Impact of invasive alien plants on native plant communities and Natura 2000 habitats: State of the art, gap analysis and perspectives in Italy

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Abstract

Invasive alien plants are a major threat to biodiversity and they contribute to the unfavourable conservation status of habitats of interest to the European Community. In order to favour implementation of European Union Regulation no. 1143/2014 on invasive alien species, the Italian Society of Vegetation Science carried out a large survey led by a task force of 49 contributors with expertise in vegetation across all the Italian administrative regions. The survey summed up the knowledge on impact mechanisms of invasive alien plants in Italy and their outcomes on plant communities and the EU habitats of Community Interest, in accordance with Directive no. 92/43/EEC. The survey covered 241 alien plant species reported as having deleterious ecological impacts. The data collected illustrate the current state of the art, highlight the main gaps in knowledge, and suggest topics to be further investigated. In particular, the survey underlined competition as being the main mechanism of ecological impact on plant communities and Natura 2000 habitats. Of the 241 species, only *Ailanthus altissima* was found to exert an ecological impact on plant communities and Natura 2000 habitats in all Italian regions; while a further 20 species impact up to ten out of the 20 Italian administrative regions. Our data indicate that 84 out of 132 Natura 2000 Habitats (64 %) are subjected to some degree of impact by invasive alien plants. Freshwater habitats and natural and semi-natural grassland formations were impacted by the highest number of alien species, followed by coastal sand dunes and inland dunes, and forests. Although not exhaustive, this research is the first example of nationwide evaluation of the ecological impacts of invasive alien plants on plant communities and Natura 2000 Habitats.

Keywords:

Competition; Ecological impact; Expert survey; Impact mechanism; Impact outcome; Natura 2000 network

1. Introduction

Biological invasions are one of the most important drivers of biodiversity loss and ecosystem degradation worldwide (Seebens et al., 2017). The establishment and spread of invasive alien species (IAS) have affected multiple ecosystem processes, including community composition, biotic interactions, and functions and services (Vilà and Hulme, 2017). Furthermore, IAS can also impact important socio-economic assets, reducing the efficiency of natural resource exploitation, affecting infrastructure effectiveness, and imposing costly management efforts (Bacher et al., 2017). IAS are indeed one of the major drivers of changes in European habitats, and increase the probability of unfavourable conservation status of natural habitats (Maes, 2013), causing a general deterioration of biodiversity and the alteration of habitat structure and functions in plant communities (Pyšek et al., 2012; Gigante et al., 2018). Therefore, it is an urgent and complex goal in invasion biology to understand the mechanisms underlying biological invasions, one crucial to predicting habitat invasibility (i.e. susceptibility to invasions) and recognising community response to invasion in order to implement actions for the restoration and long-term management of invaded habitats.

Despite there being a general awareness of the effects of invasive alien plants (IAPs), in Europe there is still a lack of exhaustive works investigating the effects of IAPs on native plant communities and on the habitats of Community Interest listed in the Habitats Directive (Council Directive no. 92/43/EEC, hereafter N2000 Habitats) (Guerra et al., 2018). The N2000 network proved to be crucial for preserving the EU's biodiversity, although there are increasing calls for improvements and adjustments (Trochet and Schmeller, 2013; Friedrichs et al., 2018). The importance of the N2000 network in tackling the risks posed by biological invasions was underlined by the European Commission in the *EU 2020 Biodiversity Strategy*, and further emphasised in the recent *EU 2030 Biodiversity Strategy*. However, there is still no common approach for protecting the N2000 network, and its efficacy in decreasing the vulnerability to invasive alien species is in large part still unknown (Guerra et al., 2018; Mazaris and Katsanevakis, 2018). Data on the presence and impact of IAS on the N2000 network is crucial to counter their detrimental impacts, and of pivotal importance when considering the effects of climate change, which are likely to increase the uncertainty associated with IAS performance (Guerra et al., 2018). Indeed, protected areas and the N2000 network could become valuable tools to tackle the spread of invasive species, especially in the light of future climate change (Gallardo et al. 2017).

In Italy, research on IAPs has gained momentum in the last 20 years (Lazzaro et al., 2019). Celesti-Grapow et al. (2009) published the first comprehensive checklist, recently updated by Galasso et al. (2018a). Several national projects and studies have been carried out in the last ten years (e.g. Malavasi et al., 2018; Celesti-Grapow et al., 2016; Lazzaro et al., 2019). Nevertheless, scientific literature concerning the impacts of IAPs in Italy is still patchy and there are no data for some taxa and N2000 habitats.

In this context, the Italian Institute for Environmental Protection and Research (ISPRA) commissioned a project to collect information on the impacts of IAPs on biodiversity and on the N2000 network in Italy. The aim was to support national implementation of Regulation (EU) 1143/2014 on IAS. The study, designed and conducted by the Italian Society of Vegetation Science (SISV), had two main aims: develop of a check-list of alien-dominated plant communities in Italy (Viciani et al., 2020); and assess of the ecological impacts of IAPs on N2000 Habitats in Italy. To achieve this second goal, we carried out a survey of the literature and of expert opinion that involved a large number of botanist members of SISV. Specifically, this survey aimed at i) verifying and listing IAPs known to affect native plant communities and N2000 Habitats on a regional and a national scale, and ii) assessing the mechanism by which species make an impact and the possible impacts exerted (i.e. impact mechanisms and impact outcomes, respectively, according to Blackburn et al., 2014) and iii) determining whether impact outcomes are exerted on specific N2000 Habitats. A supplementary aim was iv) to verify the presence of specific patterns of invasion in N2000 Habitats, hypothesising that the life form and the time since its first introduction may play a pivotal role in the threat posed by IAPs to Italian N2000 Habitats.

2. Methods

2.1 Definitions and context

We adopted the Regulation (EU) no. 1143/2014 definition of IAS as those "*whose introduction or spread has been found to threaten or adversely impact upon biodiversity and related ecosystem services*". We focused on Ecological impacts, defined as "*a measurable change to the properties of an ecosystem by an alien species*", considering only deleterious impacts, meant as "*any impact that changes the environment in such a way as to reduce native biodiversity or alter ecosystem function to the detriment of the incumbent native species*" (Blackburn et al., 2014). We included both natural and semi-natural ecosystems, considering only impacts affecting the native biota and/or ecosystem processes. Conversely, we did not consider either impacts on native species at the individual or population level, or any effect on human society (thus excluding any economic/social and health effects of IAPs).

We adopted the impact scheme of the Global Invasive Species Database (GISD 2020), as described in Blackburn et al. (2014), taking into account all possible impact mechanisms identified by the scheme, and all the ecological impact outcomes at the ecosystem/habitat level (see Table 1).

Table 1. Impact mechanisms and outcomes adopted in the survey of Italian IAPs. Each mechanism listed in the left column may result in one or more of the outcomes listed in the right column (Blackburn et al., 2014).

Impact mechanism	Impact outcomes exerted at the ecosystem/habitat level
Competition	Modification of hydrology/water regulation, purification and quality /soil moisture
Predation	Primary production alteration
Hybridization	Modification of nutrient pool and fluxes
Disease transmission	Modification of natural benthic communities
Parasitism	Modification of food web
Poisoning/Toxicity	Reduction in native biodiversity
Bio-fouling	Unspecified ecosystem modification
Grazing/Herbivory/Browsing	Habitat degradation
Rooting/Digging	Habitat or *refugia* replacement/loss
Trampling	Physical disturbance
Flammability	Modification of fire regime
Interaction with other invasive species	Modification of successional patterns
Others	Soil or sediment modification: erosion
	Soil or sediment modification: bioaccumulation
	Soil or sediment modification: modification of structure
	Soil or sediment modification: modification of pH, salinity or organic substances
	Other

The nomenclature of IAPs follows Galasso et al. (2018a). As the assessment of the effects of IAPs on habitats of community interest made up a pivotal part of our data collection, to define the habitats we followed the "Italian Interpretation Manual of the 92/43/EEC Habitats Directive" (Biondi et al., 2009) and the Interpretation manual of European Union EU28 (European Commission, 2013).

2.2 Survey strategy

Our evaluation of the current impact outcomes of IAPs in Italy was based on a survey of the literature and expert opinion. The working group was composed of 49 members of the SISV (the co-authors of the present work – mainly technicians or academic botanists, with expertise in vegetation science, N2000 Habitats and IAPs), who provided data and their knowledge of the situation at the local (regional) level or regarding specific IAPs.

We provided each expert with a spreadsheet template that included specific guidelines on the type of data required and how to fill in the spreadsheet (see Appendix 1). The template included an initial list of 184 IAPs established in Italy, taken from the National Alien Plant Species Data Base (Lazzaro et al., 2019). The contributors were asked to provide data on impact mechanisms and outcomes in their region in accordance with Blackburn et al. (2014), see Table 1. Particularly, for each species of the list, experts were asked to provide the following information: a) impact mechanism, b) impact outcomes, c) impact outcomes with specific reference to N2000 Habitats, d) data source, specifying whether it originated from i) scientific literature, ii) technical reports or grey literature or iii) expert assessment, and e) the level of uncertainty of the data provided. In addition, contributors were encouraged to add to the list any further IAPs found to have an impact.

The survey strategy adopted in the study followed the framework of the consensus-building approach (see Vanderhoeven et al., 2017), in which several rounds of structured questionnaires, with subsequent aggregation of responses followed by feedback to the experts, are used to reduce inconsistencies among assessors. In our case, in a first round of evaluation, the contributors were asked to fill in the template individually, after reading the guidelines and the referenced documentation. Data from this preliminary collection (which ended on 2017 July 31) were aggregated and presented to all contributors during a two-day workshop (2017 October 16-17), to discuss possible shortcomings and identify knowledge gaps and dissimilarities in the data collection. After the workshop, we opened a second call (conclusion in 2017 December) to allow all the contributors to homogenize the data provided and overcome the shortcomings that emerged during the workshop.

2.3 Data analyses

2.3.1 Breakdown of results on IAPs and impacts outcomes and mechanisms

The data obtained on the impacts (mechanisms and outcomes) of IAPs on plant communities and N2000 Habitats were merged into a single table. The data were cleaned and standardized, spelling mistakes were corrected and duplicate records were deleted. Data were organized to depict the overall patterns of IAP distribution across Italian regions, and to outline patterns of impact mechanisms and outcomes on native plant communities and N2000 Habitats at species and administrative regions levels.

2.3.2 Patterns of invasion on N2000 Habitats

With the aim of detecting specific trends of invasion, for all IAPs assessed as having an impact on N2000 Habitats at a national level, we collected further data regarding a) the life form, b) the number of administrative regions colonized (according to Galasso et al., 2018a and subsequent updates, Galasso et al., 2018b; 2018c) and c) the date of the first introduction in Italy (information retrieved from literature and technical sources, see Appendix 2). However, although of paramount importance, data on the time of introduction is not entirely reliable, since it may correspond either to the date of the first introduction in botanical gardens or to the first detection in nature. Accordingly, we chose to reclassify neophytes into three main groups: 1) introduced between 1492 and 1800, 2) introduced between 1800 and 1950 and 3) introduced from 1950 to date (2020). This grouping (hereafter named introduction period) reflects the main changes in global human flows, passing from the age of geographical discoveries to the XIX century (1492–1799), from colonialism to the industrial revolution and the two world wars (1800–1950), and finally from the time of the economic boom to globalisation (1951–2020).

We excluded from the analysis all the species introduced before 1492 (archaeophytes) (only eight species among those exerting impacts on N2000 habitats: *Abutilon theophrasti*, *Arundo donax*, *Cuscuta cesatiana*, *Cyperus esculentus*, *Cyperus serotinus*, *Isatis tinctoria* subsp. *tinctoria*, *Ricinus communis*, *Sorghum halepense*), and *Salvinia molesta*, whose presence in Italy is doubtful.

We analysed impacts on single N2000 habitats (as indicated by the entire N2000 code, e.g. 1210) and then on macro-categories, as indicated by the first number of the N2000 code (e.g. 1: coastal habitats, 2: dune habitats and so on; see European Commission, 2013). To avoid possible biases due to the uneven number of habitats across administrative regions, the analyses were conducted at the national level (i.e. we used number of habitats and habitat macro-categories invaded by the species in Italy).

To investigate the correlation between the number of habitats, the number of macro-categories of habitats and the number of colonized administrative regions, we ran a correlation analysis for each introduction period, we calculated the pairwise Spearman's rank correlation coefficient (Spearman's ρ) and evaluated its significance by means of the asymptotic *t* approximation.

Finally, we ran a series of generalized linear models (GLM) to study the effect of the introduction period and of the life form categories on the number of invaded N2000 habitats, the number of invaded N2000 habitat macro-categories, and the number of invaded administrative regions. Given the overdispersion of our data, we adopted a quasi-Poisson distribution and evaluated the significance of the terms with an ANOVA table. All the analyses were conducted in R environment vers. 3.6.1 (R Core Team 2019).

3. Results

3.1 Breakdown of results on IAPs and impacts outcomes and mechanisms

We collected data on 241 IAPs, 57 more than the 184 originally indicated in the template (see Appendix 2). Only a few species were reported in a high number of administrative regions and by several contributors. In general, degree of knowledge varied substantially between regions, as shown by the variation in numbers of regional records on impact mechanisms and outcomes (Figs. 1A and 1B). The number of IAPs assessed as having an ecological impact (Fig. 1C) and the distribution of impacts on N2000 habitats (Fig. 1D), varied widely between administrative regions. Similarly, compared to the total number of habitats harboured in a given region, the percentage of those exposed to some degree of ecological impact was very variable, with Lombardy and Friuli-Venezia Giulia having more than half of the habitats impacted by IAPs, followed by Molise and Sardinia (Fig. 1E). Variability also characterized the relationship between species and their impact mechanisms and outcomes. Indeed, most IAPs had very few reports of mechanisms of impact–220 out of 241 species had less than five reports of impacts–while only a handful of species had a high number of records. A similar situation was found as far as impact outcomes are concerned: most of the species had very few reports and very few species had a high number of records (see Fig. 2). Of the impact mechanisms, "*Competition*" was the most frequent, being common to around 83% of reports, followed by "*Unknown*" mechanism (4%), "*Interaction with other invasive species*" (4%) and "*Poisoning/toxicity*" (3%).

Ailanthus altissima, listed in all Italian administrative regions, was the species with the highest number of records of impact mechanisms. Competition was the main impact mechanism assigned to the species, followed by "*Rooting/digging*". Further species with a very high number of records, such as *Senecio inaequidens*, *Robinia pseudoacacia*, *Helianthus tuberosus* and *Sorghum halepense*, were all assessed as invaders with a high degree of impact in many administrative regions (see Fig 3A for main mechanisms of the first 23 species). Nevertheless, despite a high number of impact reports, most data–62%–came from expert assessments that were not experimentally verified (Fig. 4 A). Only 25% of the reports were retrieved from the scientific literature and 13% from technical reports and grey literature.

Species most frequently recorded for impact outcomes differed from those most frequently recorded for impact mechanisms: *Robinia pseudoacacia* was the species with the highest number of impact outcome records, followed by *Acacia saligna*, *Amorpha fruticosa*, *Arundo donax*, *Ailanthus altissima*, *Carpobrotus edulis*, *C. acinaciformis*, *Helianthus tuberosus*, *Senecio inaequidens*, and *Solidago gigantea* (Fig 3B). As with impact mechanisms, most of the records (78%) were from expert assessments, while 13% were retrieved from technical reports and grey literature, and only 9% from the scientific literature (Fig. 4B).

Reduction in native biodiversity was by far the most reported outcome, followed by general habitat degradation, loss of habitat and refugia, and modification of successional patterns (Fig. 5A). The ranking of threats posed to N2000 Habitats showed the same order. Indeed, a reduction in native biodiversity was cited for nearly all N2000 habitats present in Italy (81 out of 84), followed by the same outcomes named above (Fig. 5B).

Nonetheless, impacts were unevenly distributed, especially in terms of the number of IAPs impacting specific habitats, and less in terms of the number of administrative regions in which the target N2000 habitat is impacted (Fig. 6A-B). N2000 Habitat 3270 was by far the one impacted by the highest number of invasive species (79 species), followed by N2000 Habitat 6430. At the macro-category level, freshwater habitats (N2000 Habitats 3xxx) and natural and semi-natural grassland formations (N2000 Habitats 6xxx) were impacted by the highest number of alien species, followed by coastal sand dunes and inland dunes (N2000 Habitats 2xxx), and forests (N2000 Habitats 9xxx). In terms of the regional distribution of impacted habitats, freshwater habitats were generally affected in many regions, with coastal sand dunes, coastal and halophytic habitats (N2000 Habitats 1xxx) and forests also being frequently affected (Fig 6 B).

3.2 Patterns of invasion on N2000 Habitats

The 241 IAPs recorded in our survey included 167 neophytes invading the N2000 habitats; 29 species were introduced before 1800, 84 between 1800 and 1950, and 54 after 1950 (Appendix 2). Therophytes (56 species) and phanerophytes (45) were the most frequent life forms, followed by hemicryptophytes (19), geophytes (17), chamaephytes (16), and hydrophytes (14). *Ailanthus altissima*, *Robinia pseudoacacia*, *Senecio inaequidens*, *Amorpha fruticosa*, and *Carpobrotus edulis* were the most frequent invaders both in N2000 habitats (28, 25, 23, 17, 16 each respectively) and in habitat macro-categories (7, 7, 8, 6, 5 respectively), although with slightly different rankings (see Appendix 2). The number of habitats and that of habitat macro-categories invaded correlated strongly for all three periods (p value < 0.001, see Table 2), although the correlation decreased slightly from the first introduction period (before 1800; $\rho = 0.930$) to the last (from 1950 to date; $\rho = 0.845$). Showing a more strongly decreasing trend, the number of regions colonised was significantly correlated with the number of habitats ($\rho = 0.523$, p value = 0.003) and macro-habitats invaded ($\rho = 0.489$, p value = 0.007) only for the first introduction period (before 1800); while no significant correlation was found for the other two introduction periods (Table 2).

Life form categories significantly affected the distribution of species in terms of number of invaded N2000 habitats and macro-habitats, as well as in terms of number of colonised administrative regions (Table 3). Overall, chamaephytes were the most widespread invaders, invading the highest number of habitats (and habitat macro-categories), followed by geophytes, phanerophytes and therophytes; hydrophytes were specific to a small number of habitats (Figs. 7A, C). On the other hand, therophytes had spread into the highest number of regions, together with geophytes (Fig. 7E). Introduction period strongly affected the number of habitats, of habitat macro-categories, and of administrative regions invaded (Table 3). Indeed, the longer a species had been introduced, the higher the number of invaded habitats, macro-habitats and administrative regions (7 B, D, F).

Table 2 Matrices of correlation between the number of N2000 habitats (Habitats), number of macro-categories of N2000 habitats (Macro-habitats) and number of invaded administrative regions (Regions), for each introduction period. In each correlation matrix, the upper triangle (numbers in plain text) displays Spearman's rank correlation coefficient (Spearman's rho), while the lower triangle (numbers in italic) displays its significance.

Introduction Period		**Habitats**	**Macro-habitats**	**Regions**
1492 – 1799	**Habitats**	-	0.930	0.523
	Macro-habitats	*<0.001*	-	0.489
	Regions	*0.003*	*0.007*	-
1800 – 1950	**Habitats**	-	0.860	0.129
	Macro-habitats	*<0.001*	-	0.187
	Regions	*0.129*	*0.187*	-
1951 – present	**Habitats**	-	0.845	0.077
	Macro-habitats	*<0.001*	-	0.096
	Regions	*0.579*	*0.488*	-

Table 3 Analysis of the deviance table for the generalized linear models analysing the effect of life form categories and introduction period on the number of invaded N2000 Habitats (Habitats), number of macro-categories of N2000 Habitat (Macro-habitats) and number of invaded administrative regions (Regions). χ^2 = Likelihood ratio Chi-square; Df = Degree of freedom; Significance codes: P value < 0.001 ‘***’; P value < 0.05 ‘*’.

Response	**Term**	χ^2	**Df**	**P value**	
Habitats	life form	24.576	5	<0.001	***
	introduction period	28.551	2	<0.001	***
	life form×introduction period	12.005	10	0.285	
Macro-habitats	life form	23.720	5	<0.001	***
	introduction period	28.723	2	<0.001	***
	life form×introduction period	15.669	10	0.109	
Regions	life form	13.725	5	0.017	*

	introduction period	52.092	2	<0.001	***
	life form×introduction period	15.691	10	0.109	

4. Discussion

Our data showed that the general impact of IAPs on native plant communities and N2000 Habitats has still only been partially unravelled at the national level. Specifically, our study brought to light two main problems. One is that that very few data are available on the mechanisms by which IAPs exert their impact. This lack greatly reduces our ability to implement effective adaptive strategies to counteract the spread and the effects of IAPs. In addition to this, the data that are available are very unevenly distributed between regions, further reducing our capacity to understand the nation-wide effects of IAPs. Filling these gaps calls for an urgent nation-wide collaborative initiative with coordinated action programs and standard methodologies. The initiative would ideally be conducted under the auspices of ISPRA or of the Italian Ministry of the Environment and Preservation of Land and Sea, which provided funding and motivation for the present study. Also, the establishment of a national collaboration between numerous Italian research groups to participate in joint projects at the EU level (i.e. within EU LIFE programme or Horizon Europe 2021-2027), or within national scientific societies like SISV or the Italian Botanical Society (SBI), is essential to complete the picture of alien species invasion in Italy.

The differences between the impacts recorded for different Italian regions are consistent with the findings of the main catalogues of alien plants in Italy (Galasso et al., 2018a; Celesti-Grapow et al., 2009). The highest number of records was observed in the largest and most densely populated regions (i.e. Lombardy, Piedmont, and Tuscany), where human-driven land cover changes like urbanization, industrialisation, road infrastructures, and agriculture, cause higher rates of introduction (McLean et al., 2017), thereby facilitating biological invasion. The intensification of agricultural use of land has been proven to play a crucial role in the introduction, establishment and spread of IAPs due to a decline in biodiversity caused by oversimplified landscape matrices (Walker et al., 2009; Buffa et al., 2018). This is especially true for lowland riverscapes which suffer from the deterioration of water, of sediments and of hydrological regimes (Bolpagni and Piotti, 2015; Bolpagni et al., 2013), situations that have been identified as common key factors driving the establishment and spread of IAPs in newly invaded areas (Aronson et al., 2017).

However, comparatively large and densely populated regions (e.g. Lazio, Emilia-Romagna) did not show the same degree of invasion. This difference could be the result of contrasting levels of awareness between the different administrative regions in Italy. A minority of regions have already adopted specific regulatory frameworks to address the issue of biological invasions (Brundu et al., 2020), while the other regions still pay little attention to this matter. Only Lombardy, Piedmont, Aosta Valley have a list of restricted IAPs, approved by regional laws, and working groups dedicated to IAPs. In Friuli-Venezia Giulia and Tuscany only few IAPs are considered in regional laws. Finally, Liguria has established a surveillance network and a permanent working group on IAS within the Italian-French ALIEM Project. To our knowledge, all the other Italian administrative regions lack a local regulatory framework on IAPs, even if the recent promulgation of legislative decree no. 230/2017 calls for a comprehensive framework to tackle this issue. We are convinced that a decisive contribution to this matter would come from the establishment of a national list of invasive alien species of Member State (Italy) concern (see Art. 12 of Regulation (EU) no. 1143/2014), under the guidance of the Italian Ministry of the Environment and Preservation of Land and Sea. To this end, an important action aimed at the individuation of candidate species for the implementation of such a list (see Lazzaro et al., 2019) is currently being carried out by ISPRA, within the Life ASAP project (LIFE15 GIE/IT/001039).

The high number of expert-based assessments in our survey underscores the major difficulty in retrieving suitable and reliable literature on the impacts of IAPs in Italy. Indeed, direct evidence is frequently also lacking for very well-studied species, generally considered a priori to be a serious threat to biodiversity. The gaps in knowledge of the different taxa hinder the study (and management) of the impacts associated with biological invasions, with most papers focusing on a narrow set of already studied species (Hulme et al., 2013; Latombe et al., 2017). This is especially serious because data on impacts are necessary to lay the basis for any generalisation about biological invasions and are mandatory for risk assessment and management (Bolpagni et al., 2014a; Lazzaro et al., 2015).

For example, information concerning *A. altissima* mainly comes from regional reports and checklists which often lack direct measurements of the cited impacts (see Badalamenti et al., 2016; Maiorca et al., 2007). Although the impacts caused by this species are relatively well-studied (Castro-Díez et al., 2019), impacts in Italy are only documented for Sardinia (Traveset et al., 2008; Vilà et al., 2006) and the Karst area in northeastern Italy (Uboni et al., 2019) and there is very little literature on impacts outcomes on plant communities or on N2000 Habitats. Among the most studied species, *Robinia pseudoacacia* stands out as a major invasive tree in Europe (Vítková et al., 2017). Many studies in Italy have focused on the impacts of this species (Nascimbene et al., 2012, 2015; Benesperi et al., 2012; Lazzaro et al., 2018; Sitzia et al., 2018; Campagnaro et al., 2018; Gentili et al., 2019). Most authors have found evidence that the rapid expansion of this species in Italy is causing the progressive decline of native forests, with loss of species richness and diversity and a shift in species composition towards nitrophilous assemblages (Benesperi et al., 2012; Lazzaro et al., 2018; Allegrezza et al., 2019). In contrast, other authors have shown that secondary *Robinia* forests, growing on abandoned lands, may host compositionally heterogeneous plant communities and may contribute to some degree to regional biodiversity (Campagnaro et al., 2018). Nevertheless, as pointed out also by Lazzaro et al. (2018), it is worth mentioning that in many cases *Robinia* forests replace habitats considered of community interest in Europe (i.e. N2000 Habitats 9260, 91B0, 91M0, 91AA*; Montecchiari et al., 2020, and 92A0 among others).

Robinia pseudoacacia is also an important forest species, so that one option would be to apply forestry best practice to avoid its escape from areas set aside for cultivation.

Robinia pseudoacacia is also predicted to be one of the most competitive species in a climate change scenario (Kleinbauer et al., 2010), and recently Nascimbene et al. (2020) showed the effects of the interaction between climate change and invasion by *R. pseudoacacia* on the endangered lichen species *Lobaria pulmonaria.* Biological invasions and climate change (often referred to as "double trouble") are considered two of the key drivers of biodiversity loss, whose interaction will lead to a magnification of the threats to biodiversity worldwide (Mainka and Howard, 2010).

Among the highly invasive tree species, in Northern Italy *Prunus serotina* and *Quercus rubra* have also been reported to greatly impact native communities and ecosystem components at the soil level (Gentili et al., 2019; Vegini et al., 2020). *Acacia* is another genus well-studied in Italy and worldwide. The negative impacts on plant communities of these nitrogen-fixing trees are well documented for several species (e.g., *A. dealbata*: Lazzaro et al., 2014; Minuto et al., 2020; *A. pycnantha*: Lazzaro et al., 2015). Likewise, the impacts of *A. saligna* on coastal dune N2000 habitats (Del Vecchio et al., 2013; Bonari et al., 2017; Calabrese et al., 2017).

Carpobrotus acinaciformis, *C. edulis* and their hybrids (Campoy et al., 2018), is another group of invasive species widely investigated in Italy, whose impacts on both biodiversity (Santoro et al., 2012; Jucker et al., 2013) and soil conditions (Zedda et al., 2010; Santoro et al., 2011; Badalamenti et al., 2016) are well depicted. Their pattern of occurrence at the community level (Carboni et al., 2010; Sperandii et al., 2017) as well as their habitat preference, including N2000 Habitats 2120, 2210 and 2250*, have also been studied (Sarmati et al., 2019).

Some specific studies have focused on the impact of different IAPs (e.g. *Ambrosia psilostachya*, *Cenchrus longispinus*, *Erigeron canadensis*, *Oenothera stucchii*, *Senecio inaequidens*) on sand dune ecosystems in northeastern Italy, showing significant negative effects on species richness, species diversity and evenness, and plant community composition, with effects increasing from N2000 drift line habitats (1210) to fixed-dune habitats (2130) (Del Vecchio et al., 2015).

Unfortunately, once these few well-studied IAPs are excluded, most of the records of impact on plant communities and N2000 habitats collected in the present general assessment derive from expert evaluations. This applies in particular to the species listed among the Invasive Alien plant Species of Union Concern (*sensu* Regulation (EU) no. 1143/2014), both because their spatial distribution in Italy is still scattered or localized (e.g. *Alternanthera philoxeroides*, *Pontederia crassipes*) and especially because data on their impacts is still missing (with only a few exceptions; see e.g. Lastrucci et al. (2017) for *Myriophyllum aquaticum*). The lack of information may also be due to the difficulty in obtaining reliable data for plants and vegetation in aquatic ecosystems, normally extremely time- and money-consuming to sample (Azzella et al., 2017). Indeed, half of the IAPs of Union concern are aquatic or wetland plants (19 out of 36). Despite their high number in the EU list confirming the general poor state of conservation of inland waters (Brundu, 2014; Lastrucci et al., 2017), aquatic IAPs have been so far neglected or little investigated in Italy. However, several studies confirmed their pivotal role in reducing local biodiversity. Bolpagni (2013a; 2013b) and Bolpagni et al. (2017) found that *Lagarosiphon major* and *Elodea nuttallii* create extensive submerged meadows that almost completely replace native macrophyte communities belonging to N2000 habitats 3140 and 3150. *Nelumbo nucifera* and *Ludwigia hexapetala* seem to actively compete with native species (Bolpagni et al., 2014b; Villa et al., 2017; 2018; Tóth et al., 2019) due to their enhanced competitive ability for limiting resources and their tolerance to edaphic conditions variability (Tóth et al., 2019). Some specific studies focused on the impact of *Lemna minuta* on freshwater ecosystems. The results highlighted substantial negative effects on water quality and on aquatic plant and animal communities (Ceschin et al., 2019; 2020), showing that *L. minuta* causes drastic alterations to the local vegetation, often replacing native species. Similar results have been found for the most common duckweed, *L. minor*, which assimilates available nutrients faster than native species and shows a higher relative growth rate (Ceschin et al., 2016a, 2016b), characteristics that make this species highly competitive. However, the scarcity of knowledge on the majority of aquatic IAPs hinders both a correct assessment of the environmental impacts and the planning of actions to be carried out for effective recovery of impacted ecosystems.

Our survey also evidenced a group of well-known and widespread invasive herbs (i.e., *Amaranthus retroflexus*, *Ambrosia artemisiifolia*, *Artemisia verlotiorum*, *Bidens frondosa*, *Erigeron canadensis*), that are very competitive in disturbed habitats (agricultural areas, roadsides, ruderal areas) also thanks to their high propagule pressure. Ruderal species are highly opportunistic and it is worth mentioning the presence of *Phytolacca americana* and *Solanum chenopodioides* in an old-growth *Quercus ilex* urban forest disturbed by a severe windstorm in Southern Italy (Bonanomi et al., 2018). Opportunistic alien species, which invest in rapid growth and in sexual reproduction, are a challenging issue in invasion biology since their invasiveness may change during different successional stages (Domènech and Vilà, 2006). For instance, the annual *A. artemisiifolia* is completely suppressed by late colonists and perennial species after a three-year succession (Gentili et al., 2017). Conversely, the invasion of *Solidago canadensis* has been reported to modify

the trajectory of vegetation succession and to exert a higher negative effect on native diversity in older successional communities (Fenesi et al., 2015a; 2015b).
Finally, this survey showed that that the time elapsed since introduction has a highly significant effect on the number of habitats invaded. This highlights the importance of better investigating species of relatively recent introduction, which are not yet truly invasive, but which have considerable potential to invade given the size of the introduced populations. These include some species of *Eucalyptus,* especially *E. camaldulensis,* which in recent years has begun to spread in river habitats in Sicily (Badalamenti et al., 2018). In this, as in other cases, biological evolution acts on the introduced species and may enable some alien plants to occupy a broad range of novel habitats until they become invasive (Oduor et al., 2016). Tree species should be carefully monitored because although they take time to become invasive, when they do, the impact is high because of their large biomass.

5. Conclusions

Our survey is the first attempt to assess the impact of the most harmful IAPs on plant communities and on N2000 habitats throughout Italy. The study highlighted numerous knowledge gaps which, however, replicate the gaps in plant invasion science ascertained at a global level. The differences in levels of knowledge between the Italian administrative regions is likely linked to dissimilarities in awareness, as shown by regional differences in policies and legislation. Thus, a primary aim of the scientific community should be to even up disparities in knowledge at the regional level. Most importantly, we highlighted a glaring lack of evidences, even for well-known invasive species. We also exposed a lack of data on the impacts of IAPs on N2000 habitats, which ought to be a primary focus of conservation efforts. Thus, filling the knowledge gap is a mission of primary importance, to provide data both for risk analysis and to support decision makers. Our results show that Italy needs a coordinated nation-wide strategy to evaluate and manage the risk of invasion in the N2000 network. This need is even more urgent in the light of the compounded effects of biological invasion and climate change, which biodiversity management planning and policy should take into careful consideration.

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Author contributions

L.Las., R.Bol., L.Laz., G.Buf. and F.Bra. were involved in designing the methodology and coordinated the work for the data collection on behalf of Italian Society of Vegetation Science. L.Laz., L.Las., R.Bol., G.Buf., R.Gen., M.Lon. and A.Sti. were involved in data analysis and interpretation and drafting the manuscript. All authors provided data for the survey as associated of SISV, critically revised the draft of the manuscript and gave final approval for publication.

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FIGURES

Figure 1. Distribution of records on the impact of IAPs in Italy *per* administrative region. A) Distribution of records on impact mechanisms. B) Number of IAPs exerting any type of impact mechanism. C) Distribution of records on impact outcomes on plant communities. D) Number of N2000 Habitat types exposed to some degree of ecological impact by IAPs. E) Percentage of N2000 Habitats exposed to some degree of ecological impact by IAPs on the total number of Habitat harboured in the region.

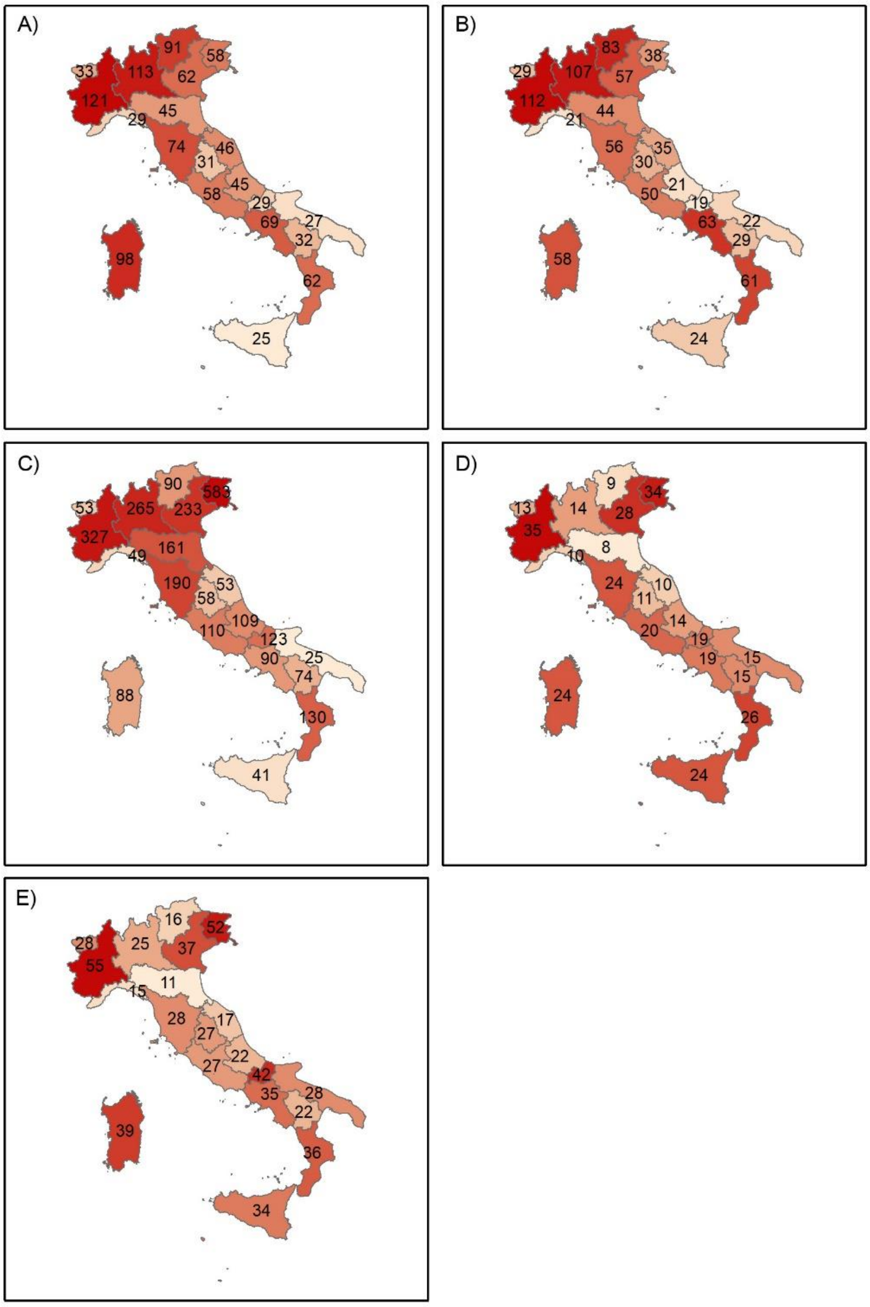

Figure 2. Number of data collected regarding the presence of impact mechanism (empty green circles, dashed line) and impact outcomes (full blue circles, solid line) exerted by IAPs in Italy.

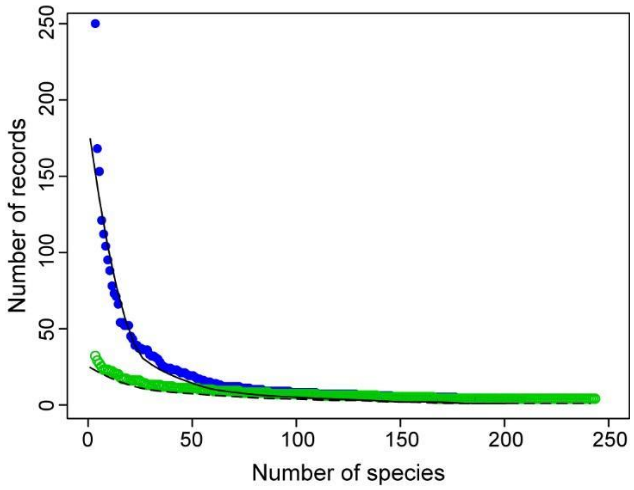

Figure 3 A) Number of regional records with specific impact mechanisms for the first 23 IAPs. B) Number of total records of impact outcomes for the first 23 IAPs.

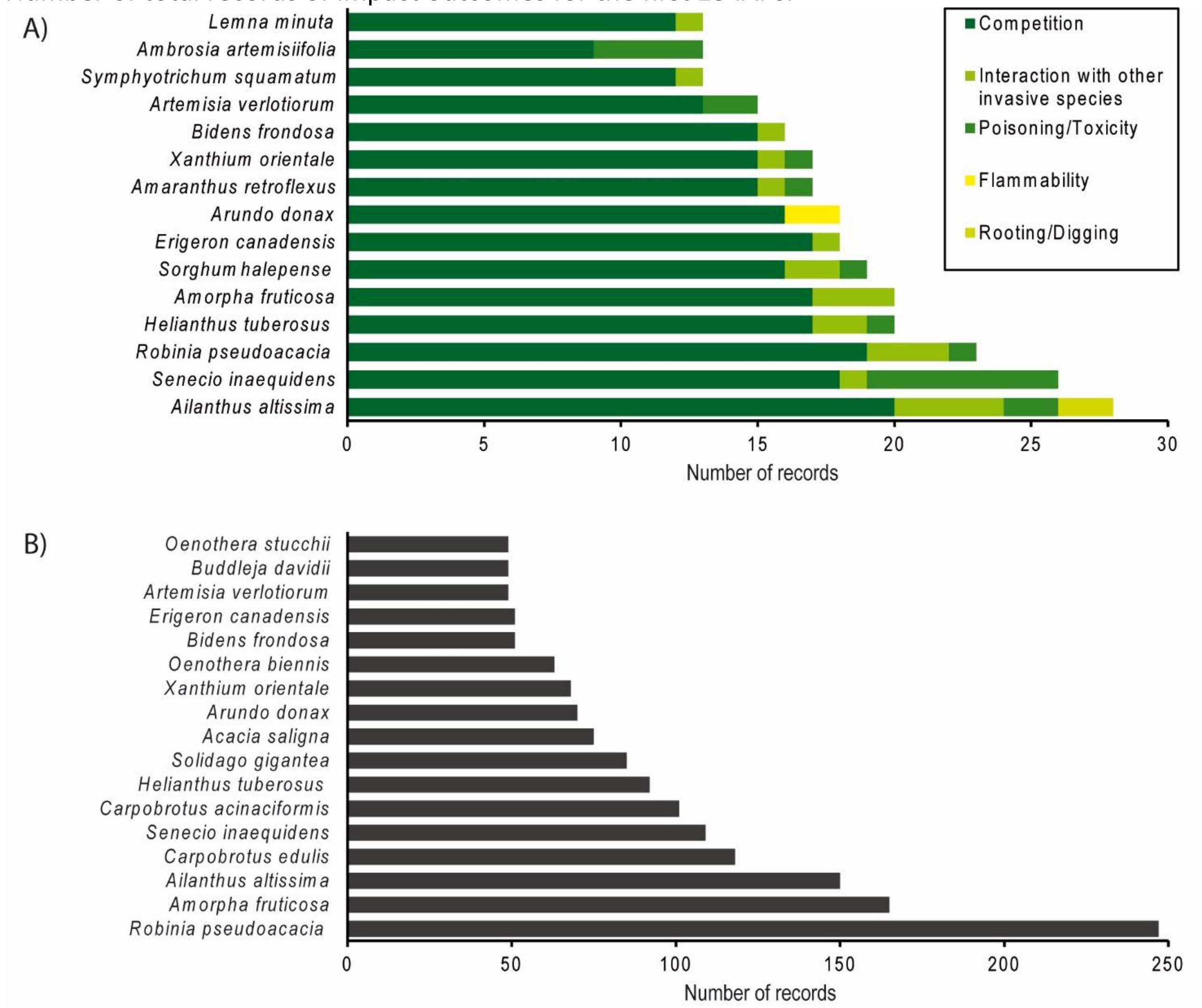

Figure 4. Source of the reports (in percentage) concerning A) impact mechanisms and B) impact outcomes for all the species and for the first ten IAPs (in descending order by number of records).

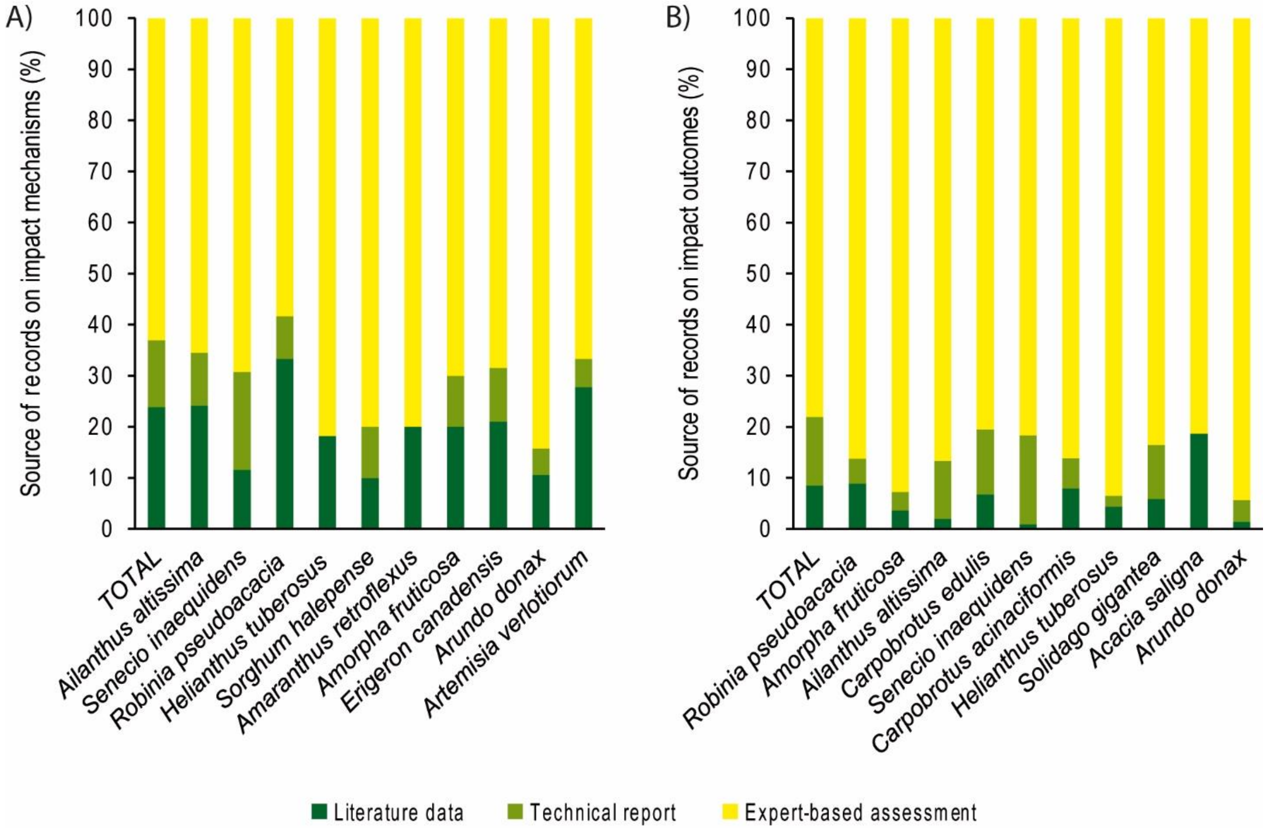

Figure 5. Impact outcomes. A) Total records (i.e. species × N2000 habitat × administrative region). B) Total number of N2000 Habitats suffering from a specific impact outcome (irrespective of species and administrative regions).

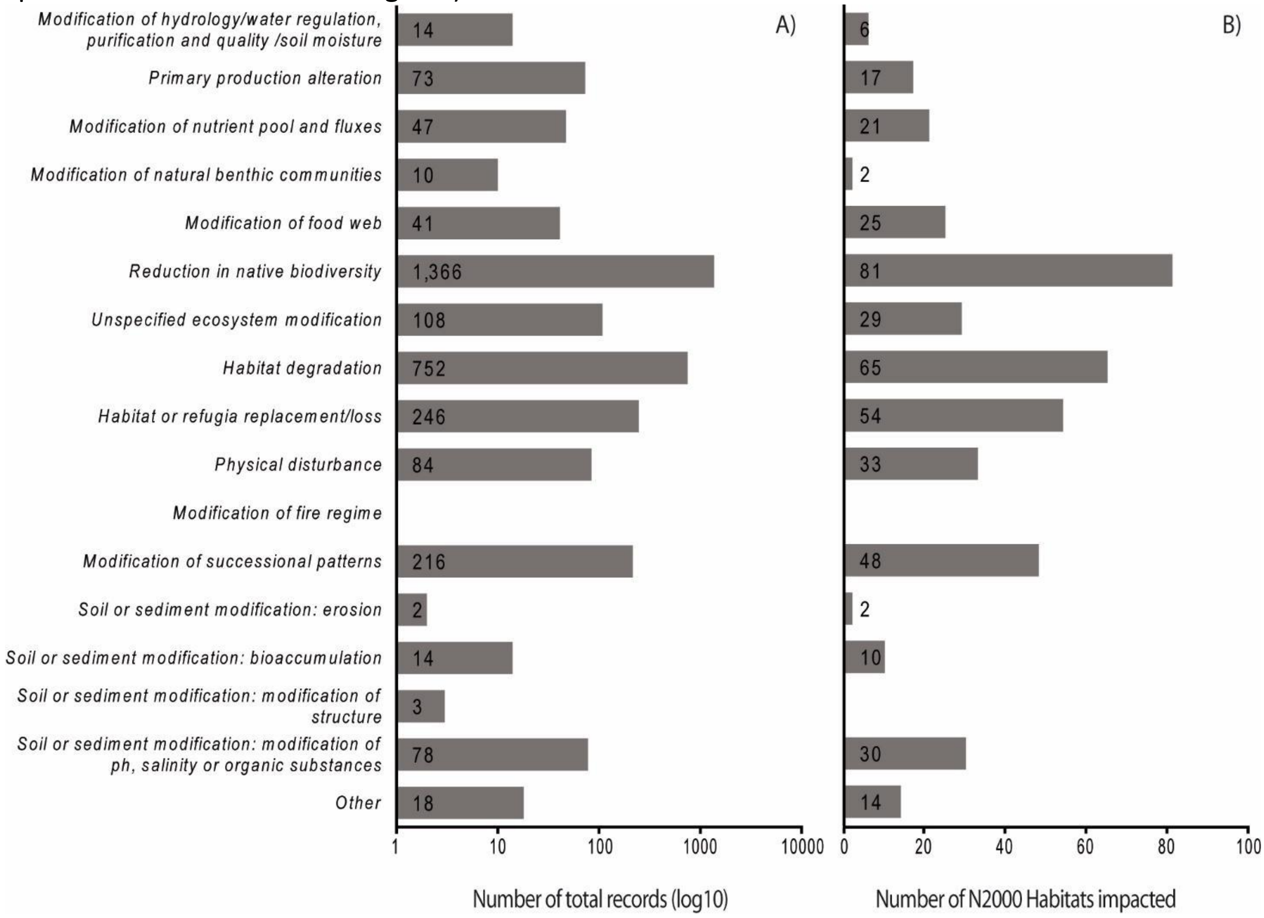

Figure 6. Data on the impact outcomes recorded per N2000 Habitat (*sensu* Habitat directive 92/43/EEC). A) Number of species exerting some degree of ecological impact for each target N2000 habitat and B) number of administrative regions in which the target N2000 habitat is impacted.

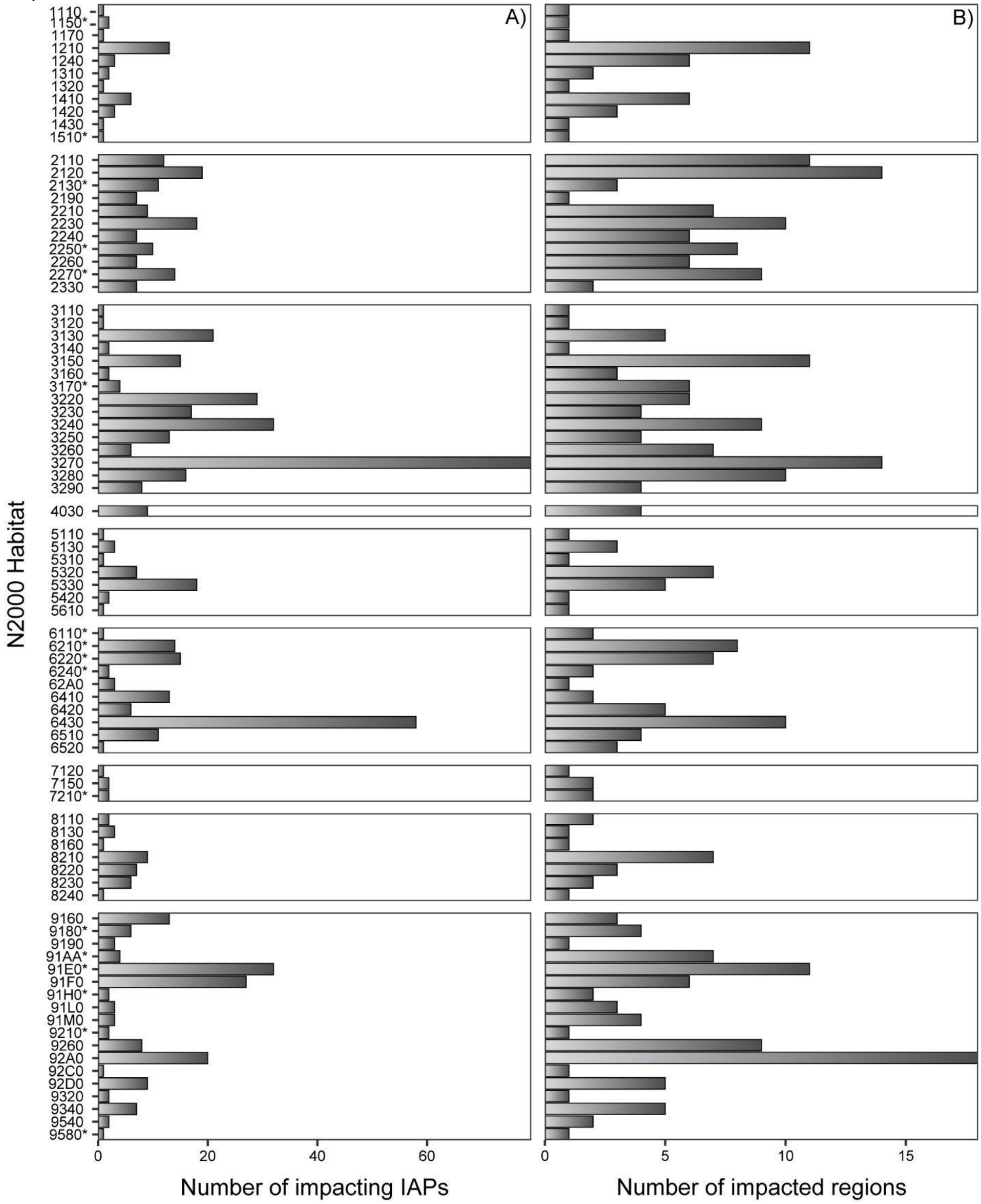

Figure 7. Effect of the life form categories (A, C, E) and introduction period (B, D, F) on the number of N2000 Habitats (Habitats), number of macro-categories of N2000 Habitats (Macro-habitats) and the number of invaded administrative regions (regions), respectively. C = chamaephytes; G = geophytes; H = hemicryptophytes; I = hydrophytes; P = phanerophytes; T = terophytes.