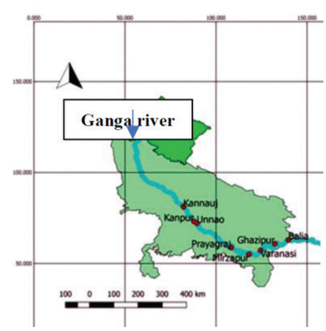

Figure 1. Figure showing the sampling locations in the Ganga river in Uttar Pradesh, India.

The CPUE was further converted as biomass percentage (Pi) of the three abundantly captured *C. carpio, O.niloticus and C. gariepinus* non-native fish at individual study location as per formula Pi = *Wi*/*Wt*, where *Wi* was the weight of non-native fish species; *Wt* was the total weight from all catches. The biomass obtained from each location was then pooled for calculating total biomass (Pf) percentage of fish from all the studied locations as per formula: $Pf = Pi1 + Pi2 + Pi3 + Pi4 + P_{in}$ over the years (ArchMiller et al., 2018) and the time rate change of non-native fish biomass during the period of 2010 to 2019 was calculated as:

$$dP/dt \propto P \text{ or } dP/dt = aP \text{ the solution was } P = P_0 e^{at}$$

Where P was the biomass at time t and P_0 was the initial biomass.

The predictive biomass was calculated as per described methodology (Okubo *et al*., 2017). Mean abundance by weight (MAW) was estimated (Leeseberg and Keeley, 2014; Singh and Srivastava, 2020). The changes in MAW were then extrapolated as biomass for the period from 2020 to 2029 (Laplanchea *et al.*, 2018). The sight ability model-fit to detection/non-detection data from marked population of the most invaded non-native invasive *C. carpio, O. niloticus* and *C. gariepinus* were then extrapolated for the next ten-year decade, i.e. 2020 to 2029 (Singh and Srivastava, 2020).

For a given predictor p among n predictors, the weight was calculated using the following equation:

Weight p =

In this process, data were fitted for all years $t_{fitted} \in \{t_{initial}, \ldots, t_{final}\}$, and then average estimated abundance and weight for all studied areas was used to predict density $d\ (s,\ t)$ for all locations during forecast years $t_{forecast} \in \{t_{final}+1, t_{final}+2, t_{final}+3 \ldots\ldots n\}$. Finally, population weight prediction was used to calculate the centroid of the population's distribution:

$$Z(t) = \frac{\Sigma^{ns}_{s=1} Z(s) \times a(s) \times d(s,t)}{\Sigma^{ns}_{s=1} (a(s) \times d(s,t)}$$

Where $a\ (s)$ was the area associated with each location s, and $z(s)$ was the measure of location (km). The biomass data in terms of weight (g) was pooled for entire stretch of 450 km of the Ganga river. The future values of standard errors followed by probability values were calculated. The changes in mean abundance by weight (MAW) was calculated as biomass at $\Delta Y_{MAW}\ (\Delta t\ /\ t_{final})$ for forecasting temporal biomass for the year 2020 Δt to 2029 as year t_{final}:

$$\Delta Y_{MAW} (\Delta t/\ t_{final}) = Y\ (t_{final} + \Delta t)\ –Y\ (t_{final})$$

Where $\Delta t \in \{2020\text{-}29\}$, the change in centroid was $\Delta Y\ (\Delta t/t_{final})$ over Δt and the forecasting year for calculating data through years 2020 to 2029 was t_{final}. The forecasted centroid as $Y_{CE}\ (t_{forecast}/\ t_{final})$ in year $t_{forecast}$ was done using the data through t_{final} and the growth model:

$$\Delta Y_{CE}\ (\Delta t/t_{final})\ l = Y_{CE}\ (t_{final} + \Delta t/t_{final}) - Y_{CE}\ (t_{final}/\ t_{final})$$

The variance are explained as $R^2(\Delta t) = 1–V(\Delta t)$, a model performing as well as the persistence forecast which had $V\ (\Delta t) = 1$ and $R^2(\Delta t) = 0$, while the model with $R^2(\Delta t) > 0$ outperforms the persistence forecast while the model with $R^2(\Delta t) < 0$ had degraded performance relative to a persistence forecast (Draper and Smith, 1998).

Climate monitoring

Water temperature changes was determined on quarterly and on annual basis for the period from 2009 to 2019 using digital thermometer so as to capture the changes/ modifications/ transformations in the water quality indicators. The rainfall data (1989-2019) of the mid-stretch in the Ganga river was collected from the *India Meteorological Department* (IMD) and district wise available information were used in our data analysis.

Statistics

All data were presented as mean ± SE. Field data obtained from different study locations were subjected to one-way analysis of variance (ANOVA) using the Statistical Package for the Social Sciences (SPSS), version 8.1. The correlation coefficients between the water quality indicators from different locations were calculated by Pearson correlation analysis. Parameters were further analyzed statistically at 5% significance level. The concrete and forecast values were calculated considering 95% lower and upper level of confidence; and the annual regression was calculated (Singh and Srivastava, 2020).

Results

Water temperature data were collected and presented over the years in the mid-stretch of the Ganga river covering from Kanpur to downstream Ballia. The annual mean minimum water temperature in the mid-stretch of the Ganga river was low in 2012, 2014 and 2018 and high during 2011, 2013 and 2019. However, the annual mean temperature increased from 0.9 to 1.88ºC over the years (Figure 2). The regression value showed that the relationship between the low and high for the base year 2010 to final year 2019 were 0.048 and 0.076 respectively. Temperature was found directly related to rainfall, with an increase in temperature at the end of the winter months i.e. January-February through spring (October-November) and finally to summer, i.e. the months of April-May. This increase in temperature was not linear, but there was a sudden temperature increase within a short period of time.

The annual rainfall data changes were synthesized from available data from IMD. The proportion of annual total rainfall occurring in the monsoon months (May-August) was 69.42% during 1989-98 which gradually decreased to 65.4% during 1910-19 and further decreased during 1989-98 to 25.28%. However, it increased in post monsoon months (September-December) from 28.32% during 2010-19 (Figure 3). Temperature and rainfall were understood as important environmental factor that triggered the maturation of brood fish expected to have different stages of maturity.

Common catches of non-native *C. carpio* contributed 47.46 % to 58.38% during study period; *O. niloticus* 29.52% to 32.89% and *C. gariepinus* 1.52 to 8.4% in the mid-stretch of the Ganga river. The size range of captured *Cyprinus carpio* was 13.5 to 52.4 cm in length and 150 to 1680 g in weight; *Oreochromis niloticus* 8.6 to 32.8 cm in length and 35g to 950g in weight; *Clarias gariepinus* 11.7 to 50.72 cm in length and 170 to 838g in weight. The *O. niloticus* appeared for the first time during 2003 in the Ganga river at Allahabad followed by common carp during 2004 and later African catfish appeared for the first time during 2011 on the same locations. The appearance of Tilapia and Common Carp synergistically and gradually increased over the years, while the third invasive fish African Catfish emerged during 2011(Figure 4). The yield of invasive Common Carp, Tilapia and African Catfish was correlated with rainfall and temperature data using ANOVA; we found that variance was $F=1.36$; $p=0.263$ for *C. carpio;* $F=1.60$; $p=0.326$ for *O. niloticus* and $F=1.63$; $p=0.101$ for *C. gariepinus*. The calculated variance value was very close for Tilapia and African Catfish indicating that climatic changes impacted these two species more than the Common Carp.

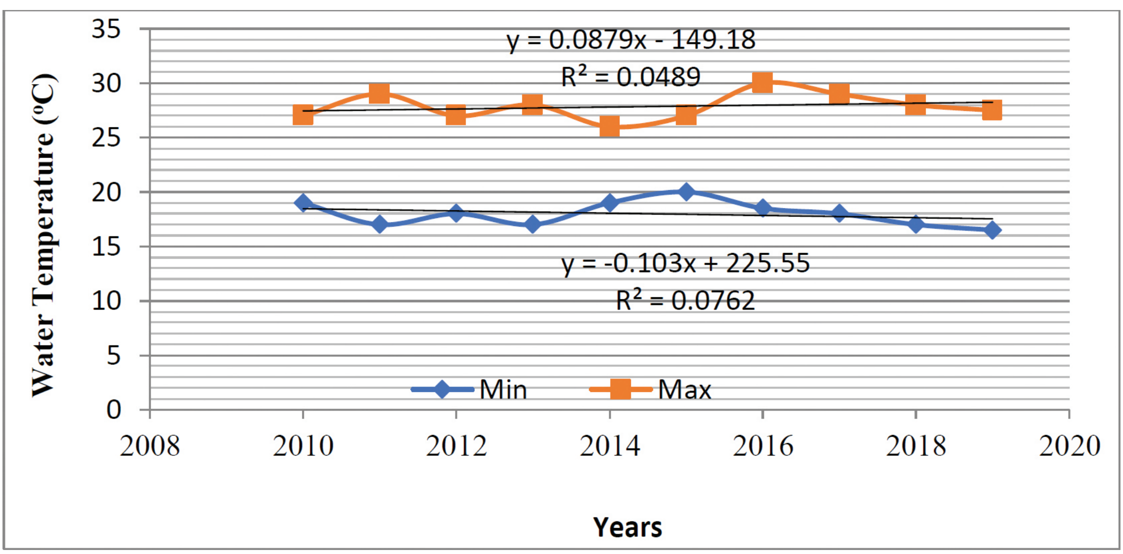

Figure 2. Annual trend in mean minimum and maximum water temperature at mid-stretch of the Ganga river during 2010-2019.

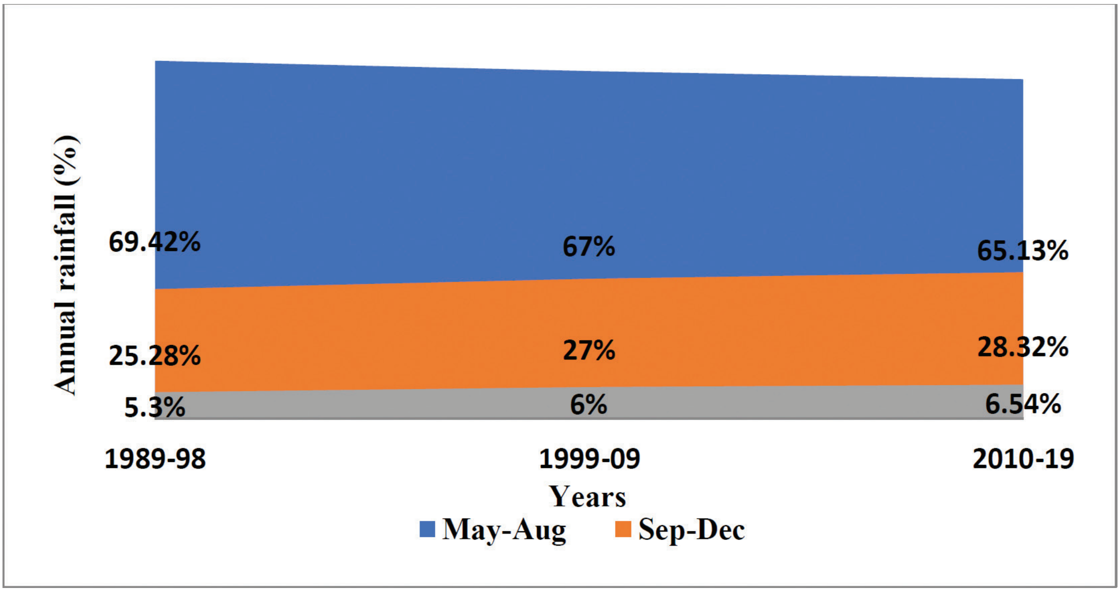

Figure 3. Shifting seasonal pattern of rainfall at mid-stretch of the Ganga river during 1989 to 2019 (Source: IMD).

Fish yield calculation based on MAW for *C. carpio* was found to consistently increase ($p < 0.05$) over the years from 2010 to 2019 and the calculated yearly values were 113.65, 127.54, 139.08, 150.99, 158.67, 174.54, 192.22, 209.06, 219.92 and 235.83 kg km^{-1} day^{-1} (Figure 5). The increase in MAW based yield of *C. carpio* was consistent and highly significant ($p< 0.001$) particularly during the period from 2016 to 2018 as compared to the base year value in 2010. In case of *O. nolitcus,* there was again a consistent and significant ($p< 0.05$) increase of MAW based fish yield over the years from 2010 to 2019 and the recorded values were 57.51, 68.02, 77.20, 83.37, 90.05, 100.52, 133.58, 148.13, 151.74 and 151.13 kg km^{-1} day^{-1} (Figure 6). However, the increase in yield of *O. niloticus* was very noticeable and highly significant ($p< 0.001$) during the period from 2013 to 2018 as compared to the base year value in 2010. The *C. gariepinus* was observed in mid-stream of the Ganga river during 2011 which consistently increased year after year. The recorded yield for the year from 2011 to 2019 were 2.41, 6.73, 14.64, 23.81, 27.45, 33.4, 36.45, 36.96 and 39.82 kg km^{-1} day^{-1} respectively (Figure 7). However, the increase in MAW based yield of *C. gariepinus* was significantly observed during the period from 2013 to 2019 as compared to the base year value in 2011 when it first appeared. The evaluated temporal predictive values for forecasted years (2020 to 2029) based on MAW values were plotted using spatio-temporal population dynamics model and the observations are presented (Fig. 5, 6, 7). The calculation for MAW based concrete yield showed that the average value was 113.65±12.6 kg km^{-1} day^{-1}during 2010 which increased to 235.83 ± 11.4 kg km^{-1} day^{-1} in 2019 showing 207.5% rise of *C. carpio* in a decade time. However, the established population of *C. carpio* showed predicted yield value of 170 ± 6 kg km^{-1} day^{-1}in 2029. The calculated yield values for *O. niloticus* was 57.51± 2.2 kg km^{-1} day^{-1} during 2010 which increased to 151.13 ± 4.6 kg km^{-1} day^{-1} in 2019. The biomass of *C. gariepinus* was 2.41 ± 033 kg km^{-1} day^{-1} in 2011, which increased to 39.82 ± 2.4 kg km^{-1} day^{-1} in 2019. The predicted yield was observed as 176 ±16.33 kg km^{-1} day^{-1} for Common Carp and 55.43 ± 6.4 kg km^{-1} day^{-1} for Tilapia in 2019 which indicated that there may be 117.87% and 116.9% yield rise in a decade's time for Common Carp and Tilapia, respectively, while 139.2% yield rise may happen for invasive African Catfish for the same period. The concrete and forecast values were calculated considering 95% lower and upper level of confidence, which was significant ($p<0.05$) and the annual regression was found $p<0.464$, $p<0.419$ and $p<0.499$ for common carp, tilapia and African catfish respectively. The confidence limit of 95% for the forecasted variance in distribution had little correlation with observed distribution. The median variance was low but it was positive for the annual

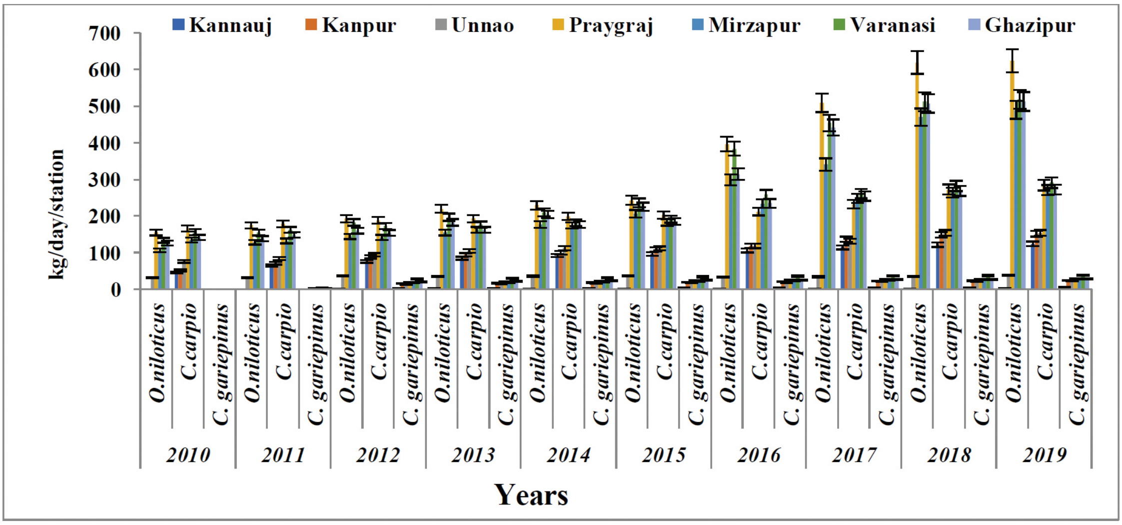

Figure 4. Fish yield of recurrent invasive fish species in mid-stretch of the Ganga river.

regression of 0.02, 0.36 and 0.42 in *C. carpio*, *O. niloticus* and *C. gariepinus* respectively for concrete value. However, it was higher which were 0.06, 0.65 and 0.69 in *C. carpio. O. niloticus* and *C. gariepinus* respectively for forecasted values showing that the general variance for the next 10 year of forecast will predict a faster increase. Obtained value for variance of R^2 (Δt) was 0.361 for *C.carpio*, 0.326 for *O. nolitcius* and 0.418 for *C. gareipinus*. The observed MAW based forecast of non-native tilapia, common carp and African catfish catch for the period of 2020 to 2029 at 95% confidence limit indicated a stable production in the Ganga river and there was a positive pattern of invasion meltdown.

Discussion

Invasive alien species have gained wider recognition by scientists and policymakers in the past decades due to their severe ecological and economic impacts worldwide (Early et al., 2016; Turbelin et al., 2017). Several freshwater fish species have been translocated as a result of human mediation and moved outside their native ranges by an array of vectors such as deliberate introductions, river corridors, and releases from aquaculture and aquaria and even illegally introduced to arrive in new environments (Singh and Lakra, 2011). An increased trend of fish invasions has been recorded over the years in inland waters of India. Climate change is expected to alter seasonal patterns over time with dramatic changes in precipitation and temperature patterns. All of these factors combine to place added stress on both native species. However, invasive species in general are much better equipped to handle these new stressors. Seasonal change in temperature has a profound effect on reproduction in fish. Temperature changes cue reproductive development particularly in monsoon spawning species. This in turn impacts population replenishment and connectivity patterns of local and invasive fishes. Warmer temperatures modifies community structure and dynamics that in turn facilitate invasions (Robert et al., 2017; Manjarres-Hernandez et al., 2021; Arnaud et al., 2021). Invasion of non-native introduced fishes even in changing environments and climate exert their effects on new habitats consequently emerging as a major threat for ecosystems around the globe, partly with irreversible consequences for the local biota (Panlasigui et al., 2018). Invasive species might cause habitat modification, extinctions of endemic species, affect human health, and thus exert enormous economic costs (Singh et al., 2013; Singh et al., 2014; Panlasigui et al., 2018). Fish invasions have also been reported to be driven by climate change where synergies between climate change and increased pressures of fish invasions invite new management challenges for freshwater ecosystem (Kernan, 2015).

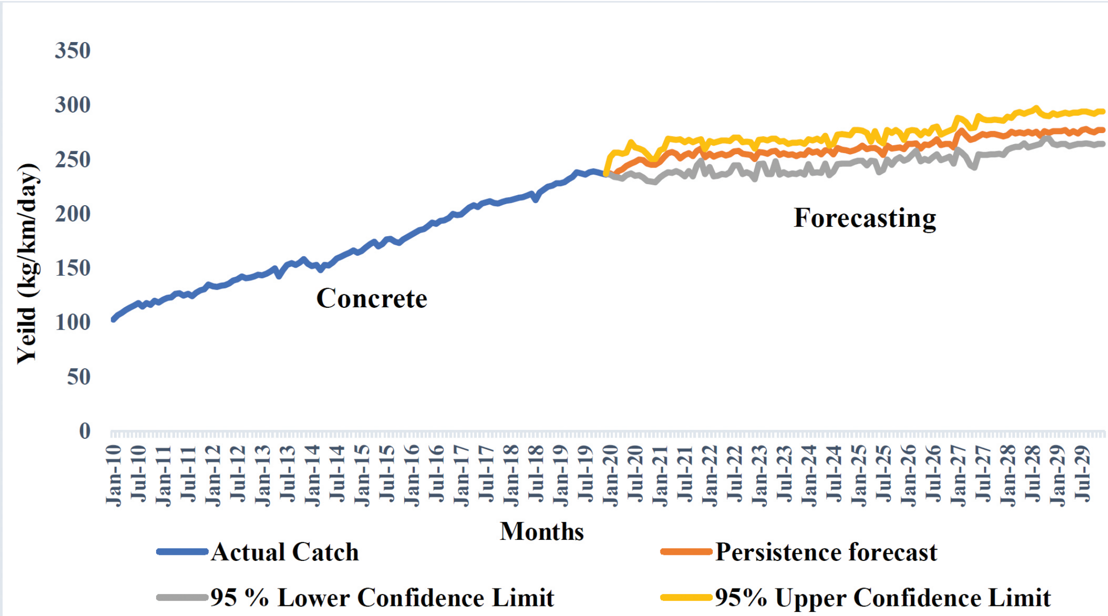

Figure 5. Invasion prediction of common carp and yield contribution in the Ganga river using spatio-temporal population dynamics model.

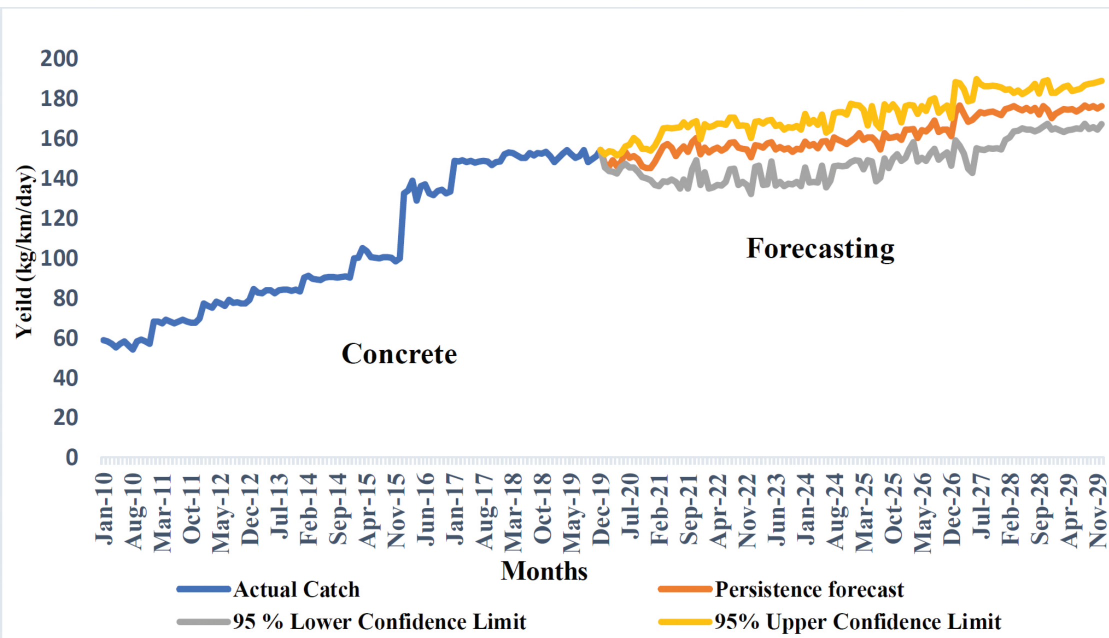

Figure 6. Invasion prediction of tilapia and yield contribution in the Ganga River using spatio-temporal population dynamics model.

India has been placed at the 10th position among highest climate risk countries in Asia based on extreme environment events (Global Sustainable Development Report 2015). Climate variables namely the temperature, precipitation, and humidity may have significant long-term implications affecting water quality and fisheries (Jayaraman and Murari 2014). Climate change has been reported to exacerbate the threats posed to the Inland fisheries by environmental stressors (Das et al., 2019). The present study presents recent data regarding increased incidence of non-native

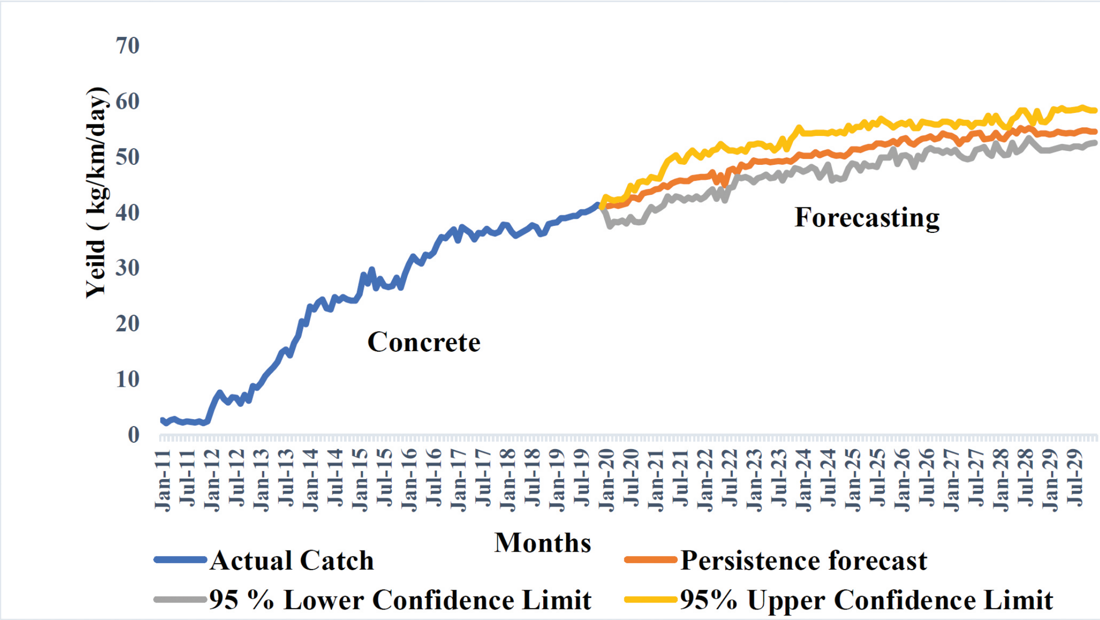

Figure 7. Invasion prediction of African catfish and yield contribution in the Ganga River using spatio-temporal population dynamics model.

invasive species in the Ganga river especially in the time of climate change. Using algorithms and predictive models, future predictions on range expansion of invasive species have been reported by several workers (Fletcher et al., 2016; ArchMiller et al., 2018; Dominguez et al., 2020). In this study, predictive future invasional changes for the upcoming decade have been presented. The MAW based predictive values when calculated has shown persistent increase of the three abundantly available invasive fish *C. carpio, O.niloticus* and *C. gariepinus* in the Ganga river during the next decade. It is interesting to mention here that both tilapia and common carp have depicted a very similar trend of establishment and have exhibited substantial growth in the Ganga river even in adversely changing environmental and climatic conditions. While the increased trend of invasion of African catfish was even faster in recent years. The increasing patterns of invasive fish species in the Ganga river has been representing occupational patterns and changed distribution of fishery resources (Singh et al., 2013). Such rise in invasive species in the river has caused decline in the local fish catches and even change in biodiversity patterns (Singh et al., 2013; Kernan, 2015; Mondal and Bhat, 2020; Raj et al., 2021).

The results of this study have shown positive and synergistic effects of Tilapia, Common Carp and African Catfish on their increased catches after invasion which strongly supports the 'Invasion meltdown' (Simberloff and Von Holle 1999; Braga et al., 2018). The findings indicate the phenomenon that non-native invasive *O. niloticus* and *C. carpio* have facilitated the invasion of the third one i.e., *C. gariepinus* with good propagation and compounded their independent impacts on native species, communities and the riverine ecosystem (Singh et al., 2013; K,ernan, 2015; Mondal and Bhat, 2020; Raj et al., 2021). The potential role of positive interactions among co-invaders has been found at the core of the invasion meltdown. The interaction of non-native tilapia, common carp and African catfish has resulted in an exacerbation of each other's effects. Thus, the resulting effect of multiple non-native species meltdown on ecosystems can be greater than the sum of the individual effects. It is thus, there is every possibility that all the three invasive fish will spread in newer areas of the Ganga river basin especially in the changing climate and environments due to their high adaptability and better survival (Deng et al., 2020). Predictive biomass of the invaded tilapia, common carp and African catfish warrant fishery managers to develop regulatory framework to contain them at the earliest. Whilst mechanical, chemical, and biological controls are the most widely used approaches for controlling invasive species, they require skilled manpower, technology, and expertise, and can be extremely costly and labour intensive. Therefore, early detection and rapid response (EDRR) is key to the management of invasive species in (Singh et al., 2013; Reaser et al., 2020). Since there is no management plan in the country to fight out invasive species in the riverine ecosystem, it is advocated that effective long-term management should be developed to address the impacts of invasive alien species (IAS) that cannot be eradicated. Policies and strategies should be developed and implemented for the long-term management of IAS in the riverine ecosystem.

Conclusions

The predictive forecast of invasive *C. carpio, O.niloticus* and *C. gariepinus* in this study provides a means for an evidence-based prioritization of species and habitats for the management of existing and future invasions of the Ganga river. Further, it has also ascertained that the presence of one invasive fish species facilitate another and compound negative impacts on the aquatic ecosystem. We thus, strongly point out that the negative effects of invasive species meltdown may be strong, even where no impact of single invasion was expected. Thus, cumulative impacts of multiple invasions will result in the replacement of native species and consequently their extinction.

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