Chapter thirty-five

A risk assessment of biological invasions in the inland waterways of Europe: the Northern Invasion Corridor case study

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INTRODUCTION

Inland waterways have provided opportunities for the spread of aquatic non-indigenous species (NIS) for many centuries (reviewed in Ketelaars 2004, Galil and Minchin 2006, Galil *et al.* 2007). Canals connecting different river basins have allowed for range extensions of many species, either by active movement and/or by ship transport. Over the past century, the potential for species to expand their range has been enhanced due to increasing trade and the construction of canals. The waterways occur at low altitudes and presently the main European corridor routes consist of an interlinked network of 30 main canals with more than 100 branches, and more than 350 ports exist in low-altitude Europe.

The European Agreement on Main Inland Waterways of International Importance (AGN) was signed under the framework of the United Nations

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Economic Commission for Europe (UNECE) in Geneva in 1996. The AGN sets down standards for a uniform infrastructure and operational procedures for the European inland waterway network (EWN). With the adoption of the AGN by the Russian Federation in 2002, the international network of European waterways defined in the Agreement now consists of approximately 28,000 km of main navigable rivers and canals, extending from the Atlantic Ocean to the Ural mountains and connecting 37 countries in Europe and beyond. Currently, the network includes Austria, Bulgaria, Croatia, the Czech Republic, Hungary, Finland, France, Germany, Greece, Italy, Lithuania, Luxembourg, The Netherlands, the Republic of Moldova, Romania, the Russian Federation, Slovakia, and Switzerland. The EWN will be further developed in the future, as more than 80 missing links and bottlenecks have recently been identified (Anonymous 2005).

Such development will enable further opportunities for NIS to extend their ranges to other river basins previously separated over geological time. The first opportunity for NIS to spread began in the late 1700s with the construction of canals connecting previously isolated river basins and linkages to European seas: Mediterranean, Black, and Azov seas to the south, and the Baltic and White seas to the north. Presently, there are four main inland water trading routes (invasion corridors) that enable in particular the range expansion of several Ponto-Caspian species through Europe (Jażdżewski 1980, Panov *et al.* 1999, Bij de Vaate 2002, Nehring 2002, Slynko *et al.* 2002, Van der Velde *et al.* 2002, Ketelaars 2004, Pienimäki and Leppäkoski 2004, Galil *et al.* 2007).

These invasion corridors include the Northern Invasion Corridor which links the southern seas (Black and Azov seas) with the Caspian Sea via the Azov Sea–Caspian waterway (the main European inland waterway number E90, including the Volga–Don Canal opened in 1952), and with the Baltic and White seas via the Volga–Baltic waterway (the main European inland waterway number E50 with the Volga–Baltic Canal first opened in 1810 and reopened after major reconstruction in 1964) and via the White Sea–Baltic Sea waterway (the main European inland waterway number E60 with the White Sea–Baltic Sea Canal opened in 1932). This largest inland European invasion corridor consists of approximately 6,500 km of waterways, representing the so-called United Deepwater System of Russia with 21 inland ports of international importance, and linking four main watersheds in European Russia (Black, Caspian, Baltic, and White seas basins) (Fig. 1). The Volga River represents the longest section in the Northern Invasion Corridor. This river is 3,530 km long and includes 12 large and more than 300 medium and small reservoirs (Slynko *et al.* 2002).

In 2003, the Russian Government adopted the national Concept of Development of the Inland Water Transport, which is likely to increase trade along the Northern Invasion Corridor. According to this concept, the United Deepwater System of Russia should be fully open for international shipping by 2010 and be integrated into the European inland waterway network. The main focus is to

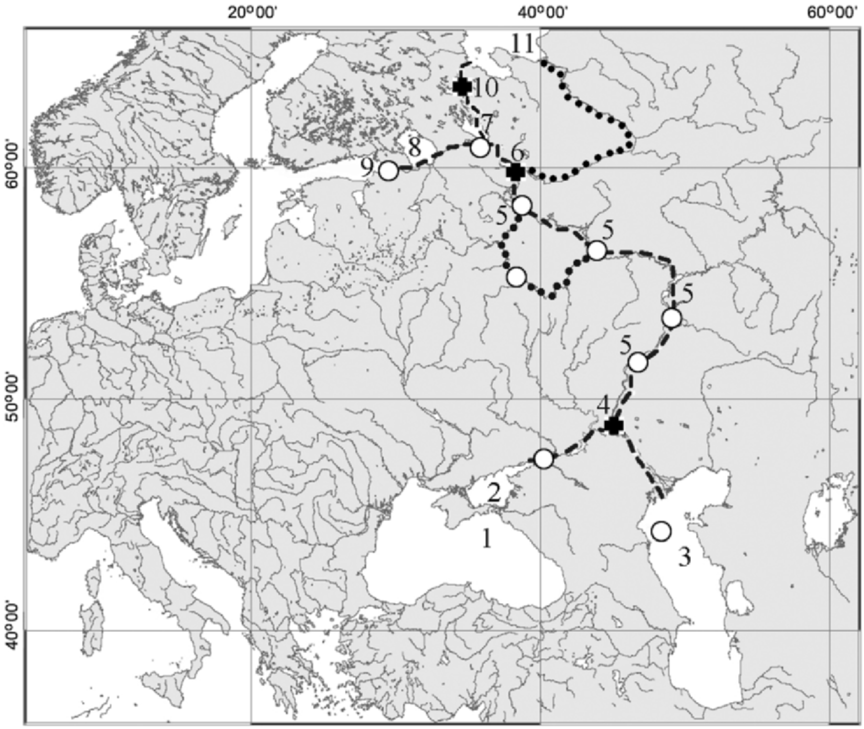

Fig. 1 The European Northern Invasion Corridor. Numbers on the map indicate: 1 – Black Sea, 2 – Azov Sea, 3 – Caspian Sea, 4 – Volga–Don Canal, 5 – Volga River reservoirs, 6 – Volga–Baltic Canal, 7 – Onega Lake, 8 – Ladoga Lake, 9 – Gulf of Finland, 10 – White Sea-Baltic Canal, and 11 – White Sea. Dashed lines indicate the main navigable waterways of the Northern Invasion Corridor, dotted line – the secondary waterways, opened cycles – the monitoring stations.

provide connections between the Volga, Don, and Danube rivers to link more than 15 European countries. These future developments may highly facilitate the transfer of NIS across European inland waters and coastal ecosystems, which require appropriate risk assessment-based management options to address risks posed by human-mediated introductions of these species.

Ecological risk assessment is a process that evaluates the likelihood that adverse ecological effects may occur or are occurring as a result of exposure to one or more stressors. The process is used to systematically evaluate and organize data, information, assumptions, and uncertainties in order to help understand and predict the relationships between stressors and ecological effects in a way that is useful for environmental decision making (Anonymous 1998). Generally speaking, the risk assessment is a part of the process of managing risks, and there are many different risk assessment approaches in different decision-making contexts and levels ranging from specific case studies to strategic regulation and policy making (Gerrard and Petts 1998). These approaches can be separated into two major distinct types: quantitative and qualitative risk assessments. However, because quantification of risks is not always possible, it is better to convey conclusions (and associated uncertainties) qualitatively than to ignore them, because they are not easily understood or estimated (Anonymous 1998). In our opinion, quantitative risk assessments, based on objective scientific judgements, can be more applicable for the local level of decision-making in case of site-specific and/or species-specific management, while the strategic regulation- and policy-making on both national and international levels can be based in large extent on qualitative risk assessment. This is particularly true if one considers the high degree of scientific uncertainty when dealing with such a global and complex ecological issue as large-scale intercontinental and intracontinental introductions of NIS.

The specific methodologies of risk assessment of shipping-mediated introductions of NIS include two main types: the environmental matching risk assessment and the species-specific risk assessment (Pienimäki and Leppäkoski 2004, Leppäkoski and Gollasch 2006). Based on these two principal approaches, we conducted a qualitative risk assessment of NIS introductions along the Northern Invasion Corridor, with the general purpose to develop a conceptual model of risk assessment of biological invasions for the European inland navigable waterways, which can be further used as a tool for management purposes.

CONCEPTUAL MODEL OF QUALITATIVE RISK ASSESSMENT FOR INLAND WATERWAYS

The qualitative risk assessment was based on the analyses of data from the national database on aquatic NIS in European Russia (Panov *et al.* 2007a), the AquaInvader information system (Panov *et al.* 2006), and other relevant sources (Slynko *et al.* 2002, Panov *et al.* 2007b). The national database includes both published information and primary field data on aquatic NIS distributions from the national monitoring network established along the whole Northern Invasion Corridor (Fig. 1).

There are five main components to the risk assessment of NIS for the navigable inland waterways we have made:

1. Identification of the principle recipient and donor areas of NIS (risk areas) and invasion routes.
2. Identification of the main vectors of NIS introductions.
3. Assessment of inoculation rates (propagule pressure).
4. Assessment of the vulnerability of potential recipient areas to invasions from past patterns and likely environmental suitability.

5. Assessment of the invasiveness of NIS both in the recipient risk area and in the potential donor areas based on known dispersal abilities, establishment success, and ecosystem impacts.

Qualitative estimations of inoculation rates and ecosystem vulnerability to invasions and species invasiveness were ranked *low*, *medium*, and *high*, and these estimations were further used for an assessment of the integrated ecosystem risk level for the main risk areas within the Northern Invasion Corridor. The analysis of these five main components was conducted for initial predictive risk assessment for selected recipient areas (risk recipient areas).

Identifying recipient and donor areas of NIS and invasion routes

There are four principle high risk areas along the Northern Invasion Corridor, which act as recipient and also as donor areas of aquatic NIS: Azov Sea (41 established NIS), Caspian Sea (46 established NIS), Volga River reservoirs (85 established NIS), and Gulf of Finland of the Baltic Sea (23 established NIS). The White Sea can be considered as a *low*-risk area, as only 10 NIS (both marine and freshwater) have become established in its basin, and currently there is no evidence of its possible role as donor area (Fig. 2). In this water system, Lake Ladoga and Lake Onega (the largest European lakes), have the lowest number of established NIS (only three), and is considered as *low*-risk area (see discussion below).

The principle donor areas of NIS for the four main recipient ecosystems include: Black Sea (25 species), Caspian Sea (four species), and Asia (three species) for the Azov Sea; Black and Azov seas (44 species) for the Caspian Sea; Lower Volga (42 species), Black and Azov seas (16 species), and Baltic Sea basin (18 species) for the Volga River reservoirs; Ponto–Caspian basin (10 species) and western Baltic (11 species) for the Gulf of Finland (Fig. 3). The principle donor areas of NIS are from southern regions. This may reflect climate change with the concomitant advantage of an available route for southern species to spread northwards.

We identified 10 patterns of NIS dispersal along the Northern Invasion Corridor, considered here to be invasion routes (Fig. 2). Along routes 1–7 we found 122 northward invasions but only 24 southward invasions along routes 8–10. Each route links the basins, seas, reservoirs, and canals as follows: route 1, the Black and Azov seas basins with the Caspian Sea via the Volga–Don Canal, resulting in 46 invasions into the Caspian Sea (Grigorovich *et al*. 2003, Panov *et al*. 2007a); route 2, the Black and Azov seas to the Volga River reservoirs, resulting in 16 invasions; route 3, the Black and Azov seas basin across two geographic barriers via Volga River reservoirs to the Baltic Sea basin (Gulf of Finland), resulting in five invasions (e.g. two species of predatory onychopod cladocerans, *Cercopagis pengoi* and *Cornigerius maeoticus*; Panov *et al*. 2007b); route 4, the Caspian Sea basin, from the Caspian and Lower

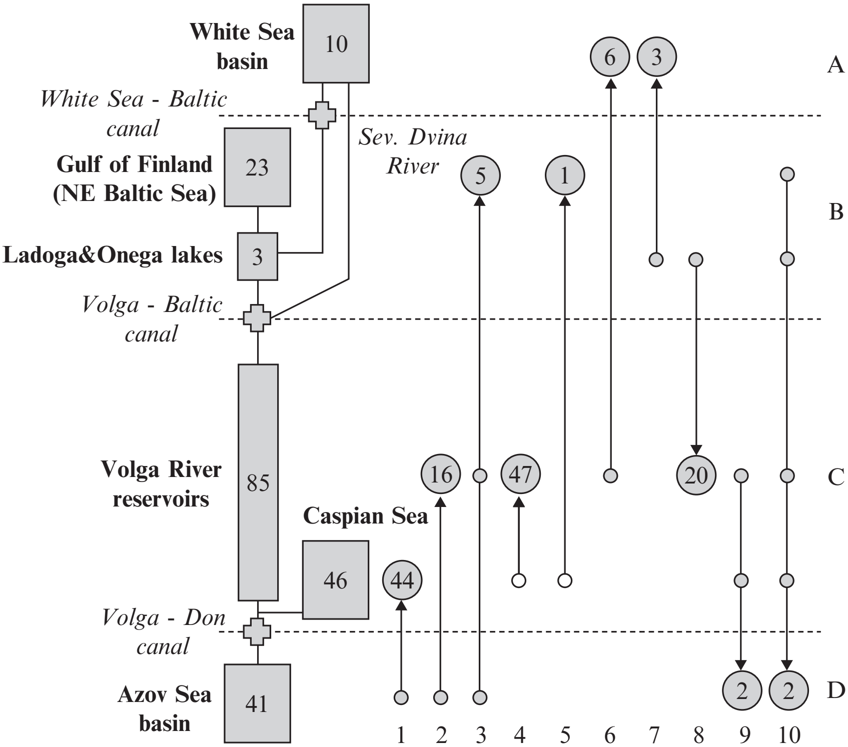

Fig. 2 Main recipient areas of aquatic NIS and specific invasion routes of their introductions within the Northern Invasion Corridor. Numbers in boxes and circles indicate the number of established NIS in risk areas (see Fig. 1) and by the invasion route, respectively. Dashed lines indicate the geographic barriers between previously isolated basins of: A – White Sea, B – Baltic Sea, C – Caspian Sea, and D – Black and Azov seas.

Volga, to the Middle and Upper Volga reservoirs, resulting in the spread of 47 species attributed, in part, to recent climate changes (Slynko *et al*. 2002); route 5, the Caspian Sea directly to the Baltic Sea, resulting in the invasion of *Evadne anonyx* (Rodionova and Panov 2006); route 6, the Caspian basin to the White Sea basin via canals linking the Upper Volga with the Severnaya Dvina River basin, the northernmost part of the Northern Invasion Corridor, resulting in the invasion of *Dreissena polymorpha* (Panov *et al*. 2007a); and route 7, the Baltic Sea basin to the White Sea basin, resulting in the invasion of two fish species and of the Chinese mitten crab, *Eriocheir sinensis* (Panov *et al*. 2007a).

Routes 8–10 are north-south movements from the Baltic basin via the Volga–Baltic Canal to the Volga River reservoirs (20+ species), from the Caspian basin via the Volga–Don Canal to the Azov Sea basin (two species),

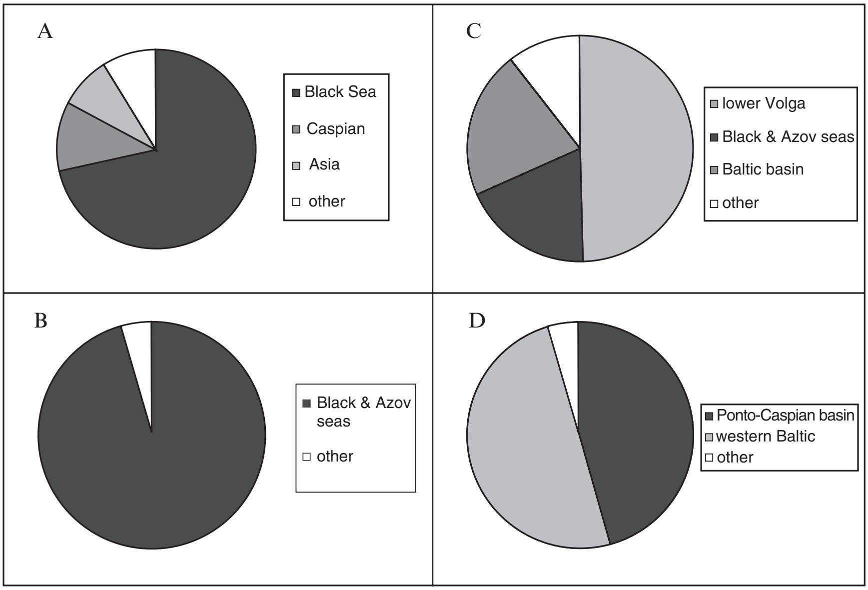

Fig. 3 Donor areas of aquatic NIS in the main risk areas of the Northern Invasion Corridor (A – Azov Sea, B – Caspian Sea, C – Volga River reservoirs, and D – eastern Gulf of Finland).

and long-distance transfer from the Baltic basin to the Azov Sea basin across two main geographical barriers via the Volga–Baltic Canal, Volga River, and Volga–Don Canal of the invasive crustaceans *Bythotrephes longimanus* and *E. sinensis* (Panov *et al*. 2007a).

Identifying vectors of introductions of NIS

In all main recipient areas within the Northern Invasion Corridor, shipping-related activities are the most important vectors of introductions of NIS. This includes direct transfers of NIS with ballast water, sediments, and hull fouling, and with migrations of NIS via navigable canals. The relative importance of shipping-related vectors has increased since the 1950s in all risk areas (Fig. 4). Long-term changes in the relative importance of different vectors indicate that shipping-mediated accidental introductions were the primary pathway of introductions into the semi-enclosed Azov Sea and the Gulf of Finland prior to 1950, whereas in the geographically isolated Caspian Sea basin and in the Volga River reservoirs other vectors, such as intentional species introductions, were prominent agents of introductions (Fig. 4). However, after the opening of the Baltic–Volga and Volga–Don canals in the middle of the 20th century, shipping also started to play the most important role for introductions of NIS

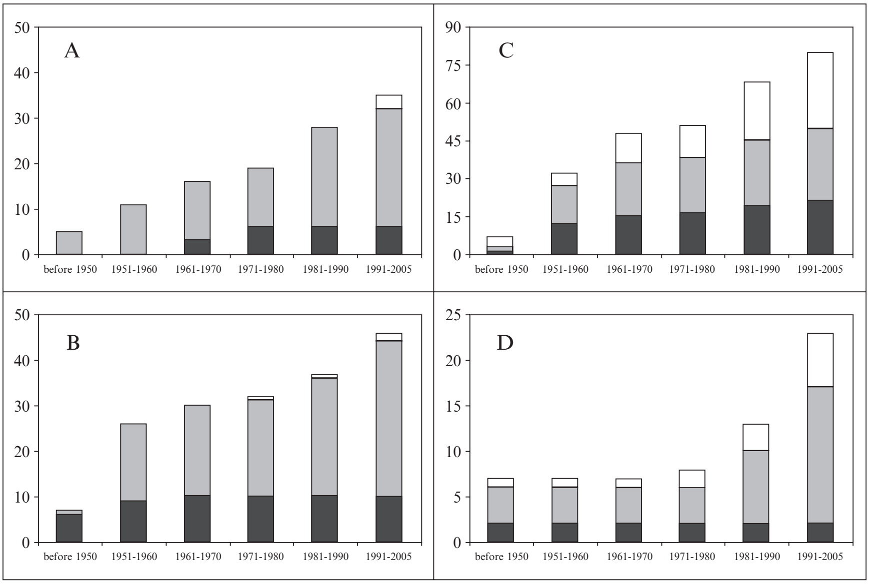

Fig. 4 Dynamics of the introductions of NIS in the four main risk areas (A – Azov Sea, B – Caspian Sea, C – Volga River reservoirs, and D – eastern Gulf of Finland) along the Northern Invasion Corridor for different vectors (black bars – intentional introductions, grey bars – shipping-mediated accidental introductions, and open bars – other vectors). Note the different scales for panels C and D.

for the Caspian Sea and the Volga River reservoirs. There is a clear trend in increasing importance of shipping-related vectors over time in all main risk areas, with greatest increase in rates of shipping-mediated introductions in the Gulf of Finland during the last 15 years (Fig. 4). The latter phenomenon can mainly be attributed to the effects of climate change that facilitates the establishment of warm-water species in the gulf (Panov *et al.* 2007b). Climate changes may also have facilitated the range expansion of some NIS during the last decades by other vectors, including natural migrations of NIS from adjacent southern areas, specifically for the Gulf of Finland and Volga River (Slynko *et al.* 2002, Panov *et al.* 2007b) (Fig. 4).

Assessing inoculation rates

The inoculation rates by propagules of aquatic NIS (including their resting stages) of the main risk areas within the Northern Invasion Corridor can be assessed only indirectly from shipping statistics that include information of volumes of discharged ballast water. However, such detailed information is often lacking, and only general statistics on the number of ships entering the

Caspian Sea and the Gulf of Finland and the volume of transported cargo are available. In 2003 and 2004, approximately 400 ships entered the Caspian Sea (mainly via the E90 water route) in each year transporting $\sim$1 million tons of cargo. In the same two years, approximately 7,000 ships with 18 million tons of cargo entered the Gulf of Finland via the E50 water route each year. However, we do not have information on the likely volumes of ballast transported and the voyage durations; such information is important in relation to survival and inoculation potential. The use of such statistics for the estimation of inoculation rates of NIS without consideration of ballast water history and the duration of ship voyage allows for only preliminary qualitative estimates and may be associated with significant uncertainty.

Indirect estimations of inoculation rates using data on the long-term dynamics of invasion rates (Fig. 4) are even more questionable and uncertain. For instance, significant increase in the number of shipping-mediated introductions of NIS for the Caspian Sea during the last 15 years (Fig. 4B) can be attributed to the increased ship traffic in this period and to the related increases in inoculation rates. However, for the Gulf of Finland, even more profound increases in the number of shipping-mediated introductions of NIS (mostly Ponto-Caspian crustaceans) have been observed during the last 15 years (Fig. 4D). These introductions were most likely mediated by climate changes, as shipping intensity in the gulf via the E50 water route did not increase compared to earlier time periods (Panov *et al.* 2007b). In contrast to the inland ports, cargo turnover in the marine ports in the Gulf of Finland increased several-fold over the last 10–15 years, and currently exceeds 100 million tons per year (Panov *et al.* 2003). This has resulted in extremely high volumes of released ballast water and, consequently, in high inoculation rates by propagules of NIS. Taking into account available data on shipping, estimated inoculation rates within the Northern Invasion Corridor are relatively *low* for the Volga River reservoirs, Ladoga and Onega lakes, and White Sea, are *medium* for the Azov and Caspian seas, and must be considered *high* for the Gulf of Finland (Table 1).

Assessing the vulnerability to invasions of potential recipient areas

Ecosystem vulnerability to invasions may depend on abiotic and biotic resistance of the specific ecosystem to the establishment of NIS. Abiotic resistance is related to the environmental match of potential donor and recipient ecosystems. Considering main donor areas of NIS outside and within the Northern Invasion Corridor (see section on identification of recipient and donor areas of NIS and invasion routes above), abiotic resistance can be roughly estimated as *low* for the Azov and Caspian seas, *medium* for the Volga River reservoirs and Gulf of Finland, and *high* for the lakes Ladoga and Onega and for the White Sea basin.

Table 1 Ranking of three factors of risk for the invasions of aquatic NIS (inoculation rates, area invasibility, and species invasiveness) and the resulting integrated risk level for six risk areas along the Northern Invasion Corridor.

Risk area	Inoculation rates	Area invasibility	Species invasiveness	Integrated risk level
Azov Sea	medium	medium	medium	medium
Caspian Sea	medium	high	high	high
Volga River Reservoirs	low	high	medium	medium
Ladoga and Onega lakes	low	low	high	medium
Gulf of Finland	high	medium	high	high
White Sea	low	low	high	medium

Limnological conditions in the glacial lakes Ladoga and Onega, such as the low conductivity of the water, make these lakes unsuitable for the progressive expansion of NIS from the Caspian Sea basin to the Gulf of Finland and White Sea region via the Volga–Baltic Canal and White Sea–Baltic Canal. Dispersal of NIS from the Caspian Sea basin to the White Sea basin is possible only via waterways connected to the Severnaya Dvina River (invasion route 6; see Fig. 2). Any non-indigenous transmissions through lakes Ladoga and Onega are likely to have taken place with human-aided processes. Presently, only two invasive crustaceans are known from these lakes, the Baikalian zebra amphipod, *Gmelinoides fasciatus* (Stebbing), and the Chinese mitten crab, *E. sinensis* (Panov 1996, 2006). Thus, the lakes Ladoga and Onega can be considered as natural barriers to the dispersal of NIS that expand their ranges along waterways, including newly built canals. Successful transmission through these lakes may only occur for certain life history stages that attach to the hull of ships and that are able to tolerate short periods of exposure to unfavourable water conditions, or via transport in the ballast water of ships.

The biotic resistance of an ecosystem is related to the strength of interspecies relationships for any new invasive species, including food supply, competition, predator-prey, and parasite–host relationships. At the present stage, estimations of biotic resistance of aquatic ecosystems towards biological invasions are largely lacking (but see Ricciardi and MacIsaac 2000, Colautti *et al.* 2004, DeRivera *et al.* 2005, Fenieva *et al.* 2006), and the development of approaches to such estimations requires further study and was not considered in our qualitative risk assessment.

Considering rough qualitative estimates of abiotic resistance (i.e. environmental matching in terms of salinity and temperature regimes), vulnerability of the studied ecosystems to biological invasions can be estimated as *low* for the lakes Ladoga and Onega and the White Sea basin, *medium* for the Azov Sea basin, and *high* for the Caspian Sea, Volga River reservoirs, and the Gulf of Finland (Table 1).

Assessing the invasiveness of NIS

Because risk areas within the Northern Invasion Corridor are serving both as donors and recipients of NIS, it is important to assess the invasiveness of NIS in these areas according to their potential to spread, establish in new environments, and affect potential recipient ecosystems (species-specific risk assessment). We used available data on the main life history traits (salinity and temperature tolerance, fecundity and patterns of reproduction, ability to produce resting stages, etc.), invasion history, and known ecological impacts (Panov *et al*. 2006, 2007a,b) for an assessment of species invasiveness in different taxonomic groups of NIS in the main risk areas.

In all main risk areas, apart from the Caspian Sea where plants dominate as NIS, crustaceans were the largest group of NIS with the highest proportion of *medium* and *high* level of invasiveness (Fig. 5). Estimated proportions of established *medium* and *high*-risk NIS for these areas were highest for the Gulf of Finland (86%), and were somewhat lower for the Azov Sea basin, Volga River reservoirs, and Caspian Sea (58%, 48%, and 39%, respectively). However, the known level of negative impacts of NIS on the ecosystem biodiversity and functions is certainly the highest for the Caspian Sea, currently experiencing severe consequences of the *Mnemiopsis leidyi* A. Agassiz invasion (Shiganova

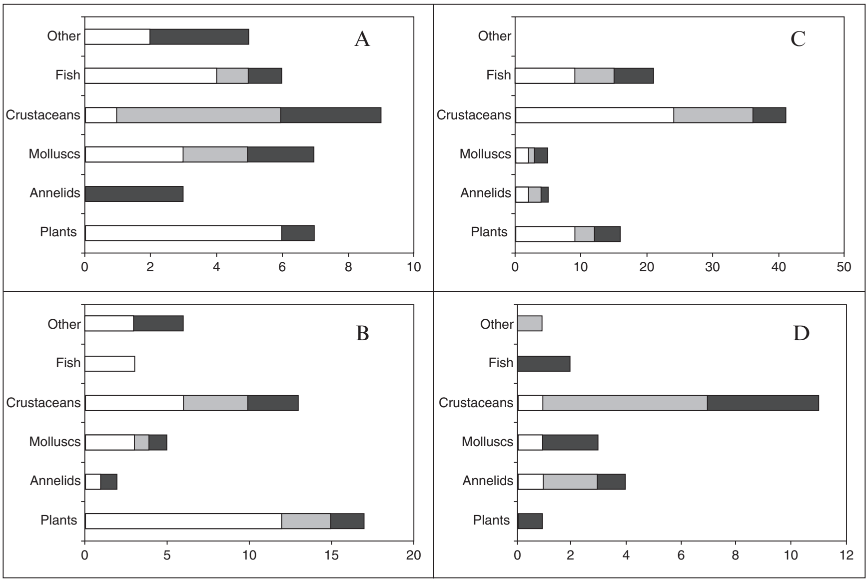

Fig. 5 Taxonomic composition of NIS in main risk areas along the Northern Invasion Corridor (A– Azov Sea, B – Caspian Sea, C – Volga River reservoirs, and D – eastern Gulf of Finland). Black bars indicate proportion of high-risk species.

et al. 2004). Compared to the Caspian Sea, the level of known negative impacts of invasive species in other main risk areas can be estimated as *medium*.

RESULTS OF THE QUALITATIVE RISK ASSESSMENT

Qualitative estimations of inoculation rates, ecosystem vulnerability to invasions, and species invasiveness (see sections above) were used for an overall assessment of the integrated risk level for each risk area within the Northern Invasion Corridor (also ranked as *low*, *medium*, and *high*). The estimated integrated ecosystem risk level was considered *high* for the Caspian Sea and Gulf of Finland, and *medium* for the rest of the risk areas (Table 1).

From the combination of environmental matching and species-specific risk assessments, we estimated likely levels of establishment for 34 key high-risk target NIS in risk areas within the Northern Invasion Corridor as a predictive risk assessment (Table 2). We deduced that the highest number of these will appear within the Gulf of Finland (17 species), followed by the Caspian Sea with seven potential new high-risk invaders. This assessment generally corresponded with the independently estimated *high* integrated ecosystem risk level for these two risk areas (Table 1).

The qualitative approach adopted here follows the predictive risk assessment first used in the Nordic Council-supported project on risk assessment of NIS in Nordic coastal waters (Gollasch and Leppäkoski 1999) for the eastern Gulf of Finland area, with a prediction of invasion of two invasive Ponto-Caspian onychopod species, *C. maeoticus* and *Podonevadne trigona* (Sars) into the eastern gulf (Panov *et al*. 1999). Subsequently, *C. maeoticus* was found in the Gulf of Finland in 2003 (Rodionova *et al*. 2005). However, the first new onychopod invader (i.e. after publication of the initial risk assessment in 1999) was another onychopod species, *Evadne anonyx*. This species was first recorded in the zooplankton of the gulf in 2000 (Rodionova and Panov 2006). *Evadne anonyx* was not considered as a high-risk species, because it had no previous invasion history and was not considered to be able to develop sustainable populations at salinities below 9 ppt (Panov *et al*. 2007b). In the eastern Gulf of Finland, *E. anonyx* successfully established in areas with water salinities as low as 1–3 ppt (Rodionova and Panov 2006). This unexpected invasion of *E. anonyx* into the eastern Baltic Sea may indicate that the most common Ponto-Caspian onychopods, not listed among our 34 high-risk species in the Table 2 [i.e. *Podonevadne camptonyx* (Sars), *Podonevadne angusta* (Sars), *Polyphemus exiguus* Sars, *Evadne prolongata* Behning], may pose some risks of long-distance intra-continental transfer if appropriate vectors of introduction are available (shipping along the Volga–Baltic inland waterway). In general, the Ponto-Caspian onychopods pose the highest risks for the Gulf of Finland, as all the non-indigenous cladocerans established in the eastern Baltic Sea belong to this group, and the rapid and successful establishment of three onychopod species

Table 2 Aquatic NIS with a high potential to become established with self-reproducing populations in risk areas along the Northern Invasion Corridor.

Taxa	Azov Sea	Caspian Sea	Volga River Reservoirs	Ladoga and Onega Lakes	Gulf of Finland	White Sea
Plants						
Pseudosolenia calcar-avis (Schultze) Sundström	1924	1934	**high**	low	**high**	low
Pseudo-nitszchia seriata (Hasle) Hasle	indigenous	1990	**high**	low	**high**	low
Skeletonema subsalsum (Cleve-Euler) Bethge	indigenous	indigenous	1957	low	**high**	low
Thalassiosira incerta Makarova	indigenous	indigenous	1967	low	**high**	low
Actinocyclus normanii (W. Gregory) Hustedt	indigenous	indigenous	1986	low	**high**	low
Chroomonas acuta Utermöhl	indigenous	indigenous	1988	low	**high**	low
Cnidaria						
Blackfordia virginica Mayer	1930s	1956	low	–	**high**	low
Bougainvillia megas Kinne	1950s	1961	low	–	**high**	low
Ctenophora						
Mnemiopsis leidyi A. Agassiz	1988	1999	–	–	medium	low
Annelida						
Ficopomatus enigmaticus (Fauvel)	1960	1961	low	–	**high**	medium
Hypania invalida (Grube)	indigenous	**high**	1960	low	**high**	medium
Marenzelleria neglecta (Sikorski and Bick)	**high**	**high**	–	–	1996	medium
Mollusca						
Rapana venosa (Valenciennes)	1956	low	–	–	low	low
Mytilaster lineatus (Gmelin)	indigenous	1919	–	–	medium	low
Teredo navalis Linnaeus	1953	medium	–	–	low	medium
Dreissena polymorpha (Pallas)	indigenous	indigenous	1953	low	1986	1970s
Dreissena bugensis (Andrusov)	**high**	**high**	1992	low	**high**	**high**
Mytilopsis leucophaeata (Conrad)	**high**	**high**	–	–	2004	low

Table 2 Continued.

Taxa	Azov Sea	Caspian Sea	Volga River Reservoirs	Ladoga and Onega Lakes	Gulf of Finland	White Sea
Crustacea						
Acartia tonsa Dana	2000	1981	medium	low	1934	**high**
Bythotrephes longimanus Leydig	1960s	low	1957	indigenous	indigenous	indigenous
Cercopagis pengoi (Ostroumov)	indigenous	indigenous	1960	low	1992	low
Podonevadne trigona (Sars)	indigenous	indigenous	1966	low	**high**	low
Cornigerius maeoticus (Pengo)	indigenous	indigenous	1970	low	2003	low
Evadne anonyx Sars	indigenous	indigenous	low	–	2000	low
Rhithropanopeus harrisii (Gould)	1960	1958	medium	low	**high**	medium
Eriocheir sinensis H. Milne-Edwards*	medium	**high**	–	–	low	medium
Callinectes sapidus M. J. Rathbun	1967	medium	–	–	low	low
Fish						
Pseudorasbora parva (Linnaeus)	1970	**high**	high	low	medium	low
Clupeonella cultriventris (Nordmann)	1970	indigenous	1964	low	**high**	**high**
Neogobius melanostomus (Pallas)	indigenous	indigenous	1968	low	**high****	medium
Neogobius fluviatilis (Pallas)	indigenous	indigenous	1960	low	**high**	medium
Neogobius iljini Vasiljeva et Vasiljev	indigenous	indigenous	1970	low	**high**	medium
Proterorhinus marmoratus (Pallas)	indigenous	indigenous	1981	low	**high**	medium
Perccottus glenii Dybowski	**high**	**high**	1981	**high**	1950	**high**
Total number of HRS	**4**	**7**	**3**	**1**	**17**	**4**

Numbers in cells indicate the year of first record; empty cells indicate that establishment is not considered possible
* adults of *E. sinensis* were recorded in all risk areas
** single specimens of *N. melanostomus* were recorded in the western Gulf of Finland in 2005 (Ojaveer 2006)

has occurred in this region during the last 15 years, facilitated, most likely, by climate changes in the region (Panov *et al.* 2007b).

It is important to note the primary importance of the Northern Invasion Corridor for most recent invasions of NIS from southern regions to the Gulf of Finland (high-risk area) and the Baltic Sea. This importance exists despite the fact that the corridor currently contributes less than 20% to the volume of cargo transported to the Gulf of Finland (approximately 20 million tons compared to around 100 million tons per year from other transport corridors) and even much less in terms of ballast water (most ballast water released in the Gulf of Finland ports originates from areas other than the Ponto-Caspian). The role of other invasion corridors in biological invasions of the gulf is minor. During the last 15 years all other invasions corridors contributed to only one successful establishment of NIS in the gulf. In 2003, the Atlantic species Conrad's false mussel, *Mytilopsis leucophaeata*, was discovered in an area affected by cooling water discharges from a nuclear power plant (Laine *et al.* 2006).

The Gulf of Finland can also be considered as a high-risk donor area of NIS for aquatic systems outside the Northern Invasion Corridor area, specifically for the adjacent inland water ecosystems (Pienimäki and Leppäkoski 2004), and the North American Great Lakes, which are connected with eastern Baltic by an intercontinental invasion corridor (see Panov *et al.* 1999, 2003, 2007b). Ponto-Caspian invasive onychopods producing large numbers of resting eggs may pose a very high risk of introduction with ballast waters, even when regular ballast water management procedures are carried out (e.g. ballast water exchange during oceanic ship voyages), which might be ineffective for the resting eggs accumulating in the sediments of ballast tanks (MacIsaac *et al.* 1999, Bailey *et al.* 2005).

Managing the dispersal of species by shipping is a priority throughout the Northern Invasion Corridor. Taking into account the most important invasion routes within this system (Fig. 2), the risk-reducing management options for ballast water and other shipping-mediated vectors should be implemented at the main entrances to the Northern Invasion Corridor, in the ports of the lower Don River (entrance to the European inland waterway E90 from the Azov Sea) and in the ports of eastern Gulf of Finland, specifically the Port of St. Petersburg (entrance to the main European inland waterway E50 from the Baltic Sea). These management options should include treatment of ballast water and sediments, and hull fouling.

CONCLUSIONS

The Northern Invasion Corridor is playing an important role in the introductions of NIS in eastern Europe; its significance may increase over time with further construction and/or improvement of navigable watercourses and with their integration into the European network of inland waterways. Past patterns of transmission of NIS are likely to be repeated in the future, resulting in a further expansion of Ponto-Caspian species and in increased invasions within the Caspian Sea basin itself. Specifically, we expect a range extension of several invasive species already established in the ecosystems along the corridor.

The qualitative approach to risk assessment of aquatic invasions, tested for the Northern Invasion Corridor in the present study, can be considered as a useful tool for management purposes and is also applicable to other main European invasion corridors. The Northern Invasion Corridor case study indicated that relevant management options should be first implemented at the entrances to the inland waterways. Examples of ''abiotic resistance'' to biological invasions, such as the soft-water lakes Ladoga and Onega, with effective natural barrier to the dispersal of Ponto-Caspian species, demonstrate the potential effectiveness of such barriers along other European inland waterways for preventing the dispersal of actively migrating NIS. The application of more accurate quantitative methodology of risk assessment of biological invasions will be possible only after the development and implementation of comprehensive information systems on shipping statistics and after the collection of detailed information on the biological traits of invasive NIS established in the recognized donor areas (including potentially invasive indigenous species). To obtain such information further studies are required.

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