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Economic costs of biological invasions in terrestrial ecosystems in Russia

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Abstract

Terrestrial ecosystems, owing to the presence of key socio-economic sectors such as agriculture and forestry, may be particularly economically affected by biological invasions. The present study uses a subset of the recently developed database of global economic costs of biological invasions (InvaCost) to quantify the monetary costs of biological invasions in Russia, the largest country in the world that spans two continents. From 2007 up to 2019, invasions costed the Russian economy at least US$ 51.52 billion (RUB 1.38 trillion, n = 94 cost entries), with the vast majority of these costs based on predictions or extrapolations (US$ 50.86 billion; n = 87) and, therefore, not empirically observed. Most cost entries exhibited

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low geographic resolution, being split between European and Asian parts of Russia (US$ 44.17 billion; n = 72). Just US$ 7.35 billion (n = 22) was attributed to the European part solely and none to the Asian part. Invasion costs were documented for 72 species and particularly insects (37 species). The empirically-observed costs, summing up to US$ 660 million (n = 7), were reported only for four species: two insects *Agrilus planipennis* Fairmaire and *Cydalima perspectalis* (Walker) and two plants *Ambrosia artemisiifolia* L. and *Heracleum sosnowskyi* Manden. The vast majority of economic costs were related to resource damages and economic losses, with very little reported expenditures on managing invasions in terrestrial ecosystems. In turn, agriculture (US$ 37.42 billion; n = 68) and forestry (US$ 14.0 billion; n = 20) were the most impacted sectors. Overall, we report burgeoning economic costs of invasions in Russia and identify major knowledge gaps, for example, concerning specific habitat types (i.e. aquatic) and management expenditures, as well as for numerous known invasive taxa with no reported economic costs (i.e. vertebrates). Given this massive, largely underestimated economic burden of invasions in Russia, our work is a call for improved reporting of costs nationally and internationally.

Abstract in Russian

Экономические потери от биологических инвазий в наземных экосистемах России. Наземные экосистемы в связи с наличием в них таких ключевых социально-экономических секторов, как сельское и лесное хозяйство, могут испытывать значительные экономические потери в результате биологических инвазий. В работе, основываясь на количественных показателях из недавно разработанной базы данных глобальных экономических потерь от биологических инвазий (InvaCost), проанализированы убытки от биологических инвазий в России – крупной (расположенной на двух континентах) и важной в экономическом плане стране. В 2007–2019 гг. величина ущерба в результате биологических инвазий в стране составила как минимум 51.52 млрд долларов США (1.38 трлн рублей, n = 94 позиции убытков), однако, подавляющее большинство оценок было основано на прогнозах или экстраполяциях (50.86 млрд долларов США; n = 87), требующих верификации. Оценки ущерба демонстрировали низкое географическое разрешение и в основном являлись обобщением прогнозных данных для европейской и азиатской частей страны (44.17 млрд долларов США; n = 72). Исключительно в европейской части России прогнозный экономический ущерб от биологических инвазий составил 7.35 млрд долларов США (n = 22). Экономические убытки в результате инвазий были задокументированы для 72 видов, большинство из которых – насекомые (37 видов). Фактический ущерб в сумме около 660 млн долларов США (n = 7) был связан только с четырьмя видами-инвайдерами: двумя видами насекомых, *Agrilus planipennis* Fairmaire и *Cydalima perspectalis* (Walker), и двумя видами растений, *Ambrosia artemisiifolia* L. и *Heracleum sosnowskyi* Manden. Подавляющее большинство убытков было связано с прямыми потерями при незначительных задокументированных расходах на борьбу с инвайдерами в наземных экосистемах. Сельское хозяйство (прогнозная оценка ущерба: 37.42 млрд долларов США; n = 68) и лесное хозяйство (прогнозная оценка ущерба: 14.0 млрд долларов США; n = 20) являлись наиболее пострадавшими секторами экономики. В целом мы сообщаем о росте экономических потерь, ассоциированных с биологическими инвазиями в России. Мы отмечаем наличие больших пробелов в знаниях об экономических потерях от биологических инвазий в других местообитаниях (в частности, в водных экосистемах), скудность оценок затрат на мониторинг, а также малочисленность или полное отсутствие сведений по экономическим потерям для целого спектра инвазионных видов (для позвоночных организмов). Учитывая крупные и все еще в значительной степени недооцененные экономические убытки, ассоциированные с биологическими инвазиями в России, наша работа призывает к улучшению отчетности по экономическим потерям на национальном и международном уровнях.

Abstract in German

Wirtschaftliche Kosten biologischer Invasionen in terrestrischen Ökosystemen in Russland. Terrestrische Ökosysteme können aufgrund des Vorhandenseins wichtiger sozioökonomischer Sektoren wie Land- und Forstwirtschaft durch biologische Invasionen besonders wirtschaftlich geschädigt werden. Die vorliegende Studie verwendet eine Teilmenge der kürzlich entwickelten Datenbank der globalen wirtschaftlichen Kosten biologischer Invasionen (InvaCost), um die monetären Kosten biologischer Invasionen in Russland, einer Wirtschafts die sich über zwei Kontinente erstreckt, zu quantifizieren. Von 2007 bis 2019 haben Invasionen die russische Wirtschaft mindestens 51.52 Milliarden US-Dollar gekostet (1.38 Billionen Rubel, n = 94 Kosten-Einträge), wobei die überwiegende Mehrheit dieser Kosten auf Vorhersagen oder Hochrechnungen basiert (50.86 Milliarden US-Dollar; n = 87) und daher nicht empirisch beobachtet wurden. Die meisten Kosten wiesen eine geringe geografische Auflösung auf und wurden zwischen europäischen und asiatischen Teilen Russlands aufgeteilt (44.17 Mrd. USD; n = 72). Nur 7.35 Milliarden US-Dollar (n = 22) wurden ausschließlich dem europäischen Teil und keiner dem asiatischen Teil zugerechnet. Die Kosten biologischer Invasionen wurden für 72 Arten und insbesondere für Insekten (37 Arten) dokumentiert. Die empirisch beobachteten Kosten, die sich auf 660 Mio. USD (n = 7) summierten, wurden nur für vier Arten angegeben: zwei Insekten *Agrilus planipennis* Fairmaire und *Cydalima Perspectalis* (Walker) sowie zwei Pflanzen *Ambrosia artemisiifolia* L. und *Heracleum sosnowskyi* Manden. Die überwiegende Mehrheit der wirtschaftlichen Kosten stand im Zusammenhang mit Schäden an Ressourcen und wirtschaftlichen Verlusten, wobei nur sehr geringe Ausgaben für die Bewältigung von Invasionen in terrestrische Ökosysteme gemeldet wurden. Die Landwirtschaft (37.42 Mrd. USD; n = 68) und die Forstwirtschaft (14.0 Mrd. USD; n = 20) waren wiederum die am stärksten betroffenen Sektoren. Insgesamt berichten wir über aufkeimende wirtschaftliche Kosten von Invasionen in Russland und identifizieren große Wissenslücken, beispielsweise in Bezug auf bestimmte Lebensraumtypen (d. H. Wasser) und Verwaltungsausgaben sowie für zahlreiche bekannte invasive Taxa ohne gemeldete wirtschaftliche Kosten (d. H. Wirbeltiere). Angesichts dieser massiven, weitgehend unterschätzten wirtschaftlichen Belastung durch Invasionen in Russland ist unsere Arbeit ein Aufruf zur verbesserten Berichterstattung über die Kosten im In- und Ausland.

Abstract in French

Coûts économiques des invasions biologiques dans les écosystèmes terrestres en Russie. Les écosystèmes terrestres peuvent être particulièrement endommagés économiquement par les invasions biologiques, notamment de part la présence de secteurs socio-économiques clés tels que l'agriculture et la foresterie. Cette étude utilise un sous-ensemble de la base de données récemment développée sur les coûts économiques mondiaux des invasions biologiques (InvaCost) pour quantifier les coûts monétaires des invasions biologiques en Russie, un pays à économie majeure qui s'étend sur deux continents. De 2007 à 2019, les invasions ont coûté à l'économie russe au moins 51.52 milliards USD (1.38 billion RUB, n = 94 entrées de coûts), la grande majorité de ces coûts étant basée sur des prévisions ou des extrapolations (50.86 milliards USD; n = 87) et, par conséquent, non observée empiriquement. La plupart des entrées de coût présentaient une faible résolution géographique, étant réparties entre les parties européennes et asiatiques de la Russie (44.17 milliards USD; n = 72). Seuls 7.35 milliards USD (n = 22) ont été attribués à la partie européenne uniquement et aucun à la partie asiatique. Les coûts d'invasion ont été documentés pour 72 espèces et en particulier les insectes (37 espèces). Les coûts observés empiriquement, totalisant 660 millions USD (n = 7), n'ont été rapportés que pour quatre espèces: deux insectes *Agrilus planipennis Fairmaire* et *Cydalima perspectalis* (Walker) et deux plantes *Ambrosia artemisiifolia L.* et *Heracleum sosnowskyi Manden*. La grande majorité des coûts économiques étaient liés aux dommages aux ressources et aux pertes économiques, avec très peu de dépenses déclarées pour la gestion des invasions dans les écosystèmes terrestres. L'agriculture (37.42 milliards USD; n = 68) et la foresterie (14.0 milliards USD; n = 20) ont été les secteurs les plus touchés. Dans l'ensemble, nous rapportons les coûts économiques croissants des invasions en Russie et identifions les principales lacunes dans les connaissances, par exemple, concernant des types d'habitats spécifiques (c.-à-d. Aquatiques) et des dépenses de gestion, ainsi que pour de nombreux taxons invasifs connus sans coûts économiques déclarés (c.-à-d. les vertébrés). Compte tenu de ce poids économique massif et largement sous-estimé des invasions en Russie, notre travail est un appel à une meilleure communication des coûts aux niveaux national et international.

Abstract in Spanish

Los costos económicos de las invasiones biológicas en los ecosistemas terrestres de Russia. Los ecosistemas terrestres, debido a la presencia de sectores socio-económicos clave, como la agricultura o la silvicultura, pueden verse particularmente dañados por las invasiones biológicas a nivel económico. Este estudio utiliza la base de datos InvaCost, desarrollada recientemente para cuantificar los costes monetarios de las invasiones biológicas a nivel global, extrayendo el subconjunto de datos correspondiente a Rusia, un país con una economía importante que se extiende por dos continentes. Desde 2007 hasta 2019, las invasiones han costado a la economía Rusa al menos 51.52 mil millones de dólares americanos (RUB 1.38 billones, n = 94 entradas de costos); la mayoría de los costos estuvieron basados en predicciones o extrapolaciones (50.86 mil millones de dólares; n = 87) y por lo tanto no fueron empíricamente observados. La mayoría de las entradas de costos tuvieron una baja resolución geográfica, ocupando ambos continentes, Europa y Asia (44.17 mil millones de dólares; n = 72). Sólamente 7.35 mil millones de dólares (n = 22) fueron asignados a la parte Europea, pero ninguno fue atribuido únicamente a la parte Rusa. Los costos de las invasiones fueron documentados para 72 especies y particularmente para insectos (37 especies). Los costos empíricamente observados alcanzaron los 660 millones de dólares (n = 7), y fueron reportados para tan sólo 4 especies: dos insectos, *Agrilus planipennis* Fairmaire y *Cydalima perspectalis* (Walker), y dos plantas, *Ambrosia artemisiifolia* L. y *Heracleum sosnowskyi* Manden. La mayoría de los costos económicos estuvieron en relación con daños y pérdidas económicas, mientras que se reportaron mucho menos los gastos para manejar las invasiones en los ecosistemas terrestres. Por su parte, la agricultura (37.42 mil millones de dólares; n = 68) y la silvicultura (14.0 mil millones de dólares; n = 20) fueron los sectores económicos más impactados. En general, mostramos los crecientes costos económicos de las invasiones en Rusia e identificamos las principales lagunas del conocimiento, por ejemplo, en relación con los gastos de manejo, o con hábitat específicos (como el medio acuático), así como con numerosos taxones reconocidos como invasores pero sin datos económicos (como los vertebrados). Dada esta carga económica masiva de las invasiones en Rusia, en gran parte subestimada, nuestro trabajo hace un llamamiento para mejorar el reporte de los costos económicos tanto a nivel nacional como internacional.

Keywords

Direct and indirect losses, insects, InvaCost, invasive species, pathogens, Russian Federation, weeds

Introduction

Biological invasions are recognised as a global threat to biodiversity, ecosystem functioning and economic development worldwide (Elliott 2003; Kovac et al. 2010; Bradshaw et al. 2016; Seebens et al. 2018). Globalisation and ongoing environmental changes (i.e. climate change and habitat alteration) have accelerated the introduction of invasive species at an unparalleled rate, leading to the circumvention of historic biogeographical barriers by many species (Maslyakov and Izhevskii 2011; Seebens et al. 2017).

Terrestrial ecosystems are known to experience severe impacts from invasive species (Stephens et al. 2019). Terrestrial invaders can disrupt the structuring and functioning of ecosystems (Holmes et al. 2009; Roques 2010; Aukema et al. 2011; David et al. 2017; Eyre et al. 2017; Kirichenko et al. 2019). Phytophagous insects and phytopathogens are amongst the most diverse and notorious invaders, causing noteworthy damage to their host plants (up to their extirpation from large areas), leading to crop harm and further irreparable economical losses (Lockwood et al. 2013; Paini et al. 2016; Musolin et al. 2018). Whilst invasions can cause significant changes in ecosystems that, in turn, lead to massive economic losses (Pimentel 2005; Aukema et al. 2011; Lockwood et al. 2013; Diagne et al. 2021), the severity of these economic impacts remains unquantified at many geographic scales where policy decisions are made.

Russia, transcontinentally located in Eastern Europe and Northern Asia, is the largest country in the world. It covers a territory of more than 17 million km^2, i.e. about 1/8 of the Earth's land surface (Borodko 2020). The country is globally known as a major exporter of natural resources, increasing connectivity to various nations and geographical regions (Bradshaw and Connolly 2016). It possesses the largest natural forests in the world, predominated by coniferous species (boreal forest, or taiga) (FAO 2012). Furthermore, Russia has a well-developed agricultural sector, which significantly contributes to the world's crop production (Liefert and Liefert 2020). By nominal gross domestic product, Russia has the 11^{th} largest economy in the world and the 6^{th} largest by purchasing power parity (World Bank 2020). Both these market values are known to be associated with invasion risk (Haubrock et al. 2021c; Kourantidou et al. 2021). Indeed, these extensive commerce and goods exchanges within and outside of the country have facilitated the introduction of invasive species, especially pests of plants, phytopathogens and weeds (Maslyakov and Izhevsky 2011; Izhevsky 2013; Ebel et al. 2016; Orlova-Bienkowskaja 2016; Karpun 2019).

Russian national literature provides extensive ecological data on the threats posed by invasive organisms to terrestrial ecosystems, in particular to forestry and agriculture. Dgebuadze et al. (2018) overviewed the biology, distribution and ecological impacts of the top 100 invasive species in Russia, i.e. the most ecologically impactful, amongst which 60% (mainly plants and insects) are affecting agriculture, forestry and urbanised ecosystems. Vinogradova et al. (2009) and Ebel et al. (2016) compiled the Black Books of invasive flora by gathering together data on diversity, primary and secondary ranges and ecological hazards of invasive plants aggressively spreading in European and Asian Russia. Kuznetsov (2005) provided the list of invasive insects and discussed their impact on the terrestrial ecosystems of easternmost Russia. More recently, Orlova-Bienkowskaja (2016) analysed the threat of invasive beetles to agriculture and forestry in European Russia, whilst Karpun (2019) focused on invasive insects causing damage to the subtropical area of the country. Baranchikov et al. (2008) and Orlova-Bienkowskaja (2014) studied the threat posed by the invasive emerald ash borer *Agrilus planipennis* (Coleoptera: Buprestidae) to ash species (*Fraxinus* spp.) in European Russia, whereas Baranchikov et al. (2011), Kerchev and Krivets (2012) and Debkov et al. (2019) estimated the ecological impact of the far eastern four-eyed fir bark beetle

Polygraphus proximus Blandford that invaded Siberia. Within the group of phytophagous insects solely, around 200 invasive species are presently known in Russia, largely in its European part (Maslyakov and Izhevsky 2011). Amongst them, a number of notorious insect pests attacking woody and herbaceous plants in forests and orchards, as well as different crops in agricultural fields have been documented in the country in the last few decades (Maslyakov and Izhevsky 2011). Despite diverse ecological studies on invasive organisms in Russia, there are few published data on economic costs associated with invasions of arthropods, phytopathogens and weeds, even on species being of economic significance in the country.

In this regard, the present paper is the first attempt to gather together data on economic losses due to biological invasions to estimate the overall costs of invasive species in terrestrial ecosystems in Russia. Specifically, it aims to define the distribution of those costs amongst taxa and economic sectors, as well as temporal trends in their development. Using data retrieved from federal sources, mainly from official pest risk assessment reports and publicly available research papers, as compiled in the InvaCost database (Diagne et al. 2020b), we synthesised the current data on actual and potential costs of invasive organisms that have recorded monetary impacts on terrestrial ecosystems in Russia. Given the increasing number of invasions documented in the country (Maslyakov and Izhevsky 2011; Orlova-Bienkowskaja 2016; Karpun 2019), we suspect an increase in overall costs associated with actual and potential invaders and, in particular, arthropods, phytopathogens and plants in terrestrial ecosystems over time, given they have been most intensively studied. We also expect a remarkable economic loss primarily due to resource damage from invasive arthropods, in particular insects, given that those invasion cases have been recorded widely in the country, both in its European and Asian parts (Maslyakov and Izhevsky 2011; Orlova-Bienkowskaja 2016; Karpun 2019), and that the group is known to be costly globally (Bradshaw et al. 2016). Moreover, we examined the compositions of costs in terms of reliability of monetary sources and whether they are based on extrapolations or empirical observations.

Methods

Data collection, filtering and standardisation

To describe the costs of biological invasions in Russia, we used cost data collected in the InvaCost database v.1.0 (2,419 entries; Diagne et al. 2020b; data link: https://doi.org/10.6084/m9.figshare.11627406). This database was complemented following two specific ways: by adding cost data collected globally from non-English documents (5,212 entries; Angulo et al. 2021b; https://doi.org/10.6084/m9.figshare.12928136) and by including costs from complementary database (ca. 2,300 entries; https://doi.org/10.6084/m9.figshare.12928145). An updated version of each of these databases is now incorporated within the core InvaCost Database (https://doi.org/10.6084/m9.figshare.12668570). The majority of recorded cost data of invasive species (i.e. cost entries, indicated as "n" in the paper) in Russia were obtained from pest risk analysis reports of the All-Russian Plant Quarantine Center (VNIIKR, Bykovo, Moscow Oblast). These data cover both categories of actual and potential invaders (often having quarantine status in the country) that have a threat to plants, especially in forestry and/or agriculture. According to the legislation of the Russian Federation in plant quarantine, the quarantine organism/agent is a species that is so far absent but has a risk of introduction, or a species that already invaded but still has a limited distribution in the territory of the country and that may significantly impact plants, resulting in economic losses (On Plant Quarantine 2014). Cost entries provided in national currency were converted to US$, based on the 2017 value (Diagne et al. 2020b). Altogether, we extracted all costs (accounting for 94 entries) related to Russia for the purpose of our analyses by filtering the "Country" column to include "Russia". The extracted dataset is provided in Suppl. material 1: Fig. S1.

Cost analyses

The analysis of costs from the InvaCost database was performed using the invacost R package v0.2-4 (Leroy et al. 2020) in R v4.0.2 (R Core Team 2019). Using the filtered data, the total invasion costs were examined according to different descriptive columns of the database (see Diagne et al. 2020b for further details):

1. Method reliability: illustrating the perceived reliability of cost estimates, based on the type of publication and method of estimation;
2. Implementation: referring to whether the cost estimate was actually realised (observed) or whether it was expected (potential);
3. Taxonomic grouping: the kingdom, class, order and species from which the cost emanated. Here, we refer to the organisms from the kingdoms: Animalia, Plantae, Fungi, and Bacteria. Nomenclature of viruses is independent of other biological nomenclature (ICTV Code 2020), with nine kingdoms defined (Virus Taxonomy 2020). For simplicity, we do not list virus kingdoms in the study but rather operate the general term "viruses".

In Animalia, as an exception, besides costs of actual and potential invaders, our study also analysed impacts of six native longhorn beetles: *Monochamus galloprovincialis*, *M. impluviatus*, *M. nitens*, *M. saltuarius*, *M. sutor*, and *M. urussovi* (Coleoptera: Cerambycidae). Distributed in some parts of Russia, they are subjected to national quarantine control because they are considered vectors of a potentially-invasive pine wood nematode, *Bursaphelenchus xylophilus* (Steiner et Buhrer) Nickle (Aphelenchida: Parasitaphelenchidae). To avoid counting native species, these beetles, represented in InvaCost database by 14 entries (cost IDs: NE4445–NE4456, NE4474 and NE4475; Suppl. material 1: Fig. S1), were excluded from the analysis and their potential economic losses were summarised and attributed to the pine wood nematode, the species that was counted in the analysis of taxonomic groups. That is because control actions for the species aim to manage the vectoring of pine wood nematode, rather than control the native species per se. On the contrary, the cost of the North American *Monochamus scutellatus* (Say) (cost ID NE4434 in Suppl. material 1: Fig. S1) was not attributed to the nematode. This non-native species may directly affect wood by boring holes and it also has a potential to distribute the nematode (Akbulut and Stamps 2020). As such, *M. scutellatus* is itself considered as being potentially invasive to Russia and was counted in the study accordingly.

4. Type of cost: grouping of categories of cost types into: (1) "Damage-Loss" referring to damages or losses incurred by invasion (i.e. costs for damage repair, resource losses, medical care), (2) "Management" comprising control-related expenditure (i.e. monitoring, prevention, eradication) and (3) "General" including mixed damage-loss and control costs (cases where reported costs were not clearly distinguished);
5. Impacted sector: the activity, societal or market sector that was impacted by the invasive species (Suppl. material 1: Fig. S1).

We also analysed the dynamics of cost reporting for the period from 2007 to 2019, given this is the range of years from which invasion costs were available for Russia in serveyed sources. We estimated the absolute and average annual costs of invaders reported in this period in Russia and the number of cost entries represented in the InvaCost database and quantified the temporal trends in accumulations of these indicators. The data entries were assigned to the year mentioned in the original source (if a single year was mentioned), to the most recent year (if a period of years was mentioned) or to the year of publication (if the year was not assigned to the cost).

In addition, we ranked all species involved in the study according to their costs (descending ranking) to show the distribution of costs across taxa. We also classified species by their quarantine status in Russia (i.e. whether they are assigned to quarantine or non-quarantine species in the country) and estimated their costs according to these groups and the taxonomic kingdom. Information on the quarantine status of species was found in legislation documents (On approval 2014, 2019). Data on quarantine status of species is given in Suppl. material 2: Tables S1.

Results

Economic costs in European and Asian Russia

The 94 invasion cost entries for Russia totalled at US$ 51.52 billion between 2007 and 2019, which was equivalent to around RUB 1.38 trillion (Suppl. material 1: Fig. S1). From these, all recorded entries were of high reliability, based on pest risk analyses and approved estimation methods (Suppl. material 1: Fig. S1). However, just 1.3% of the total costs were empirically observed (US$ 660 million; n = 7), whereas the remaining potential costs were largely based on extrapolations (US$ 50.86 billion; n = 87). Whilst

Russia spans substantial parts of continental Europe and Asia, the majority of costs were associated with both macro-regions (US$ 44.17 billion; n = 72), while US$ 7.35 billion (n = 22) was associated solely with the European part. No costs were attributed to the Asian part exclusively.

Taxonomic grouping

Overall, the 94 cost entries analysed in the study corresponded to 77 species. We reclassified the costs of six native longhorn beetle species of the genus *Monochamus*, attributing them instead to the potentially-invasive pine wood nematode. These insect species (and their 14 entries) were not counted in taxonomic grouping analysis, but instead a single entry for the pine wood nematode was taken into account. Thus, the resultant overall invasive species number, included into the analysis, was 72 (represented by 81 entries). Amongst them, insects were the leading group (37 species, 51%), followed by plants (9 species, 13%), fungi and viruses (8 species, 11% each) and bacteria (7 species, 10%) (Fig. 1). Nematodes and mites were represented by 2 (3%) and 1 (1%) species each (Fig. 1). Across insects, beetles (Coleoptera) and moths (Lepidoptera) were the most represented groups (23 species overall, i.e. 32% of all species in the study).

Quarantine vs. non-quarantine species

Amongst the 72 analysed species, 61 species (84.7%) have a quarantine status in Russia (i.e. are predicted to invade to the country from abroad, already have a limited present extent in Russia or serve vectors of potentially-invasive species). The majority of those species (i.e. 33 species) are from Animalia, followed by the representatives from Plantae and viruses (eight species each), Bacteria and Fungi (six species each). The remaining 11 species have no quarantine status in Russia, with seven species from Animalia, two species from Fungi and one species each from Bacteria and Plantae. The data on the quarantine status of the species in Russia, species origin and cost of their invasions are given in Suppl. material 2: Table S1.

Overall, species with a quarantine status accounted for US$ 50.64 billion (98.3% of all economic losses) (Table 1). Amongst organisms with quarantine status, there were in total 18 species, i.e. 16 species that already invaded Russia from abroad (they accounted for US$ 8.41 billion, i.e. 16.3%) and two national invaders that moved to the western part of the country from the eastern part (the emerald ash borer *A. planipennis* and the San Jose scale *Quadraspidiotus perniciosus* Comstock). The latter two species accounted for US$ 1.12 billion (2.2%). The potential losses from other species that are predicted to invade Russia and, thus, subjected to quarantine control there (43 species in the analysed dataset), accounted for US$ 41.11 billion (Suppl. material 2: Table S1), i.e. about four times greater than the cost of 18 quarantine invasive species. Amongst quarantine species, the potentially invasive pine wood nematode was the most costly organism, at US$ 13.93 billion (i.e. 27.5% of economic losses across quarantine organisms in Russia).

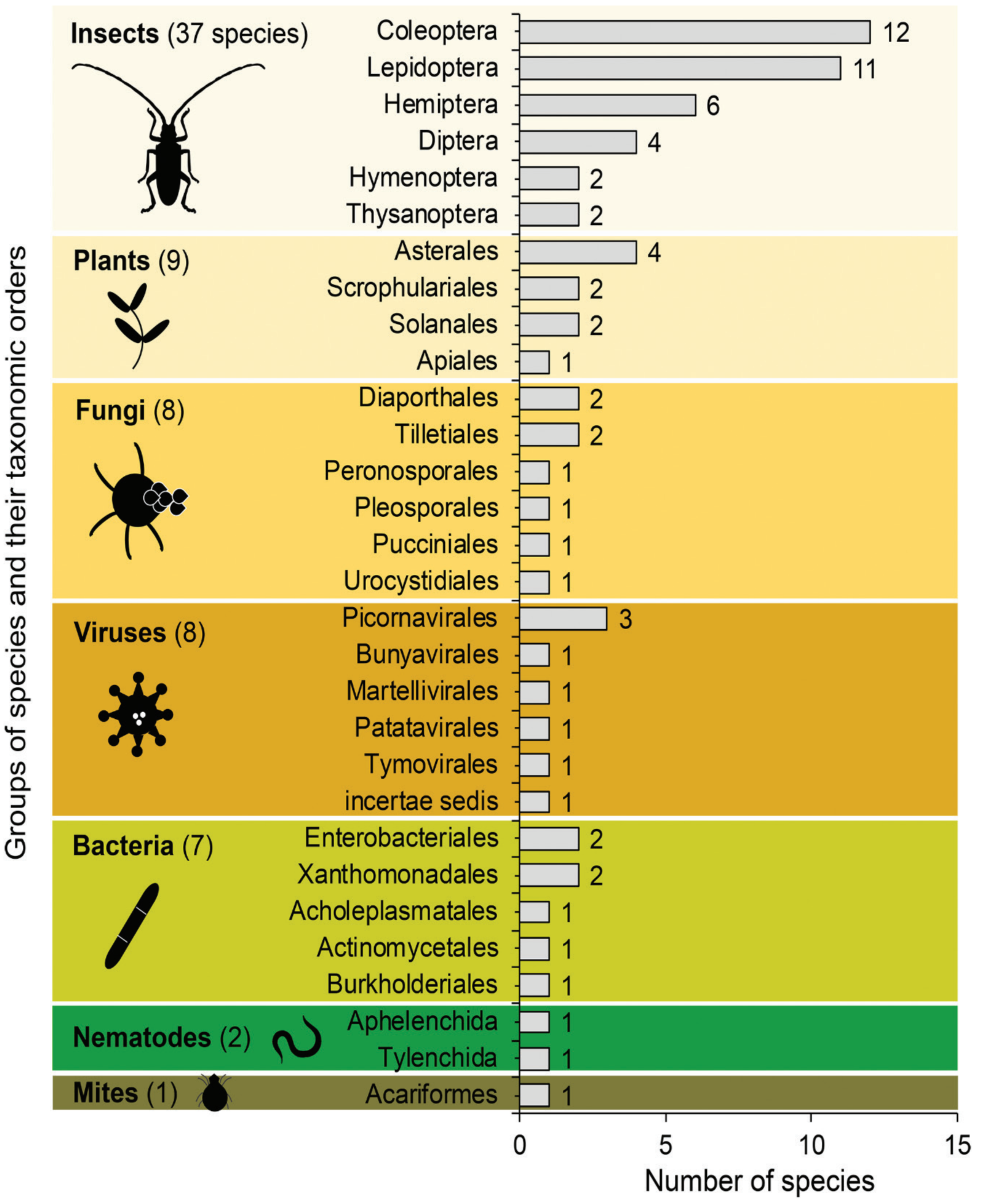

Figure 1. Number of species with estimated economic costs across respective taxonomic groups in Russia.

Non-quarantine species accounted for just US$ 0.88 billion (1.7% of all economic losses), that is around 58 times less than the cost of quarantine species. Amongst them, there are two insects, namely, *Cydalima perspectalis* and the lime leaf-miner *Phyllonorycter issikii* (Kumata) (Lepidoptera: Gracillariidae), the plant *H. sosnowskyi* and the fungal pathogen *Diaporthe helianthi* Munt.-Cvet. et al. (Diaporthales: Diaporthaceae), with those economic losses comprising US$ 0.60 billion (Suppl.

Table 1. Economic costs of quarantine and non-quarantine species in Russia*.

Species category	Number of species	Cost, US$ billion	Proportion in total cost, %
Quarantine species			
Invaded Russia from abroad	16	8.41	16.3
National invaders	2	1.12	2.2
Predicted to invade Russia	43	41.11	79.81
Non-quarantine species			
Invaded Russia	4	0.60	1.2
Predicted to invade Russia	7	0.28	0.5
Overall for quarantine species	**61**	**50.64**	**98.3**
Overall for non-quarantine species	**11**	**0.88**	**1.7**
TOTAL		**51.52**	**100**

*Data by species is provided in Suppl. material 2: Table S1.

material 2: Table S1). The remaining US$ 0.28 billion is due to seven potentially-invasive organisms (four insects, one mite, one bacterium, one fungal pathogen) (Suppl. material 2: Table S1).

Costs per taxonomic group

Overall, costs associated with invasive species from the Animalia kingdom dominated (US$ 31.48 billion; n = 46 entries), followed by Plantae (US$ 11.28 billion; n = 12), Fungi (US$ 4.46 billion; n = 8), viruses (US$ 2.94 billion; n = 8) and, lastly, Bacteria (US$ 1.36 billion; n = 7) (Fig. 2).

Amongst animals, the costs of invasions by insects represented the largest part (US$ 16.44 billion, n = 43). The proportion of other animals made US$ 15.01 billion for nematodes (n = 2) and US$ 0.02 billion for mites (n = 1). The total cost for the nematodes comprised that of the potentially-invasive pine wood nematode *B. xylophilus* (US$ 13.93 billion) and the Columbia root-knot nematode *Meloidogyne chitwoodi* Golden, O'Bannon, Santo & Finley, the agricultural crop pest (US$ 1.08 billion).

Amongst the costliest top-3 species, there were two representatives of Animalia (one nematode and one insect) and one representative of Plantae (herb). Of them, the most costly species was the potentially-invasive pine wood nematode *B. xylophilus* (Suppl. material 2: Table S1). The other two invasive species were the 28-spotted potato ladybird *Henosepilachna vigintioctopunctata* Fabricius (Coleoptera: Coccinellidae) and black-jack *Bidens pilosa* L. (Asterales: Asteraceae), with the potential damage from each estimated at around US$ 4.31 and 4.07 billion, respectively (Suppl. material 2: Table S1). Altogether, the contribution of these top-3 species to the economic losses of the country accounted for US$ 22.32 billion, i.e. 43% of costs of all species covered by the study. The species with the lowest reported cost was the potentially-invasive North American longhorn beetle, *Monochamus scutellatus*, accounting for US$ 0.015 million (Suppl. material 2: Table S1).

The distribution of costs across species was skewed, with just a few species causing high economic impacts (> US$ 1 billion) and most with a substantially lower economic impact (Fig. 3). Indeed, few individual species, i.e. 15 out of 72 (20.8%), exhibited

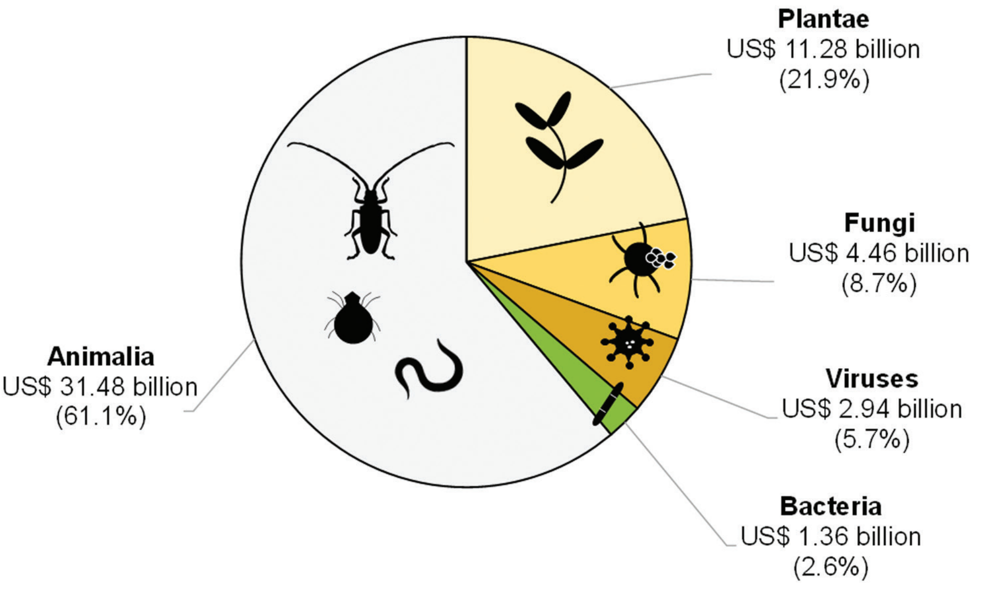

Figure 2. Distribution of economic costs across different taxonomic kingdoms in Russia, in US$ billion. For viruses, the kingdoms are not indicated and, thus, all species are treated under the general term "viruses".

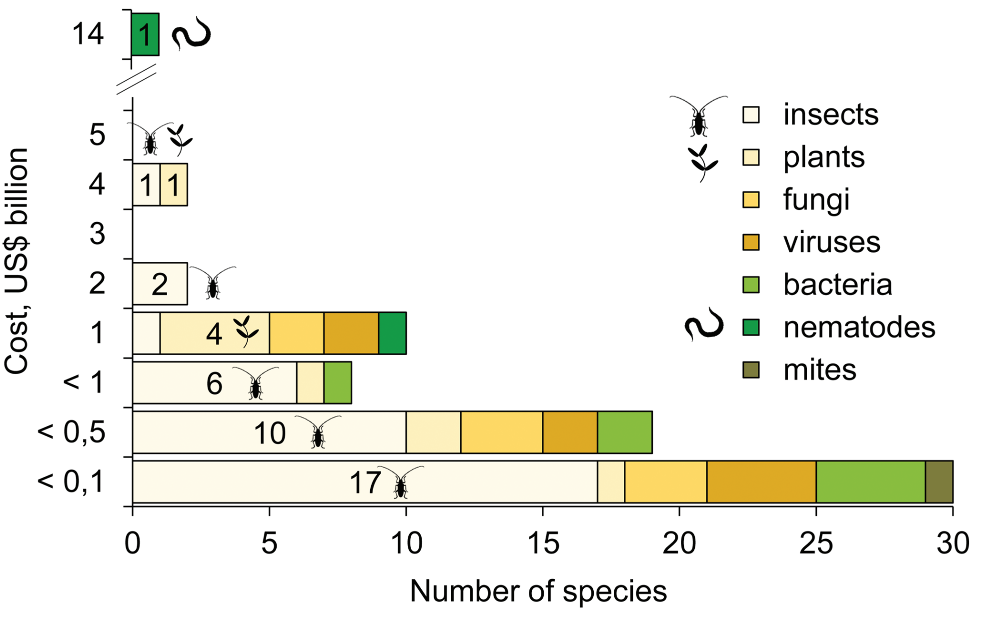

Figure 3. The ranked economic costs in different taxonomic groups of invasive species in Russia. The group with the highest number of species is indicated within each cost category (additionally marked by the respective organism pictogram).

costs greater than US$ 1 billion (Fig. 3). Conversely, twice as many species, i.e. 30 out of 72 (41.6%; amongst which, 17 species are insects), led each to an economic loss of at least a magnitude lower (Fig. 3).

Table 2. Actual losses (observed costs) in different sectors due to invasions of insect pests and weeds in Russia.

Impacted sector	Kingdom	Order	Species	Cost, US$ million
Agriculture	Plantae	Asterales	*Ambrosia artemisiifolia*	307.9
Forestry	Animalia	Coleoptera	*Agrilus planipennis*	258.9
Health	Plantae	Asterales	*A. artemisiifolia*	90.6
Public and social welfare	Animalia	Lepidoptera	*Cydalima perspectalis*	1.1
Environment	Animalia	Lepidoptera	*C. perspectalis*	0.9
Authorities-Stakeholders	Plantae	Apiales	*Heracleum sosnowskyi*	0.6
TOTAL				**660.0**

While several species contributed to the list of costly invasive species with extrapolated economic losses, only four species (two insects and two plants) remained when focusing on only observed costs (Table 2; Fig. 4). Amongst them, there were two weeds: common ragweed *A. artemisiifolia* (Asterales: Asteraceae) and Sosnowsky's hogweed *H. sosnowskyi* (Apiales: Apiaceae), those actual economic losses altogether reached around US$ 400 million in the years 2011 and 2015. The other two species were phytophagous insect pests, the emerald ash borer *A. planipennis* and the box-tree moth *C. perspectalis*, those observed costs amounting to around US$ 260 million during the period of 2011–2016 (Table 2).

Impacted sectors

The majority (97%) of the total inferred costs of US$ 51.52 billion were categorised as damage-losses in the terrestrial environment. Impacted sectors were diverse, with agriculture being the most heavily impacted sector (US$ 37.42 billion; n = 68 entries), followed by forestry (US$ 14.0 billion; n = 20). Costs inferred to health (US$ 91.92 million; n = 2), public and social welfare (US$ 1.1 million; n = 1), the environment (US$ 944.3 thousand; n = 1), authorities and stakeholders (US$ 706.7 thousand; n = 2) were of a lower magnitude (Fig. 5). The contribution of different invasive species classed to the above-mentioned sectors can be found in Suppl. material 1: Fig. S1.

Overall, 46% of all losses in agriculture (US$ 17.22 billion) were caused by Animalia, followed by Plantae (30%, US$ 11.19 billion); the contribution of phytopathogens accounted overall for 24% (US$ 8.76 billion). In total cost analysis, forestry was solely impacted by Animalia (in particular by insects and nematodes). Other sectors (health, public and social welfare, authorities and stakeholders) were affected by Plantae (herbaceous weeds), overall accounting for US$ 92.99 million, whereas the environment sector had losses due to insects solely (US$ 944.3 thousand).

Similar to the total costs, the observed costs were the highest in the agricultural sector (US$ 307.9 million; n = 1), followed closely by those in forestry (US$ 258.9 million; n = 1), health (US$ 90.6 million; n = 2), public and social welfare (US$ 1.1 million; n = 1), the environment (US$ 0.9 million; n = 1), the authorities and stakeholder sectors (US$ 0.6 million; n = 1) (full data are given in Suppl. material 1: Fig. S1). The observed costs were driven entirely by insect and plant species (Table 2).

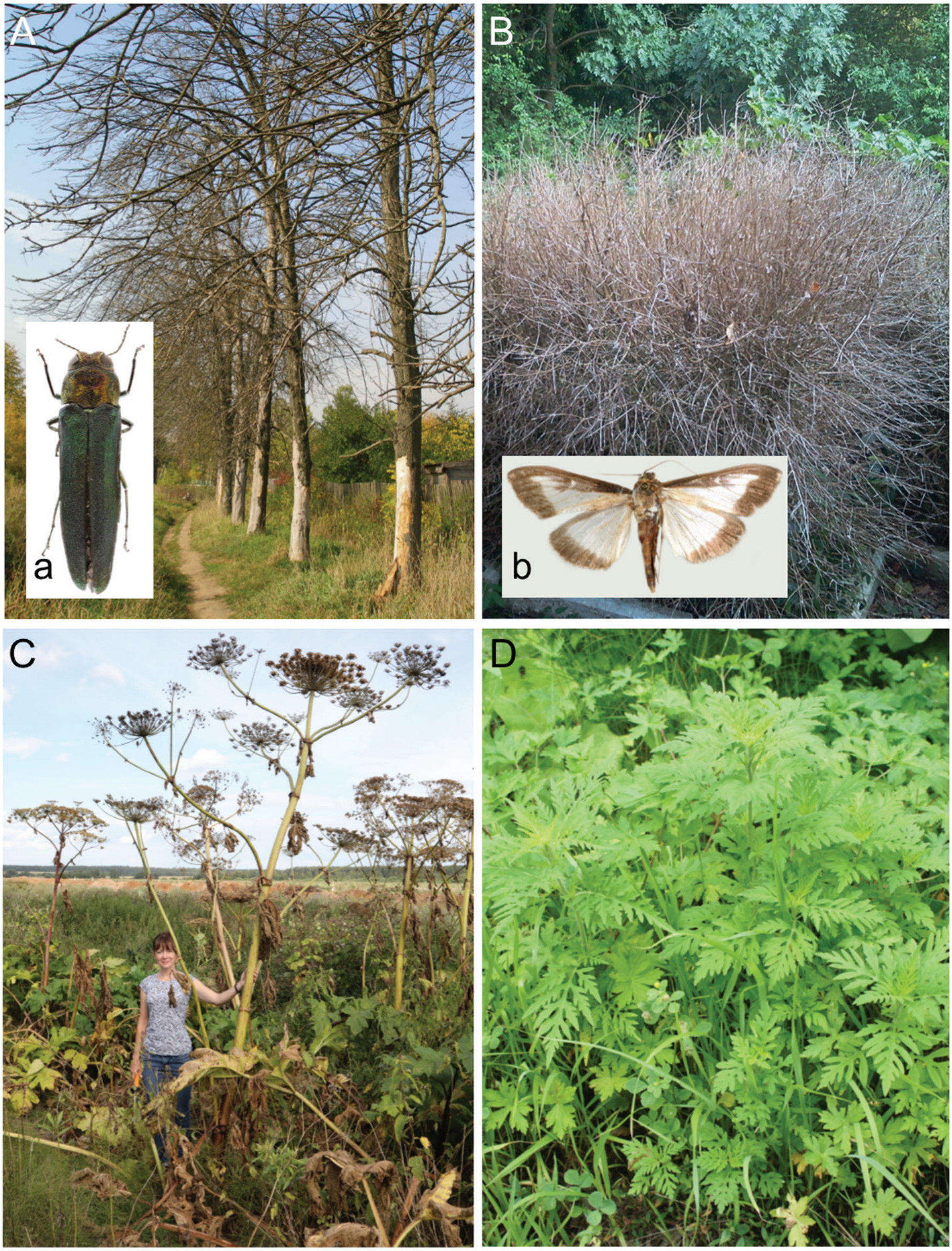

Figure 4. Four notorious invasive species with observed costs in Russia **A** the emerald ash borer *Agrilus planipennis* and associated dead trees of *Fraxinus pennsylvanica* **B** the box-tree moth *Cydalima perspectalis* and associated dead bushes of *Buxus sempervirens* **C** Sosnowsky's hogweed *Heracleum sosnowskyi* invading an agricultural field **D** common ragweed *Ambrosia artemisiifolia* in the forest canopy. **A–C** Moscow Oblast (**B** an experimental trial) **D** Primorsky Krai. Photos taken by **A, B** V. Ponomarev **C** V. Kulakov (the photo is published with the permission from the photographed person) **D** N. Kirichenko **a, b** D. Kasatkin.

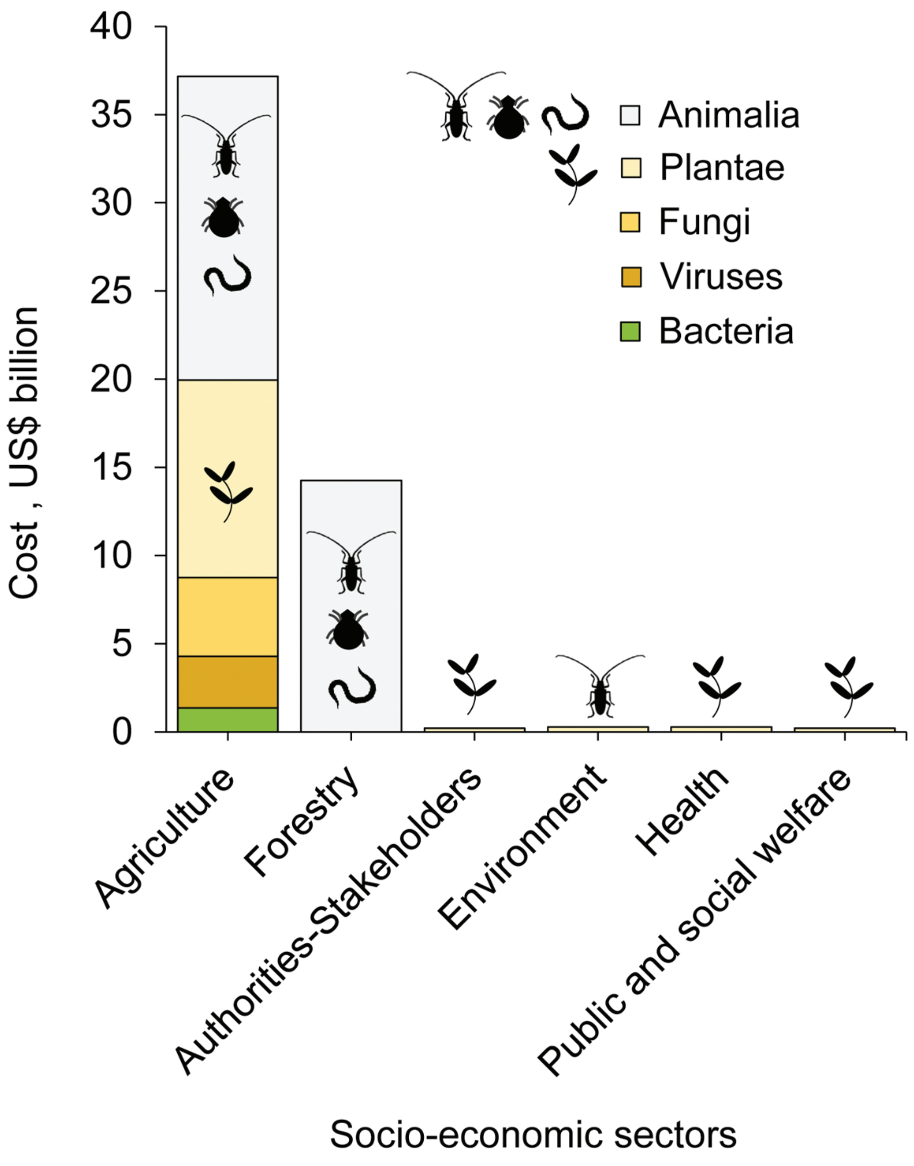

Figure 5. Total economic costs related to socio-economic sectors in Russia according to taxonomic kingdoms. The dominant groups of organisms in different socio-economic sectors are additionally marked by the respective organism pictogram.

Cost dynamics

Reported invasion costs averaged US$ 3.96 ± 3.03 billion per year (2007–2019) when considering all costs (Fig. 6A) and US$ 110.2 million per year (2011–2016) when considering only observed costs (not shown). The reported costs (analysed in absolute

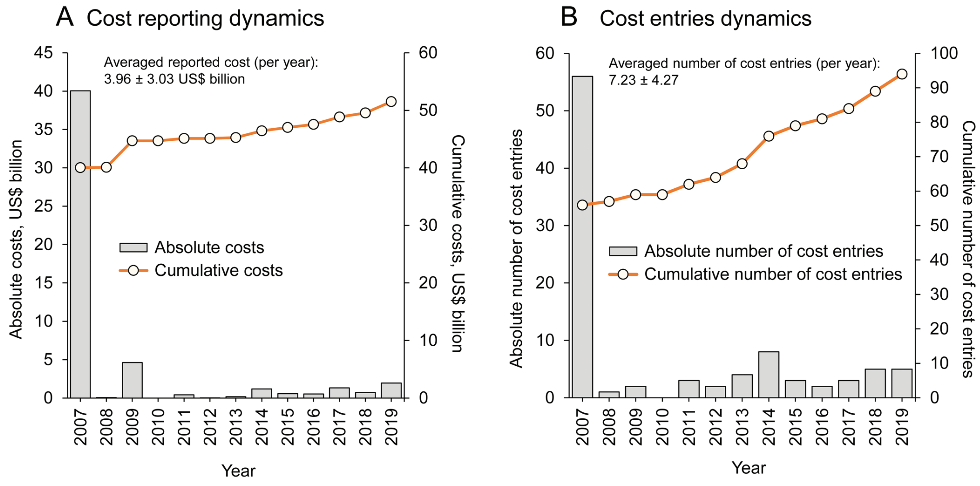

Figure 6. Temporal trends in the cost reporting (**A**) and in the number of cost entries (**B**) in Russia in 2007–2019. In both cases, the cumulative trends are additionally computed.

values) displayed a pronounced peak in 2007 (US$ 40.04 billion), followed by fluctuation from US$ 0.05 billion to US$ 1.96 billion in the period 2008–2019 (Fig. 6A). Fluctuations in dynamics were also observed when considering the total number of cost entries, with a pronounced peak in 2007 (56 entries), followed by a decrease and unstable dynamics in the following years (i.e. from 0 to 8 entries per year) (Fig. 6B). As such, it was reflecting the transition in the methodology used for assessing invasion costs in Russia after 2007, but also potentially indicating a time lag in cost reporting in the following years (see Discussion). The cumulative curves showed just a slight increase in both cases (Fig. 6A and B). No particular trend was defined when analysing the observed costs (not shown).

Discussion

Our study summarised, for the first time, the recorded economic costs of invasive species in Russia from 2007 to 2019 and showed that they amounted to a total of US$ 51.52 billion. In particular, it analysed actual and potential economic losses associated with 72 species of insects, mites, nematodes, phytopathogens and weeds, of which the majority (i.e. 85%) has a quarantine status in Russia, i.e. is subjected to federal phytosanitary control (Suppl. material 2: Tables S1). For those species, monetary data were available in pest risk assessment reports and scarce national publications, accessible online.

Despite being based on a representative number of cost entries for different taxa, it should be understood that our results do not reflect the total monetary losses associated with terrestrial invasions in Russia for the studied period, 2007–2019. In general in Russia, there are very few studies estimating resource damage and losses associated with invasive and quarantine organisms in monetary terms (Magomedov et al. 2013; Gninenko et al. 2016; Dalke et al. 2018). Further, there are hardly any publicly-available data on costs attributed to management expenditure, despite the potential cost-effectiveness of early preventative measures for invasions compared to longer term approaches (Leung et al. 2002; Ahmed et al. 2021). For those reasons, the estimates presented in this study can be considered as being very conservative.

The structure of economic costs reported here largely reflects taxonomic interests of the All-Russian Plant Quarantine Center related to the range of species posing phytosanitary risks, given that those data served as a main source for the present analysis. Thus, our study largely focuses on species (invertebrates, phytopahogens and plants) affecting the key socio-economic sectors of agriculture and forestry, but is lacking analyses of other terrestrial organisms (such as vertebrates). Those economic losses have been seldom reported in national literature (Fokin and Airapetyants 2004), despite known ecological impacts, in particular caused by mammals (Bobrov et al. 2008; Khlyap et al. 2008). Moreover, our study did not include aquatic invasive species in Russia, simply because hardly any data on economic losses associated with those organisms are available in Russian literature (Dgebuadze et al. 2018). Despite all these limitations, our study still shows that expenditures associated with terrestrial invaders and their monetary impacts to different sectors are very important in Russia and suggests they also might be important where data are missing.

Surprisingly, our analysis of recorded costs did not show a clear increase in overall costs associated with invasive species over time. This is despite a pronounced increase in global invasion rates worldwide across taxonomic groups (Seebens et al. 2017), with invasions projected to increase markedly in the coming decades (Seebens et al. 2020), as well as increasing invasion costs at the global scale (Diagne et al. 2021; Cuthbert et al. 2021b). The main explanation is that the monetary estimates have been published not in all pest risk analysis reports for organisms subjected to such analysis in Russia. Overall, in the country pest risk analysis is based on an integrative approach to define phytosanitary risks of invasive species by computing an integral index (Orlinski 2006). This index takes into account expert opinions regarding the probability of different risks (including economic) associated with invasive species and is expressed in quantitative units (Analysis of Phytosanitary Risk 2018). This, therefore, can bias our results temporally, as for the latest years we failed to extract monetary data for a number of species from pest risk analysis reports. Further, in 2008–2019, we observed significant fluctuations of costs reporting, i.e. the increase in 2009 followed by the decrease in 2010 and subsequent unstable dynamics in the following years, that overall, may indicate a time lag in cost reporting in the country.

Thus, whilst biological invasions have been a major element of global change for many recent decades (Seebens et al. 2017; Elton 2020), costs are available in Russia for only around the last two decades (Magomedov et al. 2013), further narrowing the temporal scale of our study. In turn, the lack of reported observed costs in Russia may further negate comprehensive appraisals of temporal trends in economic costs, whereas the extrapolated costs, which dominated, may potentially be more sporadic over time. In contrast to other countries within the database which are predominantly English-speaking (e.g. Bradshaw et al. 2021; Cuthbert et al. 2021a; Crystal-Ornelas et al. 2021), cost entries for the Russian economy mainly originated from non-English sources rather than from English scientific publications (Diagne et al. 2020b). This further indicates the value in considering non-English materials to improve the comprehensiveness of literature syntheses (Angulo et al. 2021b).

In accordance with our expectation, economic losses in Russia were primarily driven by invasive arthropods, in particular insects. We showed that records for insects accounted for US$ 16.44 billion, i.e. 32% of total economic losses associated with invasive species involved in the study. Indeed, it was the most diverse group of invasive species with reported costs in our study and this group is regularly documented as invasive in Russia (Maslyakov and Izhevsky 2011). This group is ecologically very plastic, having great potential to invade new regions and adapt to ongoing global changes (Garnas et al. 2016; Deutsch et al. 2018; Lehmann et al. 2020). At the world scale, insects have been identified as causing a considerable risk to agricultural and forestry practices, whereby major forest and agricultural producers and developing countries may be most severely damaged in future (Paini et al. 2016; Liu et al. 2021). In turn, global estimates of the costs of invasive insects have been determined at least US$ 76.9 billion (embracing associated goods, service and health costs), yet have been likely significantly underestimated, given the knowledge gaps at many national scales (Bradshaw et al. 2016; Diagne et al. 2021). Overall, in agricultural ecosystems of Russia, the range of harmful species having economic impacts is more diverse than the ones causing costs in forestry. Insects may lead to significant monetary losses in agriculture, accounting for around 46% of all recorded losses associated with invaders in this sector in Russia. The other half of recorded losses has occurred due to weeds and crop pathogens (fungi, bacteria and viruses).

As we showed, economic losses associated with biological invasions in forestry are also significant but still lower than in agriculture. Russia is a forested country and thus the problems emerging in the forest sector due to invasions of pestiferous organisms are of a special concern. In our study, as an exception, we analysed economic losses associated with six native-to-Russia longhorn beetles: *Monochamus galloprovincialis*, *M. impluviatus*, *M. nitens*, *M. saltuarius*, *M. sutor* and *M. urussovi* that can potentially serve as vectors of the pine wood nematode. The invasion of *Bursaphelenchus xylophilus* to Russia is considered as highly likely due to favourable climatic conditions and vast distribution of the native vectors here (Kulinich et al. 2017). It may lead to US$ 13.93 billion in annual losses (as estimated for the year 2007 in the study, see Suppl. material 1: Fig. S1 and Suppl. material 2: Table S1), which is the highest cost for terrestrial ecosystems in Russia. The pine wood nematode is known as a notorious pest causing pronounced economic losses also in some European and Asian countries (Haubrock et al. 2021c; Watari et al. 2021). In Spain, the related species of the pine wood nematode, *Bursaphelenchus mucronatus* Mamiya et Enda, has been predicted to cause loss in the forestry stock of around US$ 28 billion (estimated over a period of 22 years, i.e. about

US$ 1.27 billion per year), which is the highest economic cost associated with the invasive organisms in the country (Angulo et al. 2021a).

Despite our study having analysed a wide range of different species, the observed invasion costs were recorded only for four species: two insects (the emerald ash borer and box tree moth) and two weeds (common ragweed and Sosnowsky's hogweed). These notorious species have attracted significant attention in Russia, given their pronounced impacts on forestry (via invasive insects), agriculture and human health (via invasive weeds) (Dgebuadze et al. 2018). The cascading problems associated with their invasions in the country have resulted in a number of publications on their ecological impacts (Baranchikov et al. 2008; Reznik 2009; Orlova-Bienkowskaja 2014, 2016; Karpun 2019), including a few studies presenting data on observed economic losses due to these species, i.e. direct and indirect loss (environment) and those linked to health issues (Magomedov et al. 2013; Gninenko et al. 2016; Dalke et al. 2018). Meanwhile, a number of other invasive species, having known ecological and economic impacts in agriculture and forestry, lack cost assessments in Russia, for example, the insects: the Grape phylloxera *Daktulosphaira vitifoliae* (Fitch) (= *Viteus vitifoliae*), the silverleaf whitefly *Bemisia tabaci* (Gennadius), the western flower thrips *Frankliniella occidentalis* Pergande, the oriental fruit moth *Grapholita molesta* (Busck), the brown marmorated stink bug *Halyomorpha halys* (Stål), the potato tuber moth *Phthorimaea operculella* (Zeller), the tomato leaf-miner *Tuta absoluta* (Meyrick), *Polygraphus proximus* Blandford and harmful invasive species from other taxonomic kingdoms (National Report 2020).

Overall, the 'true' economic impact of biological invasions in Russia remains unidentified. Given that around 1,000 alien invasive species have been documented in Russia across different habitat types (Petrosyan et al. 2020), the number of species that cause economic losses, as well as over which geographic and monetary scales and in which economic sectors, remains unknown. It is, however, certain that the number of invasive species records and associated economic costs analysed in our study are much lower than aggregate economic losses which Russia faces due to biological invasions, as in the case of other countries (e.g. Haubrock et al. 2021a, b; Rico-Sánchez et al. 2021).

Conclusions

The present study provides the most comprehensive quantification of economic costs associated with invasive species in terrestrial ecosystems, in particular in forestry and agriculture, in Russia. Reported economic costs have reached US$ 51.52 billion in total for the studied period 2007–2019. In turn, we identified a number of gaps and biases in cost estimation which could provide information for future compilations of invasion costs within Russia. Firstly, a minority of costs reported in Russia from invasions have been empirically observed, with the vast majority being based on extrapolations from smaller scales. Moreover, costs were not geographically resolute, with the majority of expenditures split between European and Asian parts of Russia, impeding local-scale appraisals of costs and thus fine-scale decision-making. Secondly, terrestrial biota drove the entirety of reported costs in Russia, with no impacts reported from invasive aquatic or semi-aquatic biota, despite the massive extent of coastal and freshwater systems nationally and burgeoning global costs from aquatic invaders (Cuthbert et al. 2021b). We note, however, that this study focused on terrestrial ecosystems, because we did not intensively seek to obtain aquatic invasion costs for Russia from sources outside of published literature. Reported costs were also dominated by resource damage and losses to agricultural and forestry sectors, with very little in terms of management. This is concerning, as a lack of early-stage intervention measures could drive much greater invasion costs in future (Leung et al. 2002; Ahmed et al. 2021). Thirdly, less than 10% of recorded non-native species in Russia have recorded costs and entire taxonomic groups, such as vertebrates, are currently lacking cost estimation. Overall, we thus encourage to improve cost estimation resolution across environmental, spatial, temporal and taxonomic scales, including appraisals for costs of management interventions, not only for terrestrial invaders (including vertebrates), but also for organisms invading aquatic ecosystems in Russia. In that context, InvaCost offers an opportunity to standardise and centralise invasion cost reporting for the Russian economy and elsewhere, in a publicly available and comprehensive manner (Diagne et al. 2020a).

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Supplementary material 1

Figure S1. The distribution of economic costs across different species in Russia, in US$ billions

Authors: Natalia Kirichenko, Phillip J. Haubrock, Ross N. Cuthbert, Evgeny Akulov, Elena Karimova, Yuri Shneyder, Chunlong Liu, Elena Angulo, Christophe Diagne, Franck Courchamp

Data type: Figure

Explanation note: Cost data for particular species. A – beginning half of the graph; B – the end half. Abbreviations (see axis OX): **Henosepilachna vigintioctomaculata*, ***Stenocarpella maydis*/*S. macrospora*; ****Pantoea stewartii* subsp. *stewartii*; *****Xanthomonas oryzae* pv. *oryzae*; ******Clavibacter michiganensis* subsp. *sepedonicum*; APL tymovirus – Andean potato latent tymovirus; APM comovirus – Andean potato mottle comovirus; PRM nepovirus – Peach rosette mosaic nepovirus.

Link: https://doi.org/10.3897/neobiota.67.58529.suppl1

Supplementary material 2

Table S1. Dataset on economic losses associated with biological invasions in terrestrial ecosystems in Russia

Authors: Natalia Kirichenko, Phillip J. Haubrock, Ross N. Cuthbert, Evgeny Akulov, Elena Karimova, Yuri Shneyder, Chunlong Liu, Elena Angulo, Christophe Diagne, Franck Courchamp

Data type: Table (xslx. file)

Explanation note: Data on economic costs associated with bioinvasions in Russia. Based on InvaCost databases: Diagne et al. (2020a), Angulo et al. (2021b).

Link: https://doi.org/10.3897/neobiota.67.58529.suppl2

Supplementary material 3

Table S2. The region of origin and the quarantine status of the species in Russia involved in the study

Authors: Natalia Kirichenko, Phillip J. Haubrock, Ross N. Cuthbert, Evgeny Akulov, Elena Karimova, Yuri Shneyder, Chunlong Liu, Elena Angulo, Christophe Diagne, Franck Courchamp

Data type: Table (xslx. file)

Explanation note: Native ranges of the studied species and their quarantine status in Russia.

Link: https://doi.org/10.3897/neobiota.67.58529.suppl3