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CLIMATE CHANGE AND SPECIES INVASIONS IN AQUATIC SYSTEMS: A COMPARATIVE PERSPECTIVE (CHAOS)

Climate change and invasive species are two of the most pervasive components of global environmental change. The effects of climate change on aquatic ecosystems are manifold. These include changes in water temperature, rainfall and habitat availability, and modifications of pathways within the biogeochemical cycles and food webs. Increased temperatures and changed salinity will induce shifts in species' geographic ranges, affect ecosystem assemblages, and exert profound impacts on the exploitation of living resources. Particularly in coastal areas and transitional waters, sea level rise and changes in current and rainfall patterns will strongly alter the composition of communities. Finally, climate change is expected to decouple an organism's phenology (i.e. the timing of life cycle events), thus modifying essential interactions with competitors, mutualists, predators, prey, or pathogens.

By definition, invasive species are alien species (i.e. species intentionally or accidentally introduced by man outside their native range) that exert negative ecological, economic or human health impacts. Aquaculture, stocking, aquarium industry, canal construction, shipping, and other human activities are known to have greatly facilitated the spread of aquatic invaders, but the role of climate change on their expansion is only now being considered.

Indeed, altered thermal regimes, reduced ice cover in lakes, changed stream-flows, and increased salinity, along with increased water-use activities (e.g. canal and reservoir construction), are expected to greatly alter the transport of new species, the climatic constraints on invaders, the distribution of existing aliens, and their impacts on the native biota. They may also reduce the effectiveness of management actions to mitigate their damages, such as biological control. Among the numerous possible effects of climate change on aquatic communities, climate warming is expected to favor the establishment of many warm-water species introduced to temperate regions for aquaculture or for the aquarium trade; the impacts of alien predators on indigenous prey will be magnified and the virulence of alien pathogens to indigenous species augmented; an increased magnitude and frequency of floods will induce the natural dispersal of some aliens (e.g. zebra mussel, *Dreissena polymorpha*), whereas more prolonged droughts will favor species that survive desiccation by burrowing (e.g. the globally invasive crayfish *Procambarus clarkii*); and salinity changes in coastal waters will allow for greater invasion risks by, for example, the Chinese mitten crab *Eriocheir sinensis*. Unexpected results are likely, including loss of invasiveness by a number of alien species. Besides, some indigenous species will possibly expand their range of distribution or will counteract the spread and establishment of alien species (e.g. the blue crab *Callinectes sapidus* vs. the European green crab *Carcinus maenas* along the eastern coast of North America). However, all these effects are just hypothetical: **a synthetic approach that specifically addresses the interactions between multiple invaders and the multitude of changes expected with climate change is urgently needed**.

CHAOS' **major objective** is to provide a scientifically supported comprehensive view in aquatic ecosystems of the likely links between climate change and species invasions as two primary drivers of global environmental change. These links will be analyzed in conjunction with other important correlates of biological invasions, including geographical variables, land-use, human disturbance, transport networks, and other socio-economic factors.

The **specific objectives** of the project will be to: (1) synthesize historical data on the climate of inland waters, transitional waters, and coastal areas in the Mid-Atlantic Region of North America and Mediterranean Europe, examining the identity of the animal species introduced into these systems along with geographical, ecological, and socio-economic variables; (2) detail, by collecting *in situ* first-hand data, the synergistic effects of climate change and targeted invasive species on a range of ecosystems and their services for an area in North America selected as a model system; and (3) explore, through laboratory-based experiments, the influence of temperature and salinity on some biological traits of an invasive crustacean species of particular concern for both North America and Europe, the Chinese mitten crab, *Eriocheir sinensis*.

CHAOS' main focus --to unravel the links between climate change and invasive species in aquatic systems-- will be achieved by the means of a comparative approach. In this respect, Europe and North America are well matched for comparison because these regions are relatively well investigated, databases on aquatic allodiversity are accessible to the IO fellow and to her supervisors, and historical records on regional climate characteristics are readily available to them. A comparative approach will also facilitate the analysis of the biology and ecology of species in native and introduced ranges, and in introduced ranges subject to diverse ecological and anthropogenic pressures. In fact, several aquatic species native to North America have been introduced into Europe (e.g. the crayfish *Procambarus clarkii* and *Pacifastacus leniusculus*) and *vice versa* (e.g. the green crab *Carcinus maenas*) and some species have invaded both regions inducing similar/different impacts (e.g. the Ponto-Caspian zebra mussel, *Dreissena polymorpha*). Additionally, many of the scientific needs in Europe regarding problems generated by invasive species are equally relevant to North America, as are the needs for developing common policies and legislative measures.

Objective 1 will be accomplished by gathering both ecological and societal information from a number of sources, including international and regional databases, grey-literature, scientific publications, and interviews of experts in invasion biology. These data will provide the basis for an extensive meta-analysis using different meta-regression models, in part originally developed by the IO fellow. Knowledge about the several drivers of change will be supplemented with information available from the "Global Invasive Species Database", managed by the Invasive Species Specialist Group (ISSG) of the IUCN Species Survival Commission. Other sources of information will be the "European Alien Species Databases" being developed within the EU-funded projects *DAISIE* and *IMPASSE*, with which the IO fellow is associated. A fruitful interaction is also expected with *PESI*, "A Pan-European species-directories infrastructure" (FP7-INFRASTRUCTURES). Experts in the field of invasions in aquatic systems will be consulted, e.g. James Carlton, Alexander Karatayev, David Lodge, Hugh MacIsaac, and Greg Ruiz in North America, and Gordon Copp, Ian Cowx, Bella Galil, Stephan Gollasch, Anna Occhipinti-Ambrogi and Sergej Olenin in Europe and in the Mediterranean basin.

For **Objective 2**, the IO fellow will collect first-hand data in Long Island (NY), one of the largest islands in North America (about 3,700 km^2). Long Island represents an optimal model system, in which hypotheses on the synergistic interactions between climate change on one hand and biological invasions and other drivers of change on the other can be successfully tested. Long Island has a variety of aquatic ecosystems, from inland waters to different types of coastal areas, and is also subject to a strong human disturbance: it is highly populated (density: 2,110 km^{-2}) and hosts extensive and varied transport networks and diversified human activities, including aquaculture and tourism. This research will be new for this area, as information about the aquatic animal communities inhabiting these ecosystems is scattered across the literature and the scientific knowledge about alien species' identity and distributions as well as their vectors is surprisingly poor.

A number of field sites, selected to fully represent different aquatic ecosystems (inland waters, transitional water systems, coastal areas), will be monitored for one year, using appropriate methods of sampling per target taxon. The shared expertise of the IO fellow, her supervisors, and the host institutions will provide full coverage of the taxonomic groups collected. The expected outputs will be to generate updated inventories of animal xenodiversity and to gather information on their biology (e.g. growth rate, modes and time of reproduction, fecundity, reproductive system, etc.) and physiology (e.g. tolerance to temperature, salinity, etc.), in order to better understand their resilience to climate change. When available, data about the times and modes of introductions will be collected, along with the documented and potential impacts, including transfer of diseases and pathogens, disruption of ecosystem functioning and ecological interactions, reduction of biodiversity, and genetic introgression with indigenous species. The economic dimensions of the impacts of some alien species will be assessed through a baseline study of the socio-economy in the study area and through the analysis of the interactions between the prevailing states of the environment, including possible environmental changes, and the socio-economic structure.

The gathered data will be analyzed with geographical information softwares and appropriate multivariate statistical tests, in conjunction with abiotic parameters of the study sites, including physiographical and hydrological factors representing potentially relevant ecosystem niche dimensions (e.g. water depth, salinity, tidal range, surface, outlet width and length, sediment features, etc.). Based on the extensive regional climate data made available by the Center for Impacts of Regional Climate Change and benefiting of the expertise at the Department of Ecology and Evolution of Stony Brook University, bioclimatic models (species range or niche models) will be developed to forecast range shifts of organisms due to climate change, consequent impacts on biodiversity, and the likely effects of different management options.

Using the existing historical data, focus will be given to the changes in the species composition of communities (e.g. by measuring the ratio of macrobenthos and fish with colder affinities to those with warmer affinities) and to phenological (e.g. the timing of reproduction and seasonal migration of selected species of macrobenthos) and reproductive indices (e.g. recruitment indices and reproductive parameters). The independent impacts exerted on the systems of study by possible changes in human activities, urbanization, and management systems will be also investigated. In the end, a comprehensive picture will be drawn to illustrate if and how some aspects of climate change (e.g. altered thermal regime and increased salinity) have affected the pathways of species introduction, the likelihood of the establishment of aliens, and the multileveled impact exerted by some targeted species.

Objective 3 will be accomplished with a laboratory-based experimental approach, focusing on the Chinese mitten crab (*Eriocheir sinensis* H. Milne Edwards, 1853, Varunidae), native to central Asia. At the beginning of the 19th century this species was introduced, most likely via ballast water, into rivers in Germany, from where it rapidly spread to Holland, Belgium, France, Czech Republic, Denmark, Finland, and Sweden. Its present distribution in Europe ranges from the Bay of Biscay (France) to the northernmost and easternmost parts of the Baltic Sea, including Russia, Poland, England and Norway. In 1992 this species was first discovered in San Francisco Bay (Rudnick et al. 2005). Recently, some specimens have been also found in the Hudson River and in the lagoon of Venice, which might indicate the beginning of this species' invasion of the Mid-Atlantic North America and Mediterranean Europe. The wide concern about *E. sinensis*' invasions (listed by IUCN among 100 of the "World's Worst" invaders) is justified by the multilevel impact that juveniles and adults of this species exert on freshwater and estuarine ecosystems and on native biodiversity. This species also imposes high economic costs to commercial and recreational fishing, aquaculture, and freshwater management. It is also the second intermediate host for the human lung fluke parasite (*Paragonimus westermani*), the first intermediate vector of which, the freshwater snail *Assiminea parasitologica*, was recently found in Oregon.

Eriocheir sinensis is a catadromous species, subject to complex changes in adaptation to salinity and temperature during ontogeny: juveniles migrate upstream and sexually mature individuals migrate back downstream to reproduce. *CHAOS* will address the important question of how climate change will affect the distribution and population abundance of this species, and its competitive ability relative to other species occupying similar ecological niches. To address this question, the survival and growth of larvae, juveniles and adults, reproductive biology, and inter-specific competition will be investigated in the laboratory at the Department of Ecology and Evolution of Stony Brook University (to be continued at the Department of the Evolutionary Biology at the University of Florence) along a gradient of temperatures and salinities that mimics some effects of climate change expected in estuaries and rivers of the Mid-Atlantic North America and Mediterranean Europe (e.g. increased runoff and rainfall, warmer temperatures, increased frequency of extreme heat events, and sea level rise).