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The top 27 animal alien species introduced into Europe for aquaculture and related activities

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Summary

The information extracted from IMPASSE, DAISIE, FishBase, and FAO-DIAS inventories of alien species were used to draw a list of the 27 most utilized animal alien species for aquaculture and related activities (e.g. stocking, sport fishing, ornamental purposes) in Europe. Three variables have been considered to assess their negative ecological impacts when these species escape from aquaculture facilities: (i) their distribution across Europe (including non-EU Member States); (ii) evidence of their environmental impact in the wild; and (iii) evidence of their being vectors of non-target alien species and other hitchhikers (e.g. pathogens). Drivers of use and mechanisms of dispersal in the wild have been also considered and reviewed. Twenty of the species are freshwater fishes: alien cyprinids and salmonids have been introduced into Europe mainly for food production, sport fishing and ornamental purposes. The most widespread species are the goldfish *Carassius auratus* and the rainbow trout *Oncorhynchus mykiss*, established in 29 and 28 European countries, respectively. Notwithstanding their successful distribution in Europe, only the Gibel carp *Carassius gibelio* and the peneid shrimp *Marsupenaeus japonicus* were found to have environmental impact in all the countries of establishment. Crayfish and predatory fishes (e.g. catfishes and salmonids) cause major environmental impacts in Europe by outcompeting native species and altering habitat structure. Alien crayfish, *Procambarus clarkii* and *Pacifastacus leniusculus,* are responsible for the largest range of impacts (i.e. crayfish plague dissemination, bioaccumulation of pollutants, community dominance, competition and predation on native species, habitat modifications, food web impairment, herbivory and macrophytes removal). Cyprinids (e.g. herbivorous carps) are vectors of diseases and parasites, while salmonids (e.g. *Salvelinus fontinalis*) often cause genetic impairment of native stocks by hybridization. The importation of alien farmed (target) species frequently leads to the introduction of associated non-target species. The cultures of the Pacific cupped oyster *Crassostrea gigas* and Manila clam *Ruditapes philippinarum* were responsible for the introduction of the largest number (60) of non-native invertebrates and algae, often attached to packaging material, fouling the shell or parasitizing bivalve tissues.

Introduction

Alien species introduction in Europe is an issue of growing concern (Commission of the European Communities, 2008). Since the 1970s, scientists have been agreeing that species introduction is a major cause of biodiversity loss and impairment of aquatic ecosystems, both for coastal marine areas, brackish and inland waters (Rosenthal, 1976, 1980, 1981). A common statement is that species globalization and human mediated xenodiversity (*sensu* Leppäkoski et al., 2002) are caused by the new millennium economic policy (Leppäkoski and Olenin, 2000; Carlton, 2002; Occhipinti-Ambrogi and Savini, 2003; Galil, 2008). The study of biological invasion, as a new frontier in science, began in earnest in the late 1950s (Elton, 1958), but it is only in the last two decades that the accumulating scientific evidence has encouraged administrators and policy makers to implement strategies that may counter biological invasions in Europe (Genovesi and Shine, 2004). EU funded projects, partly or fully aimed at aquatic invasive species, have been recently completed: DAISIE - Delivering Alien Invasive Species Inventories for Europe http://www.europe-aliens.org and IMPASSE – Environmental impacts of alien species in aquaculture http://www2.hull.ac.uk/science/biological_sciences/research/hifi/impasse.aspx. The common aim of these projects was to create a network of knowledge and experts on invasion biology, providing inventories on alien species and instruments to support Community directives. Global databases such as: Fishbase (Froese and Pauly, 2008) and FAO-DIAS (http://www.fao.org/fishery/dias/en) are also important sources of information concerning the distribution and impact of cultured aquatic alien species. In 2007 the first EC regulation on alien species was approved: No 708 on 11 June 2007 (implemented rules: No. 535 on 13 June 2008) concerning the use of alien and locally absent species in aquaculture. It has been recognized that aquaculture and related activities (e.g. sport fishing, fishery stock enhancement, ornamental trade) have been important drivers of alien species in Europe in the past and that the trade in alien species needs specific rules in order to prevent target and non-target species introduction into the wild. Risk assessment procedures and quarantine protocols are now compulsory for Member States who wish to farm non-native species or release them into the wild. Both DAISIE and IMPASSE projects report that since the late middle ages about 650 non-native species (together with their parasites and associated biota) have been introduced into inland and marine waters of Europe as a result of stocking activities and aquaculture (Balon, 2004; Olenin et al., 2008).

The present paper aims to review information concerning animal alien species intentionally introduced (i.e. target) through aquaculture or related activities (e.g. fishery stock enhancement) in Europe, ranking them on the basis of the environmental impact they exert once released into the wild.

Materials and methods

IMPASSE, DAISIE, FishBase, and FAO-DIAS inventories of alien species were searched in order to extract information on the most widespread animal alien species intentionally introduced for aquaculture and related activities into Europe since the XIII Century. Twenty-seven species were firstly ranked on the basis of their distribution in the 41 EU and non-EU countries, considering only countries where they established feral populations (population status = established); 426 papers and technical reports were reviewed and the species environmental impact and likelihood of being vectors of introduction of associated non-target species (parasites, diseases, associated biota on packaging material or in fouling) have been assessed.

Distribution

The distribution of each species was assessed by comparing data from IMPASSE, DAISIE, FishBase, and FAO-DIAS inventories. In order to validate the data we considered only species reported by at least two of four inventories as being established in a given country.

Impact

The literature focused on the environmental impact of the 27 listed aquatic alien species in Europe (references regarding the impact elsewhere were not considered) was reviewed to verify information reported on the web-based species inventories. We adapted the IPCC (2005) scheme of certainty, giving the following scores: (i) Low confidence (only one paper or review reporting general environmental impact, no quantitative or experimental data), (ii) Medium confidence (more than one paper or review reporting general environmental impact, no quantitative or experimental data), (iii) High confidence (at least one paper focusing on quantitative and experimental impact evaluation), (iv) Very high confidence (more than one paper focusing on quantitative and experimental impact evaluation).

We included the ratio of countries where impacts were reported out of those where the species had been introduced as a measure of impact distribution, naming this factor 'impact euritopicity' (Greek: *eury*- wide broad + *topos* -place). Furthermore, we considered species proving to cause more types of impacts as a measure of 'impact heterogeneity'. The following nine types of impact were considered:

- Predation: predatory activity on native species.
- Hybridization: disruption of local genetic adaptations and loss of genetic integrity of native species.
- Herbivory: consumption of aquatic plants and algae, including phytoplankton.
- Habitat change: modification of physico-chemical properties of habitats.
- Food prey: new food item for native species, causing changes in food chains.
- Competition: for food or for space with native species.
- Community dominance: species causing quantitative changes in community structure in becoming the dominant species.
- Bioaccumulation: storage and magnification of toxic substances in tissues.
- Food web alteration: generally causing changes in the energetic budget of the invaded ecosystem (e.g. by removing key-stone species, primary producers, etc).

Non-target species introduction

Information on the associated unintentional introduction of non-target species (parasites / diseases, associated taxa) was gleaned from the IMPASSE database. Species-specific information, i.e. the number of non-target introductions associated with *Cyprinus carpio* was not reported, but rather the total number for the Cyprinidae. Therefore, we could only make simplifying assumptions made on maximum number of non-target introductions at family or at higher taxon level.

Statistical analysis

Working on the assumption that alien organisms of the same family are likely to have similar environmental impact (e.g. all salmonids are top predators thus a top-down control on the receiving ecosystem is expected), we applied a multivariate statistical analysis to the data matrix of impacts, using the software PRIMER (Clarke and Warwick, 1994). A Bray-Curtis similarity index was computed considering a data matrix of presence / absence per type of impact. Differences (distances) amongst the alien species were reported in a Multi Dimensional Scaling plot.

Results

Freshwater fishes are the major group introduced for aquaculture and related activities. Twenty of the 'highly implicated 27' are freshwater or anadromous fishes (salmonids), four are crayfish, two are marine / estuarine bivalves and one is a marine peneid shrimp (Table 1). Alien cyprinids and salmonids appeared to be well acclimatized to European freshwater ecosystems. The most common reason for introducing non-native species to Europe was to improve the fish market economy by diversifying the market of native species, therefore for food production (19 species). Some of these species (the crayfish *Pacifastacus leniusculus, Astacus leptodactylus, Procambarus clarkii, Orconectes limosus* and two bivalves, *Crassostrea gigas, Ruditapes philippinarum*) were initially introduced to restore fishery of native stocks depleted by diseases and overfishing. Stocking for sport fishing has been another important driver of introduction in freshwater ecosystems since 1800 (10 cases). The most widespread species in Europe is *Carassius auratus,* which established wild populations in 29 countries, introduced for ornamental reasons since 1600 (Smartt, 2001). Herbivorous carps (*Ctenopharyngodon idella*, *Hypophthalmichthys molitrix*) were deliberately introduced by environment agencies as biological control agents of algal blooms in eutrophic ecosystems (Domaizon and Devaux, 1999; Pípalová, 2002). Similarly, mosquitofishes (*Gambusia* spp.), established in 13 countries, have been used in Europe to control mosquitoes since the beginning of the 20th century (Fernandez-Delgado, 1989).

A review of the literature revealed a dearth of scientific and experimental proofs of impact, with the exception of the red swamp crayfish *P. clarkii* (48 references) and the signal crayfish *P. leniusculus* (20 references). The ecological impacts of the largemouth bass, *Micropterus salmoides*, have been widely studied in Europe (31 references), but some references are doubtful.

Examination of the eurytopic impact revealed that *C. gibelio* and *M. japonicus* are the only listed species for which impact has been reported in all countries of establishment (Ie = 100%).

Table 1
List of the most important 25 aquatic alien species voluntarily introduced in European freshwater and marine coastal waters

Species	Authority	Tg	Du	Di	NCI	Cim	Ie	Fa	Ba	Cd	Co	Fp	Hc	He	Hy	Pr
Carassius auratus	(Linnaeus, 1758)	Cyprinidae	o	1600	29	2	7	nr	nr	nr	nr	nr	nr	nr	1	nr
Oncorhynchus mykiss	(Walbaum, 1792)	Salmonidae	sf,fp	1800	28	1	4	1	nr	nr	nr	nr	nr	nr	nr	1
Cyprinus carpio	Linnaeus, 1758	Cyprinidae	fp	1200	26	7	27	nr	4	nr	1	nr	1	nr	2	1
Salvelinus fontinalis	Mitchell, 1814	Salmonidae	sf	1850	23	2	9	nr	nr	nr	1	nr	nr	nr	1	nr
Lepomis gibbosus	(Linnaeus, 1758)	Centrarchidae	sf,o	1800	22	10	45	2	nr	1	3	nr	1	nr	nr	7
Pacifastacus leniusculus	(Dana, 1852)	Astacidae	rf,fp	1920	20	7	35	7	1	1	20	nr	3	2	nr	4
Ameiurus nebulosus	(Lesueur, 1819)	Ictaluridae	sf	1800	19	4	21	nr	1	1	1	1	nr	nr	nr	1
Astacus leptodactylus	Eschscholtz, 1823	Astacidae	rf,fp	1830	15	nr	Nr	nr	nr	nr	nr	nr	nr	nr	nr	nr
Micropterus salmoides	(Lacépède, 1802)	Centrarchidae	sf	1800	15	6	40	nr	4	4	10	nr	nr	nr	nr	17
Ctenopharyngodon idella	(Valenciennes, 1845)	Cyprinidae	b,fp	1950	15	8	53	1	2	nr	nr	nr	4	3	nr	nr
Hypophthalmichthys molitrix	(Valenciennes, 1844)	Cyprinidae	b,fp	1940	15	4	27	2	nr	nr	nr	nr	1	1	nr	2
Ameiurus melas	(Rafinesque, 1820)	Ictaluridae	sf	1800	15	3	20	nr	3	4	2	nr	nr	nr	nr	1
Orconectes limosus	(Rafinesque, 1817)	Cambaridae	rf,o,fp	1970	14	4	29	nr	2	nr	4	nr	4	nr	nr	nr
Procambarus clarkii	(Girard, 1852)	Cambaridae	rf,fp	1970	13	4	31	10	3	3	10	4	18	12	nr	6
Crassostrea gigas	(Thunberg, 1793)	Ostreidae	rf,fp	1900	13	4	31	1	3	2	2	nr	2	nr	1	nr
Gambusia affinis	(Baird & Girard, 1853)	Poeciliidae	b	1920	13	2	15	nr	2	nr	nr	nr	nr	nr	nr	1
Coregonus peled	(Gmelin, 1789)	Salmonidae	sf,fp	1940	12	1	8	nr	nr	nr	nr	nr	nr	nr	3	nr
Coregonus lavaretus	(Linnaeus, 1758)	Salmonidae	sf,fp	1880	11	2	18	2	nr	nr	nr	nr	nr	nr	nr	nr
Aristichthys nobilis	(Richardson, 1845)	Cyprinidae	fp	1940	10	3	30	2	2	1	3	nr	nr	2	nr	1
Sander lucioperca	(Linnaeus, 1758)	Percidae	sf	1800	9	4	44	1	2	nr	1	nr	1	nr	nr	3
Carassius gibelio	(Bloch, 1782)	Cyprinidae	fp	1600	7	7	100	nr	nr	3	nr	1	1	nr	2	nr
Perccottus glenii	Dybowski, 1877	Odontobutidae	fp	1910	6	3	50	nr	nr	3	nr	nr	nr	nr	nr	2
Ruditapes philippinarum	(Adams & Reeve, 1850)	Veneridae	rf, fp	1950	6	4	67	nr	nr	nr	4	nr	1	nr	nr	nr
Ictalurus punctatus	(Rafinesque, 1818)	Ictaluridae	sf,fp	1900	4	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr
Oncorhynchus kisutch	(Walbaum, 1792)	Salmonidae	fp	1960	3	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr
Marsupenaeus japonicus	(Bate, 1888)	Penaeidae	fp	1980	2	2	100	nr	nr	nr	3	nr	nr	nr	nr	nr
Mylopharyngodon piceus	Richardson, 1846	Cyprinidae	fp	1960	1	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr

Tg, taxon group; Du, most important drivers of uses or reasons which promoted the voluntary introduction of the species (fp, food production; sf, sport fishing; rf, stocking for restore fishery; o, ornamental; b, biocontrol); Di, first date of introduction in Europe; NCI, number of countries in which the species established feral populations; Cim, number of countries in which the species caused impact; Ie, index of impact eurytopy (Cim ⁄ NCI*100); Fa, n. references concerning food web alteration, generally causing changes in the energetic budget of the invaded ecosystem (e.g. by removing key-stone species, primary producers, etc); Ba, bioaccumulation, storage and magnification toxic substances in tissues; Cd, community dominance, species causing quantitative changes in community structure in becoming the dominant species; Co, competition for food or for space with native species; Fp, food prey, new food item for native species, causing changes in food chains; Hc, habitat change, modification of physical-chemical properties of habitats; He, herbivory, consumption of aquatic plants and algae, including phytoplankton; Hy, hybridization, disruption of local genetic adaptations and loss of genetic integrity of native species; Pr, predation, predatory activity on native species; Nr, no high confidence references.

Predation, competition with native species, and bioaccumulation of water pollutants (e.g. heavy metals, pesticides, PAH's, etc) are the most important threats posed by aquacultured alien species.

The crayfish *P. clarkii* (eight types of impact) and *P. leniusculus* (seven types of impact) showed the largest heterogeneity of impacts, from outcompeting native species to altering food web composition and habitat structure (Fig. 1; Table 1). There are no indisputable references (in terms of experimental assessment) of environmental impact for the crayfish *A. leptodactylus*, the grass carp *Mylopharyngodon piceus,* the catfish *Ictalurus punctatus,* and the salmon *Oncorhynchus kisutch*.

Alien species of one family do not necessarily cause similar environmental impact (Fig. 2). The stress value of the MDS plot (< 0.2) indicates a confident representation of distances. The salmonids *Oncorhynchus mykiss* and *Salvelinus fontinalis* are both top predators, but whereas the former is claimed to be a disruptor of the food web and a predator of native species (Oscoz et al., 2005), the latter is a strong competitor also capable of hybridizing with other salmonids (Cucherousset et al., 2008).

Analysis of the number of associated non-target introductions per fish family or higher taxon group revealed that bivalves (*C. gigas, R. philippinarum*) were responsible for the majority of introductions in Europe (60), mainly shell foulants or macroalgae used for packaging live oysters and clams (Breber, 2002; Verlaque et al., 2007). Farmed cyprinids were responsible for introducing 31 parasites ⁄ disease agents (Fig. 3).

Discussion

It is recognized worldwide that aquatic alien species pose a threat both to marine (Ruiz et al., 1997; Leppäkoski et al., 2002) and freshwater (Ricciardi, 2003; Gherardi, 2007a) ecosystems. The crisis in wild fisheries and globalization of the market (Casal, 2006) lead to an increase in man-mediated movements of aquatic species. This has already caused the introduction of new species or translocations within Europe of those aliens which have been introduced in historical times. The latter category includes the improperly named 'naturalized' alien species, a term often used for an alien species 'that has a self-sustaining and spreading population with no human assistance'. Also 'naturalized' aliens have caused environmental impacts.

An accurate review of the current state of knowledge concerning vectors of species introductions and of the potential risks associated with each broad category of vectors has been provided by ICES (2005). As far as European countries are concerned, a recent study carried out within the framework of the EU-funded Project DAISIE has examined the vectors of introductions; a different situation was found between Atlantic and Northern coasts and the Mediterranean Sea. The main pathways of the alien metazoan taxa recorded

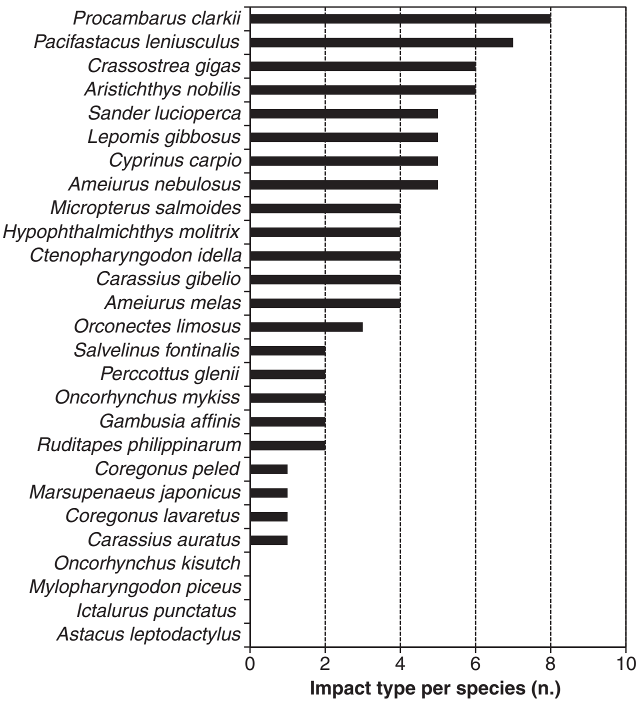

Fig. 1. Impact heterogeneity expressed as number of impact types per species. Impact types are: 1) food web alteration, 2) bioaccumulation of toxic substances in tissue, 3) community dominance in native ecosystem, 4) competition for food or space with native species, 5) introduction of new food item in the ecosystem, 6) modification of physical-chemical properties of habitats,7) consumption of aquatic plants and algae, 8) hybridization with native species and loss of genetic integrity, 9) predatory activity on native species

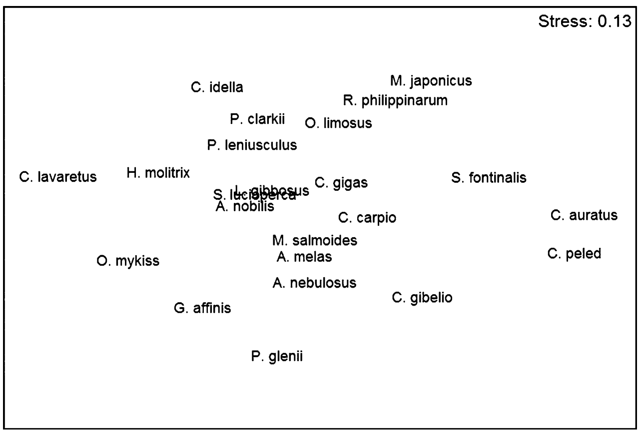

Fig. 2. MDS. Multidimensional scaling plot of distances (Bray Curtis similarity index) among alien species. Read: *O. mykiss, O. kisutch, S. fontinalis, C. peled, C. lavaretus* are all belonging to the Family Salmonidae but they show different types of environmental impact, therefore they do not cluster in the MDS plot

off the Atlantic coast of Europe are vessels (hull fouling ⁄ ballast) (47%), aquaculture (24%), and aquaculture ⁄ vessels (primary or secondary introduction) (13%). The majority of aliens in the Baltic Sea were introduced by vessels (45%) and aquaculture (18%). Most of the alien species in the Mediterranean have entered through the Suez Canal (54%), vessels (21%), aquaculture (11%), and canals ⁄ vessels (primary ⁄ secondary introductions) (10%). However, it has to be underlined that these percentages are only a 'best estimate' because the introduction vector is often uncertain.

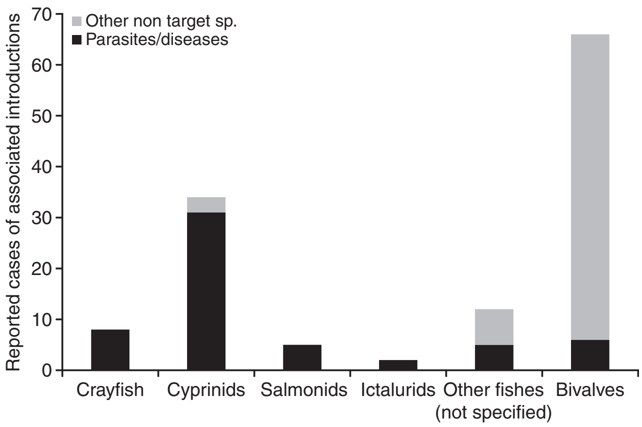

Fig. 3. Cases of associated introduction of non target species (parasite and diseases; other non target hitchhikers) to the worst 27 European aquacultured aliens

The present review identified 27 aquatic alien species being intentionally introduced by man, some of them entirely for aquaculture purposes, others initially in search for a replacement of lost native species (due to introduced diseases via life transport of commercial marine products to open markets; e.g. crayfish) but more recently also being employed in aquaculture. All of these species have established self-sustaining populations, several of them long before aquaculture began in Europe.

Given that it is impossible to eradicate widely spread species, interception or closure of new pathways are probably the only effective strategies for reducing future impacts of new introductions (Carlton and Ruiz, 2005). To single out one pathway is not effective and will scientifically not lead to any restriction while an integrated approach will be needed to effectively reduce the spread of alien species. Major pathways of introduction concern international shipping (Carlton, 1999; Ruiz et al., 2000; Gollasch, 2006), pleasure boating (Minchin et al., 2006), sport fishing (Rosenthal, 1980; Molony et al., 2003) and finally aquaculture as a business implicated in all three of these vector categories. Theoretically aquaculture, with its fixed and licensed locations, can be more effectively controlled than any of the others mentioned above. Aquaculture is also expected to be deeply influenced by harmful alien species (e.g. disease and parasites) introduced by the other human pathways mentioned above (shipping, recreational boating and sport fishing). On the other hand, rearing facilities would act as potential reservoir for spreading of those alien not initially introduced for farming. Therefore, a priority in science of biological invasion is moving towards a less sectored approach to the management of alien species providing holistic models which will consider interactions between major pathways of introduction.

It is the aim of invasion biologists to provide easy-to-handle analytical frameworks for a correct as possible explanation of the existing data on invasive alien species. In this paper we attempt to integrate and critically review information (collected within specific EU funded projects and peer-reviewed literature) and present a list of the most problematic alien species intentionally introduced into Europe for aquaculture, stocking and related purposes that have 'naturalized' in wild aquatic ecosystems. We deliberately focused in reviewing only their negative environmental impact as a question of major concern for conservation biologists. There are, in fact, few cases in scientific literature that show positive environmental impacts of farmed alien species in Europe. As an example, oyster and mussel rafts in the Rias of Vigo (Spain) has become an effective buffer zone to protect the area against nutrient floods and toxic algal blooms (Tenore et al., 1982).

Summarizing our results we came to the following conclusions:

Environmental impact is not related to the successful establishment of a species. Some alien species that established extensive populations in Europe, such as *C. auratus* (29 countries) and *O. mykiss* (28 countries), do not show severe environmental impacts. On the other hand, *C. gibelio* (seven countries) caused significant impact in all countries of introduction. Moreover, levels of impact for a same species can be different in different European countries, as for the crayfish *P. leniusculus* that has been causing lager impact in southern European countries than in northern ones. For example, in Scandinavia, where temperature are generally lower in summer, the impact of the crayfish in terms of herbivory and macrophytes removal is almost identical to the native noble crayfish (*Astacus astacus*) (Nyström and Strand, 1996).

Environmental impact is species-specific. Species belonging to the same family or even genus exert different types of impact. The salmonid *Coregonus lavaretus* has altered the native food web by selectively preying on zooplankton (Langeland and Nøst, 1995), while its congener *C. peled* has caused genetic impairment by hybridizing with *C. lavaretus* in countries where the latter is native (Kirtiklis and Jankun, 2006).

Heterogeneity of impact is an important factor to consider when assessing species impact. The crayfish *P. clarkii* and *P. leniusculus* have caused a wide range of environmental impacts (e.g. crayfish plague dissemination, habitat modifications, predation, competition, bioaccumulation of heavy metals and other water pollutants etc) (Gherardi, 2006, 2007b; Tricarico et al., 2008), while other species, such as *C. auratus* and *C. peled*, may cause one type of impact only (hybridization). A species affecting the ecosystem by various means should be considered a major concern.

Introduction of associated non-target species is a function of specific morphological characters of the species and of its delivery methods to the aquaculture facility and to the market. The intentional movements of the bivalves *C. gigas* and *R. philippinarum* were responsible for the introduction in Europe of the largest number (60) of non-native invertebrates and algae, often as shell foulants or in packaging material. Therefore, movement and marketing of bivalve seed or adults must adhere to strict guidelines and provisions in order to prevent the unintentional introduction of their associated non-target organisms.

Stocking for restoring fishery and for sport fishing were also important causes of alien species introduction and establishment in Europe well before aquaculture for food production took place. There are several species listed which are now used in aquaculture but which were originally introduced for other purposes in Europe. The crayfish *P. clarkii* and *P. leniusculus* were initially introduced to restore fishery in southern and northern Europe, respectively, in order to find an alternative to declining native *Astacus* populations (Anonymous, 1901; Abrahamsson, 1973; Hasburgo, 1978; Richards, 1982; Hogger, 1986; Brinck, 1988). Another crayfish, *A. leptodactylus,* has been introduced into western Europe from easterly countries for the same reasons (Holdich, 1987). Certainly, parallel to this stocking development, between 1901 and 1980 people became gradually interested in culturing the introduced species also for commercial purposes. Initially, this was at a very small scale: large-scale introductions using hatchery programs to promote release were long on the way. Salmonids (*O. mykiss, S. fontinalis, C. peled, C. lavaretus*), ictalurids (*Ameiurus nebulosus, A. melas, I. punctatus*), percids (*Sander lucioperca*), and centrarchids (*Lepomis gibbosus, M. salmoides*) freshwater fishes were initially stocked in lakes and rivers for sport fishing. Later, hatchery programs took place both for performing a systemic restocking in open waters or for food production (i.e. salmonids) (Molony et al., 2003). As regards marine species, two bivalves, the Pacific oyster *C. gigas* and the Manila clam *R. philippinarum*, have been stocked in European lagoons in order to replace native species that had undergone severe reductions in population (Cesari and Pellizzato, 1985; Breber, 1992; Héral and Deslous-Paoli, 1990).

In comparison, there are less examples of alien species which have first been introduced for farming purposes: carps in Eastern Europe (e.g. *C. carpio; Aristichthys nobilis, C. gibelio*) (Welcomme, 1988; Özuluğ et al., 2004) and since the 1980s the peneid shrimp *M. japonicus* in southern Europe (Lumare et al., 1989; Arrobas et al., 1993; Blachier et al., 1993).

'*Guilty until proven innocent*'. Despite the large number of scientific publications on alien species produced in recent years, we lack information (relating to quantitative and experimental assessments) on the possible impact of species which are commonly used for aquaculture in Europe, such as the crayfish *A. leptodactylus*, the grass carp *M. piceus,* the catfish *I. punctatus* and the salmonid *O. kisutch*. As a precautionary approach, these species should be considered 'guilty until proven innocent'. Therefore investigation of their potential of establishment in the wild and possible environmental consequences are imperative. Specific tools of risk assessment methods have been developed for this aim (Copp et al., 2009; Tricarico et al., 2009).

The present review reports a classification of impact for alien species that has been introduced into Europe since the middle age using an analytical method based on scientific publications. Although a scheme for confidence in references was adopted, it is worth considering a bias of results due to a major uncertainty: the lack of information on impact in a country of introduction cannot be statistically and scientifically linked to a true lack of impact. Besides, a larger amount of information for some aliens does not depend only on more evident impact of these organisms but, in a few cases, on the intensity of studies in that region. As a consequence the only way to qualify and quantify, with the highest certainty, alien species impact is to consider it specifically at the small scale of a study area.

Assuming that any species newly introduced in an ecosystem is certain to have an impact in terms of its functioning, all aquatic alien species introduced into Europe are interacting in some way with the native communities. Those interactions, sometimes 'invisible' or not measurable (Carlton, 2002), become study subjects when the introduced population visibly affects various levels of biological organization: genetic, population, community, habitat ⁄ ecosystem (Reise et al., 2006), thus becoming measurable (Olenin et al., 2007). This statement supports results obtained by the present review, where as 'worst alien' we consider not only the most widespread species in Europe, but also species which have been studied more for their environmental impact, especially when they were studied in different European countries and cause different types of impact. Therefore, an assessment on a European scale would lead to generalization, but a realistic assessment on that scale can only be performed by bibliographical analysis.

In conclusion, this review gives a picture as accurate as possible on the most problematic animal alien species cultured in Europe. Attention and resources should be focused on those species of the list which are characterized by evident eurytopy and heterogeneity of impact type, such as the crayfish *P. clarkii*, *P. leniusculus,* the carps *C. gibelio*, *C. idella*, *A. nobilis* and the largemouth bass *M. salmoides*. Finally, the oyster *C. gigas* and the clam *R. philippinarum* deserve particular attention as a vehicle for introduction of associated non-target organisms.

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