Journal of Environmental Management 327 (2023) 116896

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Knowledge and perceptions of invasive plant biocontrol in Europe versus the rest of the world

Hélia Marchante [a], Elizabete Marchante [b], Laura Verbrugge [c], Suzanne Lommen [d,e], Richard Shaw [f,*]

[a] Coimbra Polytechnic Institute, Higher Agrarian School of Coimbra, Centre for Functional Ecology, Bencanta, 3045-601 Coimbra, Portugal
[b] Centre for Functional Ecology, University of Coimbra, Department of Life Sciences, Calçada Martim de Freitas, 3000-456 Coimbra, Portugal
[c] Water and Development Research Group, Aalto University, Espoo, Finland
[d] Section Plant Ecology and Phytochemistry, Institute of Biology, Leiden University, Sylviusweg 72, 2333 BE, Leiden, the Netherlands
[e] Koppert Biological Systems, Veilingweg 14, 2651 BE Berkel en Rodenrijs, the Netherlands
[f] CABI Europe-UK, Egham, Surrey, TW20 9TY, United Kingdom

ARTICLE INFO

Keywords:
Biological control
Europe
Weeds
Public perception
Survey

ABSTRACT

Biological control (BC) of invasive alien plants (IAP) can be an effective environmental management approach. It has only very recently been adopted in Europe and is underutilized compared to other continents where this method has been successfully implemented for over a century. This is in sharp contrast to the BC of invertebrate pests, which has been taken up widely within Europe. It has been suggested that this is related to the risk-adverse attitude of Europeans towards weed BC. Scientific and public perception have a major influence on environmental policy actions. Public perception and knowledge regarding BC is an understudied subject despite its relevance for the application of this management alternative. We aimed to assess the knowledge and perception of BC of IAP among European professionals compared with their peers from other continents. To this end we conducted an online survey including multiple choice and open questions among over 700 people professionally engaged with managing the natural environment, of which approximately half were from Europe (EU) and the others from outside (non-EU). We assessed relationships between the geographical location of the respondents and their knowledge, and perceptions of BC of weeds *versus* BC of invertebrate pests. We found that respondents' location influenced both perceptions and knowledge of BC for weeds. Compared to non-EU respondents, EU professionals showed less appreciation for BC (e.g., regarding safety, sustainability, and cost-effectiveness), and perceived it as a riskier method, particularly in the case of practitioners and researchers. More profoundly insect pest BC tended to be considered less safe than weed BC for non-EU respondents. Confidence in weed BC as a method, as well as in the validity of the associated pre-release risk assessments, strongly increased with the level of expertise in weed BC. While a much higher proportion of non-EU respondents were correctly aware of the presence/absence of BC in their own countries and identified successful examples of BC accurately, both groups of respondents were similarly aware of unsuccessful BC examples, including BC agents against animals, stressing the bias of EU respondents towards examples of BC failure. The appreciation of weed BC in Europe could be elevated by a combination of increasing knowledge of the technique and pre-release risk assessment and promoting successful examples of weed BC, which may bring major benefits for the management of IAP across the region.

1. Introduction

Invasive alien species and their negative impacts on biodiversity and the economy are commonly recognized by European scientists, managers and authorities who have adopted legislation to prevent and manage their introduction and spread (EU Regulation no 1143/2014 (EU, 2014)). Invasive alien plants (IAP) in particular, are responsible for substantial negative impacts, through their ability to transform

* Corresponding author.
E-mail addresses: hmarchante@esac.pt (H. Marchante), emarchante@uc.pt (E. Marchante), lauraverbrugge1@gmail.com (L. Verbrugge), SLommen@koppert.nl (S. Lommen), r.shaw@cabi.org (R. Shaw).

https://doi.org/10.1016/j.jenvman.2022.116896
Received 1 August 2022; Received in revised form 25 November 2022; Accepted 25 November 2022
Available online 2 December 2022
0301-4797/

ecosystems and landscapes profoundly as well as cause major economic costs (Novoa et al., 2021; Diagne et al., 2021). Their management is often technically challenging due to biological persistence (e.g., numerous long-lived seed banks) and survival strategies (e.g., vigorous/resprouting or coppicing, long distance dispersal of both seeds and vegetative propagules) of many species, frequently combining to generate vast areas of invasion. "Traditional" management, relying solely on physical and chemical control, can thus become prohibitively expensive, as well as often not being successful in the long term.

Biological control (BC) involves the use of a natural enemy, such as a parasite, predator, or pathogen, of a (target) species to maintain its population density at a lower level than would occur in their absence (de Bach, 1964). BC has a long history dating back to 304–877 AD in China where an ant species common in natural habitats would be released into orchards for pest control (Sforza, 2021). BC is nowadays frequently considered a key ecosystem service and a sustainable method of pest management as well as contributing to the beneficial reduction in the use of chemicals to control invasive alien species (Sforza, 2021). One specific type of BC is Classical Biological Control (CBC) which involves the importation and subsequent release and establishment of a non-native natural enemy for the control of its host species in its expanded range where it has become invasive. CBC is potentially the most controversial form of BC, even amongst the scientific community, because it involves the intentional and permanent introduction of one alien species to control another. The earliest known example of CBC of weeds took place approximately 200 years ago (in 1821) when *Dactylopius ceylonicus* (Green) was released to control *Opuntia monacantha* (Willd.) Haw in India (Tryon, 1910), a release that proved successful. To date, there have been over 500 biological control agents (BCA) released against at least 220 IAP species in 130 countries (Winston et al., 2014). Despite the long and extensive history of successful release of BCA against IAP worldwide (Schwarzländer et al., 2018a), the substantial economic benefits (van Wilgen et al., 2004; Mouttet et al., 2018), the rarity of significant non-target impacts (Suckling and Sforza, 2014), and the long list of high potential European weed targets (Sheppard et al., 2006), the technique has largely been overlooked until very recently in Europe (Shaw et al., 2018).

In 1962, one insect gall-former (*Procecidochares utilis* Stone, the eupatorium gall fly) had been intentionally released in Madeira Island (Portugal) to control the invasive plant *Ageratina adenophora* (Spreng.) King & Rob (*Asteraceae*) (Vieira, 2002)), with little follow up after establishment (Pupo, 2016). In 1969, the leaf beetle *Altica carduorum* Guérin-Méneville was released against *Cirsium arvense* (L.) Scop. (*Asteraceae*) in the UK but failed to establish (Baker et al., 1972). To our knowledge, since then, no other BCAs have been released for IAP control until 2010 (Shaw et al., 2016, 2018). The recent intentional introductions in Europe, in chronological order, are the Japanese knotweed psyllid *Aphalara itadori* Shinji against *Reynoutria japonica* Houtt. (*Polygonaceae*) in 2010 (UK) and 2020 (NL), the rust fungus *Puccinia komarovii* var *glanduliferae* against *Impatiens glandulifera* Royle (*Balsaminaceae*) in 2014 (UK) (Tanner et al., 2015; Varia et al., 2018), the gall wasp *Trichilogaster acaciaelongifoliae* (Froggatt) against *Acacia longifolia* (Andrews) Willd. (*Fabaceae*) in 2015 (Portugal) (Marchante et al., 2017) and the gall-forming mite *Aculus crassulae* Knihinicki & Petanović versus *Crassula helmsii* (Kirk) Cockayne (*Crassulaceae*) (Knihinicki et al., 2018; Varia et al., 2022). Most recently in 2020, again in the UK, the weevil *Listronotus elongatus* (Hustache) was released against *Hydrocotyle ranunculoides* L. f. (*Apiaceae*) (D. Djeddour pers. comm.). This slow take-up in Europe of an otherwise globally accepted management technique is particularly interesting given the extensive use of CBC against pest arthropods both inside the glasshouse (Minks et al., 1998; Eilenberg et al., 2000) and outside for which 176 species of exotic arthropods have been released in Europe (Gerber and Schaffner, 2016). Whilst it is too early to judge the long-term effects of the recent biological control agent releases in Europe, there are indications of establishment and early effects at least for the gall wasp *T. acaciaelongifoliae* (López-Núñez et al., 2021), the rust fungus *Puccinia komarovii* var *glanduliferae*, the weevil *L. elongatus* and the gall-forming mite *Aculus crassulae* seem to be establishing a spreading locally in the UK (R. Shaw pers. comm.). Additionally, there are some notable examples of successful weed BC in Europe which resulted from accidental or unintentional introductions (reviewed by Shaw et al., 2018). However, we hypothesise that a general lack of history of intentional CBC in Europe is likely to affect people's level of awareness and understanding of the principles and practice of CBC.

Recent explorations of challenges and constraints of BC in Europe and beyond, mainly identified technical and practical limitations (Barratt et al., 2018; Shaw et al., 2018; Schwarzländer et al., 2018b). Public (including scientific) and policy support is critical for BC implementation (Thomas and Willis, 1998; Ghosheh, 2005; Vurro and Evans, 2008). In democratic societies – such as Europe - public perception is long recognized to have a major influence on policy decisions and environmental actions taken (Wilkinson and Fitzgerald, 1997) specifically when they are funded by public money and applied on public or shared lands (Messing and Brodeur, 2018) such as is the case for most CBC to date. Research on public perceptions of BC, however, is relatively scarce and fragmented, specifically when the target audience is the scientific and technical community. Past studies from Australia and New Zealand suggest that a general lack of understanding among the public is one of the main barriers to implementing BC measures (Ravel, 1999). A Canadian study concluded that BC is preferred over pesticide use in food production, however they also identified a clear need to "educate" the general public on biological pest management (McNeil et al., 2010). More recently (Messing and Brodeur, 2018), stressed that researchers and practitioners should communicate more to increase awareness and public and regulatory support for BC.

One question that remains unanswered however, is *why* people might oppose the use of BC for managing IAPs. In the field of invasive animal management, a public perception study on the use of genetic manipulation for controlling invasive fish in the Great Lakes area (USA) showed that the involved stakeholders were excited to have a new tool for control, but they were also concerned about potential unintended consequences (Sharpe, 2014). These concerns were related to unintended ecological impacts as well as additional costs for development and interference with ongoing control projects. Understanding the concerns and fears underlying any opposition to BC is essential for effective engagement of conservation practitioners and scientists (Warner et al., 2009; Warner, 2012). Indeed, in New Zealand, where IAP BC is widely and regularly applied, public consultation happens at the beginning of a programme once a target is proposed (Ehlers et al., 2020). The apparent bias or 'mistrust' against IAP BC had also emerged during an exploratory survey amongst the delegates of the Ecology and Management of Alien Plant Invasions (EMAPI) 2018 Conference, conducted by the authors. 101 delegates out of 189 completed the survey, of which most were European, and when asked whether lab/quarantine studies can adequately determine the field safety of a proposed biocontrol agent, over 50% either agreed or strongly agreed. However, when asked whether an agent is likely to attack non-target plants or crops after being tested for specificity and approved for release, only a third of delegates either agreed or strongly agreed, suggesting that some scientists were willing to ignore the evidence from the literature and their own understanding of lab studies and "let their hearts rule their heads" (Shaw et al., 2017). The results from this exploratory survey drove the authors to investigate further and begin the study now presented.

In this context, our main objective in this study was to examine the knowledge, experience, and perceptions of BC of IAP in Europe amongst researchers and other professionals concerned with biological invasions. Specifically, we aimed to answer the following research questions: 1) What is the difference in knowledge and perception of BC of IAPs between professionals from the EU (with hardly any adoption of the method) and professionals in non-EU countries including where BC of IAP is common? 2) Does the perception of BC differ when the target is an

IAP or invertebrate pest? 3) How does knowledge of, and experience with, BC affect perception of BC? We assessed these by means of an online survey distributed amongst relevant professionals worldwide.

2. Material and methods

2.1. Questionnaire design

We collected our data using an online questionnaire. The questionnaire included three main sections, each with six questions. The first section addressed demographic descriptors (age, gender) geographic location (country of residence/work) and experience level (education level, profession, and self-assessed level of expertise in BC). The second section included questions on knowledge of the use of BC against IAP and insect plant pests in the country of residence/work, on the use of BC in general, and on the perceived safety of use of BC against IAP. Furthermore, we asked respondents to give one example of successful and unsuccessful classical biological control agents. The third section was designed to examine respondents/perception of BC, including their opinions on the use of BC to manage IAP, the potential reasons for not using BC against IAP in their country of residence/work, and their level of agreement with different statements about the BC of IAP. The full questionnaire is available in the Supplementary Material S1.

Most questions were closed, with either one or multiple answers possible. Statements were measured on a 5-point scale ranging from “Always” to “Never” or from “Strongly agree” to “Strongly disagree”. Open questions were used to ask for species examples (section 2) and potential reasons for the disparity of BC use in the EU compared with the rest of the world (section 3). To avoid multiple interpretations, we provided a definition of classical biological control (CBC) at the beginning of the questionnaire as follows: “This control method involves the identification and release of natural enemies, normally arthropods or fungi, from the native range of the invasive plant/weed for the permanent control of the target weed in the invaded range. This is carried out after host range safety testing often in a quarantine facility and normally permissions are only granted after some form of risk assessment by the relevant authorities in the release country.” The survey was kept quite short (taking ca. 15 min to complete to maximise the number of responses and avoid incomplete responses.

2.2. Data collection

The questionnaire was supplied online using SurveyMonkey® and a link was generated to provide access to the survey. Our survey targeted researchers, policy makers and other professionals in the field of biological invasions, in particular those working with IAP, environmental management, and nature conservation. We expected the target audience to have some understanding of the topic, though the extent of this knowledge was likely to vary considerably. We targeted professionals in the EU (including the UK), as well as those in countries outside Europe, which included countries where BC against IAP has been widely used for many decades, e.g., South Africa, USA, and Australia.

The link was distributed using mailing-lists targeting respondents in the EU and globally, including lists of environmental related conferences (e.g., EMAPI, International Symposium on Biological Control of Weeds), topic-relevant list servers (e.g., Aliens-list, ENTOMO-L, Belgian Forum on Invasive Species), institutional lists of the authors, professional societies and working groups (e.g., Society for Conservation Biology, regional sections, Portuguese Society of Ecology, International Organization of Biocontrol, European Weed research Society). In addition, we advertised the survey via relevant accounts on Twitter and Facebook (e.g., International Association for Open Knowledge on Invasive Alien Species (INVASIVESNET), Espécies Invasoras em Portugal, Grupo de Investigación en Especies Invasoras). Participation in this study was voluntary, anonymous, and respondents were able to withdraw at any stage.

The questionnaire was available between 14th June and July 17, 2018. A total of 796 unique responses to the survey was received. All data were collected and stored in accordance with the General Data Protection Regulation (GDPR). None of the questions asked for personal information. In cases where personal information such as names or email-addresses were provided voluntarily, we deleted this information from the dataset before distribution amongst the team for analyses. Respondents were informed about the purpose of this study on the first page of the survey and agreed to participate in this study via an OK button. They were also offered the chance to receive summarised data.

2.3. Data analysis

Incomplete responses and responses from respondents with unrelated occupations (not from our target population) were removed from the analyses, resulting in 702 responses being analysed. The information about the country of work/residence was used to assign respondents to the EU (including all countries on the European continent including the UK) and non-EU groups. Responses of “other” occupations were checked and whenever logic were assigned to one of the following categories: researcher, manager, policy maker, or kept as “others”. Reported examples of successful or unsuccessful BC were checked for accuracy and categorised according to target type (weed/invasive plant BC vs. insect/invertebrate pests BC vs. another target – e.g., rats or rabbits) and geographic area (EU vs. non-EU). The answers to the open-ended question about “Why biocontrol is little used in Europe compared to the rest of the world” were analysed qualitatively by two of the authors and grouped into categories (Supplementary Material S2). We compared the responses provided by EU respondents and by non-EU respondents where appropriate. Statistical significance of differences between EU and non-EU groups were determined using Two Proportion Z-Test ($p < 0,05$; function computed in Excel), after verification of its assumptions.

3. Results

3.1. Sample characteristics

Of the 702 responses, distributed by 67 countries, 57% came from Europe and of these, almost half the answers came from the only two countries that had actually introduced biological control agents against IAP on their territory before the time of the survey (Portugal and the UK). The remaining 43% of the answers came from other continents. In the case of non-European respondents there was a high representation from Africa (mostly South Africa), North America (mostly USA) and Oceania (mostly Australia; Table 1), i.e., from continents and countries where BC is used most. A detailed distribution of respondents by country of origin/work is available in Supplementary Material S3.

Respondents came from different age groups, with the majority ranging between 25 and 64 years old. More than 75% were highly educated, having either an MSc or PhD degree, and most were either researchers or practitioners (ca. 85% together) (Table 2). About 60% of the respondents considered that they had “some knowledge” about BC of

Table 1
Region of respondents distributed by continents where they currently work/live. In each continent where respondents from a country were dominant, its percentage, from the continent, is indicated. (N = 702; 303 non-EU; 399 EU).

Continent (countries)	Responses (%)
Europe (mostly from UK and Portugal)	**56.8%** (27.1% UK, 17.0% PT)
non-Europe	**43.2%**
Africa (mostly South Africa)	12.1% (78.8%)
North America (mostly USA)	11.0% (88.3%)
Oceania (mostly Australia)	11.8% (67.5)
Asia	6.1%
South America	2.1%

Table 2
Characterization of respondents concerning age, level of education, type of occupation, level of expertise on biocontrol of invasive plants and gender.

Age	%	Education	%	Occupation	%	Expertise	%	Gender %	
18 to 24	2.1	High School	2.7	Researcher	50.9	Expert	18.5	Male	57.8
25 to 34	21.4	Technical	3.3	Practitioner	35.5	Some knowledge	62.1	Female	41.3
35 to 44	23.8	BSc	16.1	Policy maker	8.3	Little/no knowledge	18.4	Other	0.9
45 to 54	27.4	MSc	32.5	Other	5.4	Other	1.0		
55 to 64	16.8	PhD	45.4						
65 or older	8.5								

IAPs, while only 19% identified themselves as experts in the field; and ca. 20% had little or no knowledge about the subject. More men than women provided responses (Table 2).

3.2. Knowledge about biocontrol

When asked if BC was used against invasive plants/weeds in the country where they live/work, significantly more respondents from non-EU countries said “yes” (86%) than EU respondents, where only around half respondents (48%) answered “yes”, with the other half of EU respondents either responding that it was not used or didn’t know (Table 3). As for BC used against insects/plant pests, despite the majority (over 75%) of both EU and non-EU respondents reporting that it was used in their countries, the non-EU proportion was still significantly higher than those in the EU (Table 3).

A much higher proportion of EU respondents acknowledged the use of BC against insects/plant pests in the EU compared to its use against invasive plants, while in non-EU countries it was very similar between the 2 taxonomic groups.

The “yes/no” of respondents were then cross-checked with the known existence of BC in their own countries. Of those that responded with a “yes” or “no” answer rather than “don’t know” or skipped, a remarkable 99% of non-EU respondents were correct (258 out of 261) whilst only 72% of EU respondents were accurate (240 out of 334). Within the EU, of the 94 respondents who were not correct 67 of them answered that weed BC was used in their country when it has not yet been, as opposed to the 27 who thought not when it has been. It is also worth noting that the three incorrect responses from non-EU countries were also false positives.

For respondents answering that BC was not used against invasive plants in their own country, they were asked about why they thought this is the case. The most selected answer by EU respondents was “Lack of successful examples in the country or region/continent” followed by “Research and administrative procedure being too complex/expensive/long” which was also the second most frequently mentioned reason by non-EU respondents (Table 4). This last group also referred to a “Lack of framework for regulation at National/Regional level”. We did not find any significant differences between respondents from EU and non-EU regions, except for the response “Lack of framework for regulation at National/Regional level” which was chosen more often by non-EU, both regarding invasive weeds and insect/plant pests. The number of respondents that answered the same question regarding BC against insects/plant pests was much lower, but the reasons most frequently picked were rather similar (Table 4).

Table 3
EU and non-EU respondent’s answers (in %) to the questions “As far as you know, is biological control used against INVASIVE WEEDS in the country where you live/work?” and “(…) against INSECTS/PLANT PESTS (…)?” (N = 702; 303 non-EU; 399 EU).

	Is BC against INVASIVE PLANTS/ WEEDS used in your country			Is BC against INSECTS/PLANT PESTS used in your country		
	EU	**Non-EU**	*p-value*	**EU**	**Non-EU**	*p-value*
Yes	48.0	86.1	<0.001	77.4	86.8	0.002
No	34.8	9.2	<0.001	10.5	5.0	0.007
Don’t know	16.3	4.6	<0.001	12.0	8.3	0.104

Table 4
EU and non-EU respondent’s answers to the questions “Why do you think BC against INVASIVE WEEDS is not used?” (N = 167) and “(…) against INSECTS/PLANT PESTS is not used?” (N = 57). Multiple answers were possible; values refer to the number of times each option was selected; only respondents answering “No” to previous question answered.

	BC against WEEDS			BC against INSECT PESTS		
	EU	**Non-EU**	**p -value**	**EU**	**Non-EU**	**p -value**
Lack of successful examples in the country or region/ continent	**71**	**14**	*0.917*	**15**	7	*0.454*
Research & administrative procedure too complex/ expensive/long	**59**	**16**	*0.154*	**13**	6	*0.523*
Lack of framework for regulation at National/ Regional level	**46**	**17**	***0.006***	9	**10**	***0.001***
Public distrust/concerns about safety	41	6	*0.386*	**12**	3	*0.518*
Biological control is generally not accepted	35	4	*0.214*	7	2	*0.761*
Invasive weeds are not perceived as a large problem	33	11	*0.089*	9	3	*0.907*
Other techniques are already effective	34	4	*0.241*	10	2	*0.393*
Other (please specify)	20	7	*0.164*	4	4	*0.101*
Number of respondents that answered NO in each situation (N)	139	**28**		**42**	**15**	

When compared to non-EU countries, significantly fewer EU respondents ($p < 0.001$) claimed to know successful biological control agent examples (87% vs. 57%, respectively). No difference was found between groups regarding their knowledge of unsuccessful examples ($p = 0.339$) (Fig. 1).

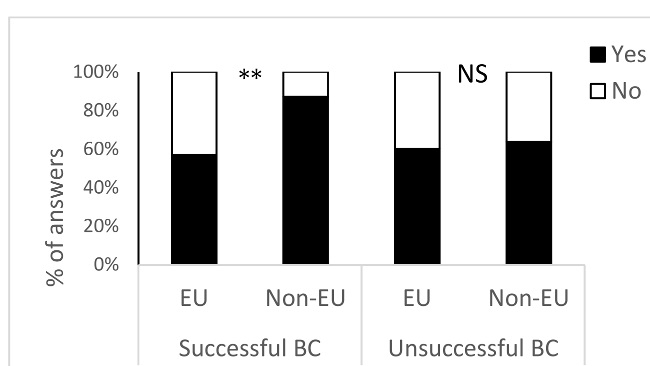

Fig. 1. EU and non-EU respondent’s answers to the questions “Do you know an example of SUCCESSFUL classical biological control (of any non-native target, plant, insect or other animal)?” and “(…) UNSUCCESSFUL (…)?” (N = 702). ***$p < 0.001$. NS = non-significant.

Eighty-five percent of the non-EU respondents reported an example (which was not necessarily a correct one) of a successful biological control agent and/or their target species (i.e., with a specific species or genus name), compared to 52% of EU respondents. The accuracy of these examples also varied between regions with non-EU recipients recording an accuracy rate of 88% and their EU equivalents only achieving 67%. The most frequently-mentioned agents were quite different amongst respondents of different regions (Table 5): EU respondents mentioned agents that are present in the EU, intentional (*Trichilogaster acaciaelongifoliae* against *Acacia longifolia; Torymus sinensis* against *Dryocosmus kuriphilus*) or accidental introductions (*Stenoplemus rufinasus* against *Azolla,* also frequently mentioned by non-EU) or famous examples from overseas, such as *Cactoblastis cactorum* against *Opuntia* or ladybugs against aphids. Non-EU respondents more frequently recalled agents for *Opuntia* (*Cactoblastis* as EU respondents but also *Dactylopius*), *Eichhornia* (*Neochetina,* less reported by EU), and *Tamarix* (*Diorhabda*, never mentioned by EU respondents) as successful (Table 5). Seven out of ten examples of successful BC by EU respondents referred to weed BC and three were cases of BC of insects. Except for rabbits (at the lower end of the Top 10 for both regions), the full top 10 of non-EU respondents comprise weed BC examples.

Regarding unsuccessful examples, the two regions had similar numbers with 58% of EU and 61% non-EU respondents being able to report BC agents and/or targets, which were correct in 82.3% and 82.8% of the cases, respectively. The most well-known unsuccessful example was *Rhinella marina*/cane toad, which was mentioned most often by respondents from both regions (Table 6). *Harmonia axyridis*/Harlequin ladybird was also frequently recalled by EU respondents ahead of *Aphalara itadori* (the first agent intentionally released against an invasive plant in EU/UK but not yet having impact), and “common knowledge” examples such as foxes and myxomatosis to control rabbits in Australia.

Non-EU respondents frequently referred to *Lantana* (on 15 occasions) and thistles (in general, several target species (on 17 occasions), including several agents) (Table 6). The top 10 of unsuccessful agents included several examples where the targets were neither insect pests nor weeds, but vertebrates (rabbits, mice, rats etc.). It is notable that only three unsuccessful top 10 examples given by EU respondents (vs. 6 of non-EU) were weed biocontrol agents.

Table 5
Top 10 most mentioned examples, by EU and non-EU respondents, of SUCCESSFUL species of Biological Control Agents (N = 484). Numbers in parentheses are not part of Top 10 of the Region; they refer to the number of times the species was reported and are included because they are part of the other Region Top 10. The left column refers to the type of biocontrol: wb – weed biocontrol; ib - insect biocontrol; o – other target.

BC	Target (common ID)	Biological control agent	EU	Non-EU
Wb	*Azolla*	*Stenopelmus rufinasus/Azolla* weevil	25	11
Wb	*Acacia longifolia*	*Trichilogaster acaciaelongifoliae*	14	(3)
Wb	*Opuntia*	*Cactoblastis (C. cactorum,* genus)	14	26
Ib	Aphids	Ladybugs/*Adalia bipunctata/ Coccinellidae*	12	(1)
Ib	*Dryocosmus kuriphilus*	*Torymus sinensis*	11	(0)
Ib	insects …	*Bacillus thuringiensis*/BT	11	(1)
Wb	*Eichhornia crassipes*	*Neochetina* (sp. ID; genus; weevil …)	8	14
Wb	*Salvinia*	*Cyrtobagous salviniae*/Salvinia weevil	7	8
Wb	*Opuntia*	*Dactylopius* (spp.and species ID)/ cochineal	5	16
Wb	*Hypericum perforatum*	*Chrysolina* beetles	5	9
O	rabbit	*Myxomatosis*	5	6
Wb	*Tamarix*	Diorhabda/tamarisk beetle	(0)	11
Wb	*Parthenium hysterophorus*	*Zygogramma bicolorata*	(1)	8
Wb	*Lythrum salicaria*	*Gallerucella* spp./Neogallerucella	(0)	7

Table 6
Top 10 most often mentioned examples, by EU and non-EU respondents, of UNSUCCESSFUL species of Biological Control Agents (N = 447). Numbers in parentheses are not part of Top 10 of the Region; they refer to the number of times the species was reported and are included because they are part of the other Region Top 10. The left column refers to the type of biocontrol: wb – weed biocontrol; ib - insect biocontrol; o – other target.

BC	target (common ID)	Agent	EU	Non-EU
Ib	Dermolepida albohirtum/cane beetle	*Rhinella marina/Bufo marinus/* cane toad	49	46
Ib	Aphids	*Harmonia axyridis*/ladybeetle/ Harlequin ladybird	48	5
Wb	Japanese knotweed	*Aphalara itadori*/psyllid	11	(0)
O	rabbits	*Myxomatosis*/rabbit viruses	11	(0)
O	rabbits	*Vulpes vulpes*/fox	10	(1)
Wb	Carduus, Cirsium, Silybum, …	*Rhinocyllus conicus* (EU-6; non-EU-11)/*Cirsium* agents	8	17
Ib	Anopheles/mosquitos	*Gambusia* (affinis, sp, …)	7	(2)
Wb	Centaurea/Cirsium	*Urophora* spp.	5	4
O	rats, snake, rabbits	mongoose	4	6
o	mice, rats	cats	4	(2)
wb	Lantana	agents *Lantana* (some ID others general)	(2)	15
Wb	*Eichhornia crassipes*/ water hyacinth	agents on *Eichhornia crassipes* (some ID others general)	(3)	6
wb	Opuntia spp	*Cactoblastis* (4) + other *Opuntia* agents (2)	(3)	6
wb	Ulex/gorse	*Ulex* agents (*Agonopterix* 2); moth 1); coleoptera 2))	(0)	6
O	Rabbits	Stoats	(2)	5

3.3. Perceptions of biocontrol

When asked the question: “With reference to biological control for managing INVASIVE WEEDS, which of these statements do you most agree with?” respondents from both regions most often chose the answer “An environmentally safe and sustainable alternative to control invasive weeds”, though the proportion of non-EU respondents that chose this option was higher ($p < 0.001$, Table 7), particularly amongst practitioners and researchers (Table 8). A significantly higher percentage of EU respondents considered BC of invasive weeds “A risky alternative to control invasive weeds” ($p < 0.001$, Table 7), particularly practitioners and researchers (Table 8). Significantly more researchers from non-EU countries consider BC as “The best option to control invasive weeds”.

When comparing the answers to the question above between respondents with different levels of knowledge about weed BC, we found that experts more often consider it to be an environmentally safe and sustainable alternative (ca. 70%) when compared to respondents with lower levels of self-assigned knowledge (Table 9). Moreover, responses from EU and non-EU respondents were different particularly for respondents that describe themselves as having “some knowledge” about

Table 7
Percentage of EU and non-EU respondents responding to the question “With reference to biological control for managing invasive WEEDS, which of these statements do you most agree with?” (N = 702). Values above 30% and significant differences are in bold.

	EU (%)	Non-EU (%)	*p* -value
The best option to control invasive weeds	8	14	***0.025***
An environmentally safe and sustainable alternative to control invasive weeds	**40**	**57**	***0.000***
A risky alternative to control invasive weeds	**33**	13	***0.000***
Interfering with nature	5	1	***0.016***
Other (please specify)	14	16	*0.584*

Table 8

The percentage of EU and non-EU respondents responding to the question "With reference to biological control for managing INVASIVE WEEDS, which of these statements do you most agree with?" considered their type of occupation (N = 702). Values above 30% and significant differences are in bold.

	Researcher			Practitioner			Policy maker			Other		
	EU (%)	**Non-EU (%)**	p-value	**EU (%)**	**Non-EU (%)**	p-value	**EU (%)**	**Non-EU (%)**	p-value	**EU (%)**	**Non-EU (%)**	p-value
The best option to control invasive weeds	9	15	***0.048***	8	11	*0.360*	11	0	*0.133*	5	25	*0.066*
An environmentally safe and sustainable alternative to control invasive weeds	**45**	**57**	***0.022***	**30**	**56**	***0.000***	**58**	**65**	*0.599*	**36**	**56**	*0.224*
A risky alternative to control invasive weeds	30	12	***0.000***	**39**	13	***0.000***	21	10	*0.290*	**41**	13	*0.057*
Interfering with nature	4	2	*0.258*	6	1	*0.055*	3	0	*0.464*	5	0	*0.387*
Other (please specify)	13	14	*0.846*	17	19	*0.770*	8	25	*0.073*	14	6	*0.464*

Table 9

The percentage of EU and non-EU respondents responding to the question "With reference to biological control for managing INVASIVE WEEDS, which of these statements do you most agree with?" considered the level of expertise on BC of invasive plants (N = 702). Values above 30% and significant differences are in bold.

	Expert			Some knowledge			Little/no knowl.			Other		
	EU (%)	**Non-EU (%)**	***p-value***	**EU (%)**	**Non-EU (%)**	***p-value***	**EU (%)**	**Non-EU (%)**	***p-value***	**EU (%)**	**Non-EU (%)**	***p-value***
The best option to control invasive weeds	17	17	*0.916*	10	12	*0.394*	**1**	**13**	***0.002***	0	0	–
An environmentally safe and sustainable alternative to control invasive weeds	72	65	*0.465*	**37**	**55**	***0.000***	33	43	*0.316*	33	100	*0.212*
A risky alternative to control invasive weeds	7	4	*0.443*	**34**	**13**	***0.001***	43	33	*0.325*	17	0	*0.659*
Interfering with nature	0	1	*0.458*	3	1	*0.135*	8	3	*0.371*	33	0	*0.495*
Other (please specify)	4	13	*0.112*	16	18	*0.513*	14	7	*0.277*	17	0	*0.659*

BC: significantly more non-EU respondents considered BC a safe and sustainable alternative, while significantly more EU respondents considered it a risky alternative (Table 9).

The survey included a number of statements describing impacts of invasive alien species and the effectiveness and risk of BC, with answering categories ranging from "always" to "often" (Fig. 2). Non-EU respondents were more positive about all statements about BC safety, sustainability, environmental friendliness, and cost-effectiveness, using "always" or "often" to classify them, more frequently than their EU peers. More than 80% of non-EU respondents recognized that invasive species are often or always a threat to biodiversity, compared to ca. 70% of EU respondents. The use of BC against insect pests was considered as safe by fewer non-EU (67%) and EU (50%) respondents than BC of weeds (80% and 55%, respectively). About one in ten of the EU respondents (13%) did not have an opinion regarding the cost effectiveness of BC.

When the responses regarding some of the above statements were analysed considering respondents' expertise on weed BC a pattern arose: the level of expertise affects appreciation of all aspects analysed [cost-effectiveness, sustainability (Fig. 3) and safety (Fig. 4) of weed BC] with scores clearly showing an increasing pattern as the level of expertise on weed BC raises, which was particularly marked in relation to the sustainability of BC (Fig. 3a) and safety of weeds BC (Fig. 4), where "always" and "often" exceeded 90% in respondents from both regions. Additionally, it is also clear that EU scores (if "always" and "often" are both considered) are frequently lower among the non-Experts, but more

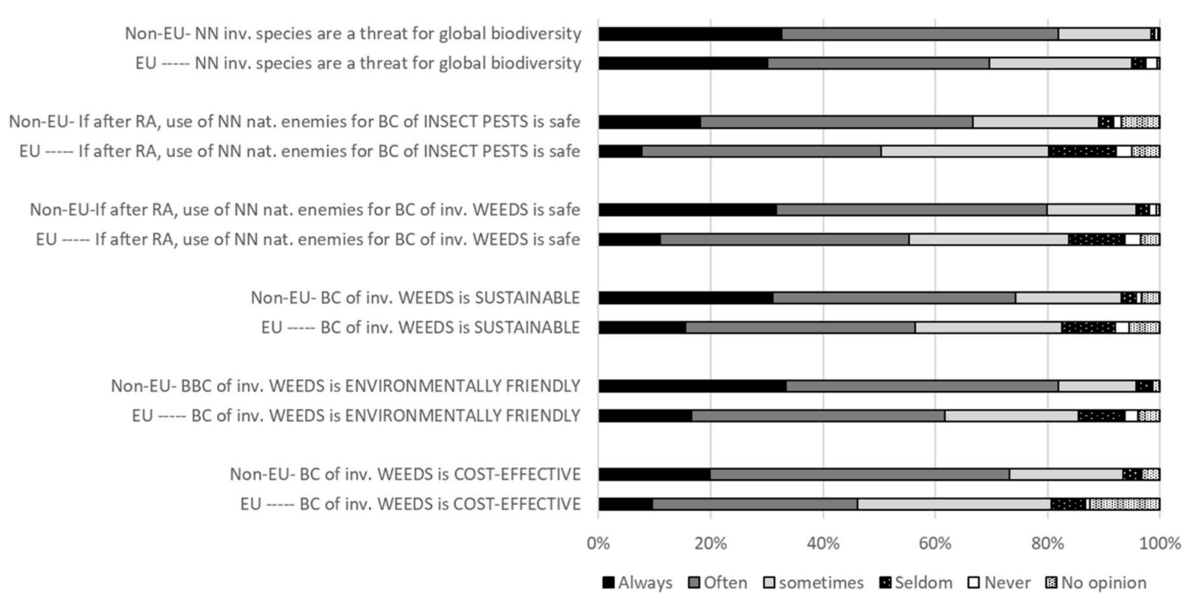

Fig. 2. Percentage of EU and non-EU respondents (N = 702) classifying statements (from always to never) that describe impacts of invasive alien species and the safety, sustainability, cost-effectiveness, and potential risks of biocontrol of weeds/insect pests. In y axis, some words were shortened to increase readability: NN = non-native; inv. = invasive; RA = risk assessment; nat. = natural; BC = biocontrol).

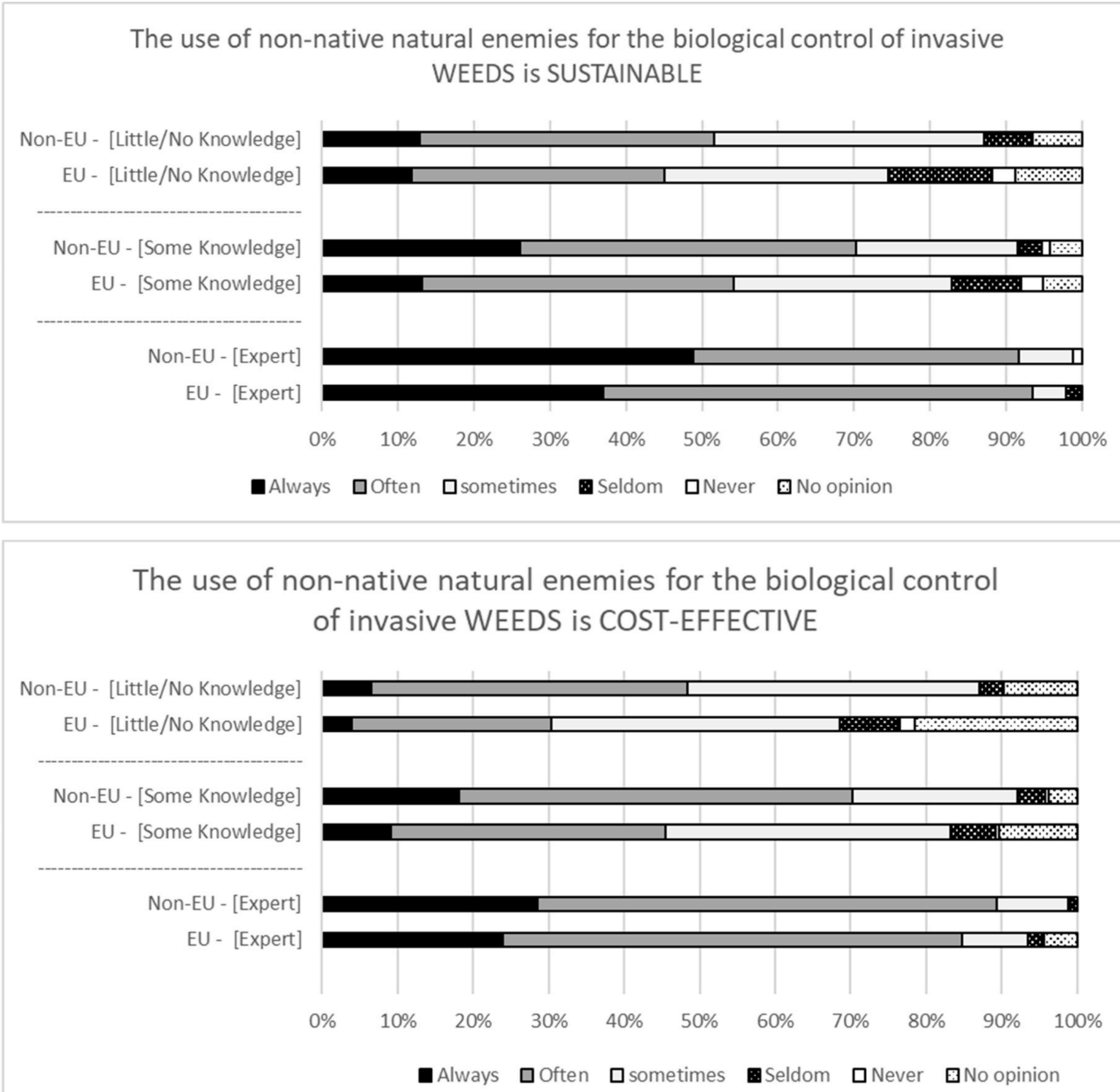

Fig. 3. Average scores to statements about weed biocontrol, including a) sustainability, and b) cost-effectiveness of BC of invasive weeds according to respondents' level of expertise.

like non-EU among specialists (Fig. 3).

Independent of the influence of the region, Experts more often considered the use of non-native natural enemies for the BC of weeds in the wild as safe if applied after rigorous risk assessment (over 50% of the Non-EU respondents answered "always" safe, reaching over 90% if "often" safe is also considered), and safer than for the BC of insect pests (ca. 25% of both EU and non-EU respondents answered "always"; around 80% when gathering "often" safe) (Fig. 4). The other knowledge groups selected "Sometimes" safe more often, more pronouncedly as the level of knowledge decreased, when referring to safety of BC after rigorous risk assessment (Fig. 4) with quite similar trends amongst different BC targets (weeds and insect pests).

Regarding the more technical aspects of BC, 70% of respondents from non-EU countries "strongly agree" or "agree" with the adequacy of lab/quarantine tests to determine BCA safety, compared to 42% of those from the EU reporting similar confidence. In fact, almost 35% of EU respondents expressed disagreement/strong disagreement regarding this statement. When presented with the statement that a BCA is likely to attack non-target plants or crops after being tested for specificity and approved for release, over 55% of non-EU respondents disagreed with the statement (>76% if including "neither agree or disagree"), while only <34% EU respondents disagreed (Fig. 5). 90% or more respondents, from either EU or non-EU, strongly agree/agree that all BCAs, whether new or used elsewhere, should have a full pest risk analysis (Fig. 5).

Responses to the open question of why so little BC against invasive plants takes place in Europe compared to the rest of the world, revealed that the two most often mentioned categories, both by EU and non-EU respondents, were related to 1) BC being considered risky (e.g., BC being unsafe and negative public opinion) and 2) due to difficulties associated with regulations and procedures for the introduction of biocontrol agents (e.g., lack of regulatory harmonization across countries, very demanding procedures and protocols, etc.) (Fig. 6). EU respondents also mentioned more often that chemical (or other) controls used in Europe worked and were dominating, and that there was a lack of research interest and funding.

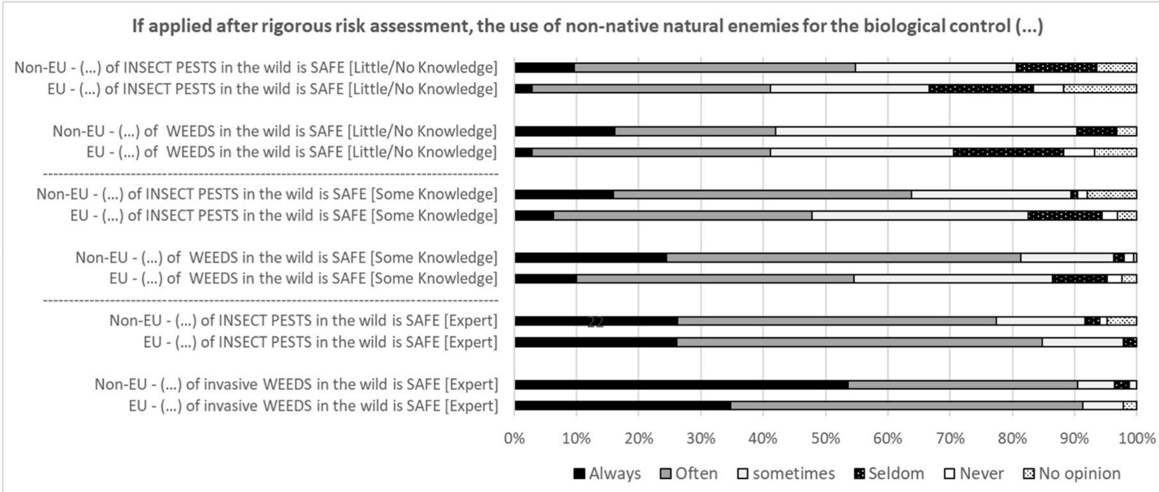

Fig. 4. Average scores for statements about the safety of biocontrol of weeds and insect pests, from non-EU and EU, considering their level of expertise regarding BC, regarding two statements: safety of BC of invasive weeds, vs. BC of insect pests, after RA.

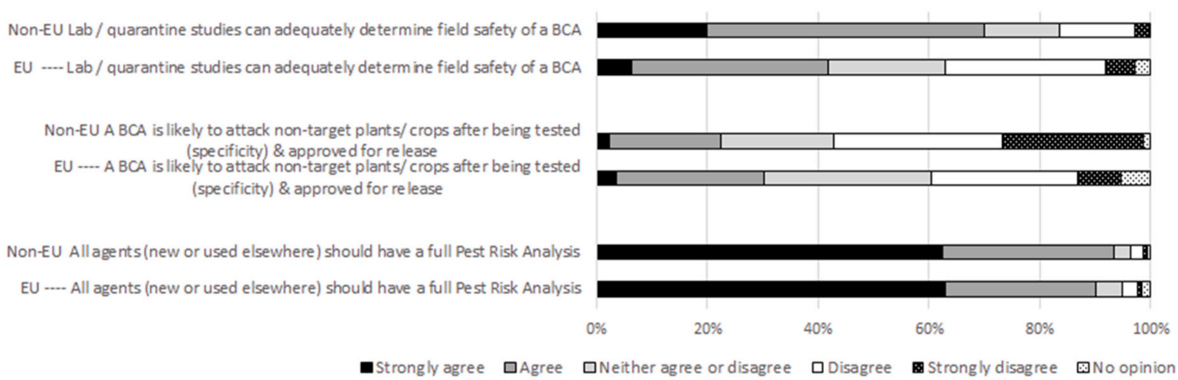

Fig. 5. Percentage of EU and non-EU respondents answering to statements about risk analysis and field safety of the use of Biological Control Agents (BCA).

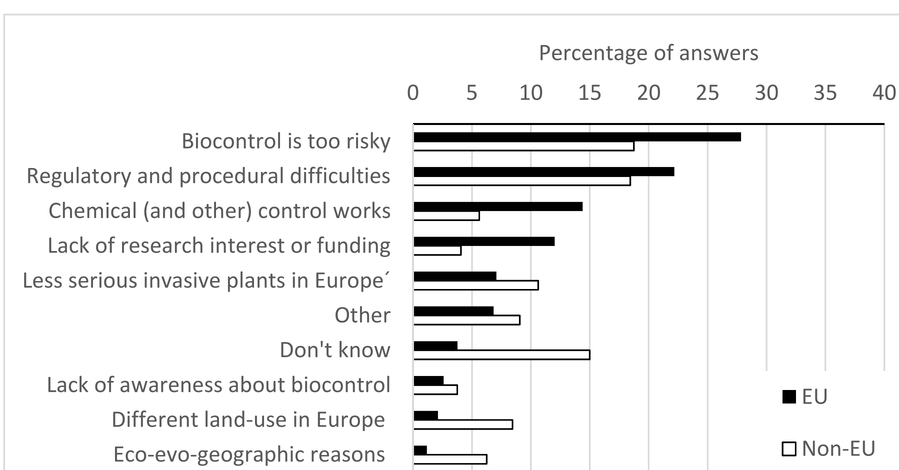

Fig. 6. Responses to the open question "Weed biocontrol is little used in Europe compared with the rest of the world. Why do you think this may be?" after categorization.

4. Discussion

4.1. Knowledge and perceptions of biological control in EU vs. non-EU countries

In this study, we compared the knowledge and perception of EU and non-EU researchers, policy makers and other professionals in the field of biological invasions regarding biological control (BC). In general, our findings suggest that knowledge of BC is higher amongst non-EU than EU respondents. Non-EU respondents had a remarkably accurate understanding (99%) of whether BC was used in their own country, while EU respondents not only had lower knowledge, but almost one in five (ca. 17%) considered erroneously that weed BC was used in their country. In addition, our study highlights that while the majority (ca. 85%) of non-EU members know of successful examples of BC and are indeed able to name them correctly (in 88% of cases), only about half of the EU respondents could give an example of successful BC, of which one-third were incorrect. The perceived knowledge of unsuccessful examples was similar amongst both regions with around 60% of all respondents able to name examples which were correct around 80% of the time. In other words, when comparing knowledge of successful *vs.* unsuccessful examples, we found that non-EU respondents are more aware of successful cases, while EU respondents know more about examples of failure. This can be particularly helpful to better understand the reasons behind any reservations over the use of BC in Europe (see next section).

When giving examples, non-EU respondents named more recent and/or specific unsuccessful examples (species or genera) including weed/invasive plants BCA (e.g., *Lantana, Carduus, Cirsium, Ulex* agents) while EU respondents more frequently mentioned historical examples including several against vertebrates (e.g., fox and *Myxomatosis*) or highly publicised examples (e.g., cane toad or *Harmonia*). The latter could be explained by the fact that few BCA are in use in Europe. Interestingly, respondents from both regions identified several species as both successful and unsuccessful (e.g., *Myxomatosis*, *Aphalara*, *Cactoblastis*) although not in large numbers. Most of these examples could be attributed to the difficulty in deciding on success of agents, but in the case of *Cactoblastis,* however, it could be explained by the very real contrasts between extraordinary success in most of the introduced range and the situation in North/Central America, where its accidental arrival poses a threat to native cacti (Zimmermann et al., 2001). Somewhat curiously, the successful examples mentioned by EU respondents included some of the few IAP BCAs present in the region (e.g., *Trichilogaster acaciaelongifoliae* and *Stenopelmus rufinasus*), despite lack of successful examples being identified as one of the main reasons for lack of use of BC against IAP.

Not only was respondents' knowledge different between the regions, but there were also contrasts in the perceptions of risk and effectiveness of the technique. For instance, we found that the perception of BC as being a "safe, sustainable and environmentally friendly tool" was relatively high in both regions, however, it was consistently more positive regarding all topics in non-EU regions. For example, when compared to non-EU respondents, EU respondents more often disagreed with the statement regarding the adequacy of lab/quarantine tests to determine BCA safety. EU respondents were also more inclined to consider that agents may attack non-targets even after passing the safety testing process. Dismissing this perception as 'mistrust' may be tempting but also too hasty, as trust is complex and determined by multiple factors, such as trust in institutions, trust in models, or trust in people that need to follow procedures. Further research is needed to determine the reasoning behind these answers and whether they are trust-related or not, but the implication is that work is needed to explain the efficacy of safety testing and highlight the reassuring results of post-release non-target monitoring.

The selection of BC as being "the best option" was quite minimal, and particularly low in the EU, except amongst experts. We also found that the perception of BC safety was higher amongst those that considered themselves experts in the subject. This was independent of the region and reinforces the case that better-informed people accept more the BC of IAPs something shown in other areas including acceptance of evolutionary theory for example (Weisberg et al., 2018). In this light, the recent calls for communication and education to increase awareness and public and regulatory support for BC (McNeil et al., 2010; Messing and Brodeur, 2018) appear to be justified.

4.2. BC of insects' pests vs. weeds

Fewer respondents considered BC of insects/plant pests as always/often safe, when compared to BC of weeds in both EU (where the difference was ca. 5%) and non-EU (ca. 15% difference) groups. This suggests some understanding of the relative safety of the two groups of agents and perhaps the level of safety testing required or the track record post-release. Weed/IAP BC is better established and requires more extensive testing (van Lenteren et al., 2006). If weed BC would be considered as always/often safe by more people alongside a deeper knowledge of successful examples in future driven perhaps by awareness raising efforts, this should help to increase its acceptability in the EU, particularly when compared to insect BC that is already frequently used. There is a possibility that other factors are at play including negative perceptions of insect predators and parasites and the widespread awareness of the negative impacts of *Harmonia axiridis* as well as the likelihood that more "weed-aware" people were approached to comment. Despite BC being commonly considered a more sustainable and cost-effective methodology (Page and Lacey, 2006), less than 50% of the EU respondents consider the technique being "often/always" cost-effective; reinforcement of this information could also be a worthy subject for communication about BC.

4.3. Reasons for non-use of BC against invasive weeds in Europe

Two questions from our survey shed more light on why people might oppose the use of BC for managing IAPs. The most often selected reason by EU respondents was the lack of successful examples in their own region. Interestingly this was also in the top three reasons by non-EU respondents and reinforces the importance of having good examples to create awareness and motivate additional use of this technique. In this context, new releases such as the Japanese knotweed psyllid in the UK (Shaw et al., 2018) may not be the best example to use until impact is evident and indeed visible. Conversely, the *Acacia longifolia* gall wasp released in Portugal (López-Núñez et al., 2021) provides more visually impressive results. Although not strictly a classical BCA, the azolla weevil was rightly perceived as a successful agent by respondents since it has largely replaced traditional physical control measures for this floating weed in the UK where it is mass produced and redistributed (Reeder et al., 2018) but it is an exception to the general rule of post-release stable equilibrium between host and agent and may raise expectations too high for actual eradication which is never the goal of classical biocontrol. Unsuccessful examples were commonly acknowledged by respondents in both regions, confirming previous studies even from regions with a long history of BC as Hawaii (Johnson, 2016). Yet, the good examples, correctly identified, were much more evident in answers from non-EU respondents than from EU respondents. It would seem that with EU respondents, the recall of negative examples is easier than positive ones probably due to the lack of use and awareness of CBC. Interestingly, the 52% of EU respondents that were able to name successful examples frequently highlighted the few biological control agents present in their territory which shows that good news can spread well or that recent news is more memorable. However, the results may be considered somewhat biased in that almost half of the respondents (ca. 47%) were from the UK and Portugal where weed BC has been pioneered in Europe (Shaw et al., 2018). The European "delay" in using BC may in fact be driven by a lack of awareness of successful existing examples from the field, or even the existence of the technique amongst policy makers in particular.

Other frequently selected reasons for the lack of BC use in Europe include “Research and administrative procedure being too complex/expensive/long” or “Lack of framework for regulation at National/Regional level”. Luckily, the speed of the authorization process is improving in the countries that are BC active in Europe. The authorization for the release of the first weed biocontrol agent in Portugal, *T. acaciaelongifoliae*, took around 12 years (Shaw et al., 2018) but since its release and initial signs of successful establishment, the authorization to test two new *Melanterius* spp. for other *Acacia* spp. was much quicker (less than one year to start testing, H. Marchante, pers. comm.). This pattern follows the same experience in the UK, and once the first agent has paved the way in a country it seems future applications will become easier. A possible explanation is that the lack of any non-target damage reassures regulators and politicians of the safety of this measure and that their pioneering decision was without negative consequences.

The replies to the open question on lack of use in Europe (albeit the limited answers) seem to suggest that respondents from both regions consider BC as “too risky” with EU respondents suggesting this more often. In the related multiple-choice question, answered by all respondents, risk was also selected but only ranked 4th place. Accordingly, when respondents were asked to choose a sentence to describe BC (apart from the distinct application in EU vs non-EU), the sentence “A risky alternative to control invasive weeds” was also commonly chosen. This concern over risk was consistent across all occupations (from practitioners to researchers) and knowledge levels but was especially pronounced (ranking 1st), in EU practitioners and EU respondents that describe themselves as having “little knowledge” on BC. In general, non-EU respondents in almost all occupations and levels of knowledge were more confident in the use of BC, which may be related to them knowing more about it and being more aware of successful examples. Again, one possible explanation for this disinclination of EU respondents to use BC is that they are less familiar with successful examples (and more familiar with unsuccessful ones) - despite world data showing the opposite, i.e., that there are more successful cases of BC than unsuccessful ones (Winston et al., 2014).

Other reasons suggested for the lack of use of BC in Europe were that: (1) chemical (or other) controls used in Europe work and are dominating, and (2) that there was a lack of research interest and funding to BC. Despite the fact that the use of chemicals in Europe has been raised as a possible reason, it may become an ephemeral issue at the medium term with increasing restrictions and public resistance (see more in 4.5). The lack of research interest and funding to BC may eventually be overcome if public awareness about BC continues to rise following more successful introductions thereby driving demand.

4.4. Limitations of our study

Our survey targeted higher educated professionals working in environmental management globally. We received a reasonably equivalent number of responses from EU and non-EU countries; however, our data also has a number of limitations/biases that need to be considered. Firstly, respondents from outside the EU often came from a limited group of countries where BC is used more often (for example, for Africa 79 out of 97 responses came from South Africa), failing to reach/sample proportionally the many other countries on that continent. Secondly, respondents were likely to have more knowledge of weeds than of arthropod pests due to our participant-sourcing approach that mostly targeted plant science communities. Nonetheless, a high proportion of respondents answered that they were aware of the utilisation of BC on pests in their country. The target audience of our study was probably more knowledgeable about, and had perhaps a more favourable attitude towards, BC than citizens in general; further research is needed to investigate this topic amongst the broader general population.

4.5. Implications for BC of invasive plants in Europe – can it be welcomed as a management tool in the future?

This survey work suggests that some work may be required to increase awareness and acceptance of weed biocontrol but other factors may also widen the opportunity for an expansion in use of IAP BC in Europe. First, the EU Invasive Species Regulation (Reg. EU 1143/2014) which requires Member States to take action against invasive alien species listed as being of Union Concern, mentions BC specifically as a tool to be considered and includes 40 IAP after the 2022 revision. Second, a general shift in public opinion away from the use of synthetic chemical pesticides and the large-scale reluctance to use herbicides on or near water or amenity land (Gaspar, 2021) in Europe gives room for alternative and integrated methods of invasive species management. It would be interesting to further investigate the general perceptions of community/ecosystem effects, and a comparison of weed BC versus other control methods.

As supported by the research presented above, broader uptake of BC is only likely to happen at pace if the public, including not just general citizens but also researchers, practitioners as well as their advisors and representatives, are aware of and convinced of the validity and safety of weed BC. Other studies have already shown that public awareness may be key to increase knowledge and support for IAP management (Cordeiro et al., 2020). Other authors highlight that it is important to understand the public to develop properly-informed and appropriate campaigns, strategies, and policies (Shackleton and Shackleton, 2016). A well-planned engagement campaign from the BC community is needed. Based on our findings, we suggest such a campaign to: (1) promote safe and successful examples, (2) increase general knowledge on weed BC, (3) include information about the sustainability and higher cost-benefits of BC when compared to other control methods, and (4) clarify and emphasise the rigorous safety testing procedures and risk-assessment requirements. Some authors (Hayes et al., 2008), argue that facilitated face-to-face dialogues can be very effective in building trust among key groups to be engaged in BC; although it involves substantial effort, it may prove easier and cheaper in the long run than a less interactive approach. For those countries not well-versed in weed BC, the azolla weevil may provide a suitable entry point, if the weed and the agent exist in the Member State. This is because the weevil can be considered as “ordinarily resident” and therefore requiring less licensing for redistribution, than would be for a novel introduction and the results are likely to be impressive and convincing.

In a broader sense, worldwide, Sun et al. (2022) recently highlighted that some reconciliations between advocates and critics of IAP BC is also needed in order to achieve a closer collaboration between the two groups hopefully leading to more and better IAP BC in the future. Additionally, other authors stress that in every BC process public engagement should be broad and start from the early stages, especially when there is potential for significant conflict, as better-informed people are more likely to give their support (Johnson, 2016).

In conclusion, weed biocontrol is practiced more extensively and with more acceptance outside of Europe than within and this research reveals some of the patterns in knowledge and perception of the technique. If uptake in Europe is to emulate that of the rest of the world, then there is a need to generate a greater awareness with a suggested focus on successful examples and the stringent safety measures and track record of modern weed biocontrol.

Credit author statement

All authors conceived the study and planned the experimental design/survey. HM, EM, SL and RS conducted data analyses. All authors wrote the manuscript with very regular discussions. All co-authors revised and approved the final version of the manuscript and all co-authors reviewed the resubmission contents.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Data availability

The authors do not have permission to share data.

Acknowledgements

Funding: EM and HM were supported by the Portuguese Science Foundation – FCT/MCTES by grant UIDB/04004/2020. SL received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 786624. RS is supported by CABI is an international intergovernmental organization, and we gratefully acknowledge the core financial support from our Member Countries (and lead agencies) including the United Kingdom (Foreign, Commonwealth and Development Office), China (Chinese Ministry of Agriculture), Australia (Australian Centre for International Agricultural Research), Canada (Agriculture and Agri-Food Canada), Netherlands (Directorate-General for International Cooperation) and Switzerland (Swiss Agency for Development and Cooperation).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.116896.

References

Baker, C., Blackman, R., Claridge, M., 1972. Studies on Haltica carduorum Guerin (Coleoptera: chrysomelidae) an alien beetle released in Britain as a contribution to the biological control of creeping thistle, Cirsium arvense (L.) Scop. J. Appl. Ecol. 9, 819–830.

Barratt, B.I.P., Moran, V.C., Bigler, F., van Lenteren, J.C., 2018. The status of biological control and recommendations for improving uptake for the future. BioControl 63, 155–167. https://doi.org/10.1007/s10526-017-9831-y.

Cordeiro, B., Marchante, H., Castro, P., Marchante, E., 2020. Does public awareness about invasive plants pays off? An analysis of knowledge and perceptions of environmentally aware citizens in Portugal. Biol. Invasions 22, 2267–2281. https://doi.org/10.1007/s10530-020-02247-z.

de Bach, P., 1964. Biological Control of Insect Pests and Weeds. Chapman and Hall Limited, London.

Diagne, C., Leroy, B., Vaissière, A.-C., et al., 2021. High and rising economic costs of biological invasions worldwide. Nature 592, 571–576. https://doi.org/10.1038/s41586-021-03405-6.

Ehlers, G.A.C., Caradus, J.R., Fowler, S v, 2020. The regulatory process and costs to seek approval for the development and release of new biological control agents in New Zealand. BioControl 65, 1–12. https://doi.org/10.1007/s10526-019-09975-9.

Eilenberg, J., Enkegaard, A., Vestergaard, S., Jensen, B., 2000. Biocontrol of pests on plant crops in Denmark: present status and future potential. Biocontrol Sci. Technol. 10, 703–716.

EU, 2014. Regulation (EU) No 1143/2014 of the European Parliament and of the Council of 22 October 2014 on the prevention and management of the introduction and spread of invasive alien species. Off. J. Eur. Union 317, 35, 21.

Gaspar, C.J.F., 2021. Citizens' Perceptions on Weeds and Their Control Using Synthetic Chemical Herbicides. Doctoral dissertation, Universidade de Coimbra.

Gerber, E., Schaffner, U., 2016. Review of Invertebrate Biological Control Agents Introduced into Europe. CABI, Wallingford, UK.

Ghosheh, H.Z., 2005. Constraints in implementing biological weed control: a review. Weed Biol. Manag. 5, 83–92. https://doi.org/10.1111/j.1445-6664.2005.00163.x.

Hayes, L.M., Horn, C., Lyver, P.0.B., 2008. Avoiding tears before bedtime: how biological control researchers could undertake better dialogue with their communities. In: Julien, M.H., Sforza, R., Bon, M.C. (Eds.), Proceedings of the XII International Symposium on Biological Control of Weeds (22-27 April 2007). CAB International, Wallingford, UK, 376382. La Grande Motte, France.

Johnson, M.T., 2016. Managing Conflict over Biological Control: the· Case of Strawberry Guava in Hawaii.

Knihinicki, D.K., Petanović, R., Cvrković, T., Varia, S., 2018. A new species of Aculus mite (Acari: eriophyidae), a potential biocontrol agent for Australian swamp stonecrop, Crassula helmsii (Crassulaceae). Zootaxa 4497, 573–585.

López-Núñez, F.A., Marchante, E., Heleno, R., et al., 2021. Establishment, spread and early impacts of the first biocontrol agent against an invasive plant in continental Europe. J. Environ. Manag. 290 https://doi.org/10.1016/j.jenvman.2021.112545.

Marchante, H., López-Núñez, F.A., Freitas, H., et al., 2017. First report of the establishment of the biocontrol agent Trichilogaster acaciaelongifoliae for control of invasive Acacia longifolia in Portugal. EPPO Bull. 47, 274–278. https://doi.org/10.1111/epp.12373.

McNeil, J.N., Cotnoir, P.-A., Leroux, T., et al., 2010. A Canadian national survey on the public perception of biological control. BioControl 55, 445–454. https://doi.org/10.1007/s10526-010-9273-2.

Messing, R., Brodeur, J., 2018. Current challenges to the implementation of classical biological control. BioControl 63, 1–9. https://doi.org/10.1007/s10526-017-9862-4.

Minks, A., Blommers, L., Ramakers, P., Theunissen, J., 1998. Fifty years of biological and integrated control in Western Europe: accomplishments and future prospects. In: 50th International Symposium on Crop Protection. Part I. Universiteit Gent 63 Faculteit Landbouwkundige En Toegepaste Biologische Wetenschappen, pp. 165–181. Mededelingen.

Mouttet, R., Augustinus, B., Bonini, M., et al., 2018. Estimating economic benefits of biological control of Ambrosia artemisiifolia by Ophraella communa in southeastern France. Basic Appl. Ecol. 33, 14–24. https://doi.org/10.1016/j.baae.2018.08.002.

Novoa, A., Moodley, D., Catford, J.A., et al., 2021. Global costs of plant invasions must not be underestimated. NeoBiota 69, 75–78. https://doi.org/10.3897/neobiota.69.74121.

Page, A.R., Lacey, K.L., 2006. Economic Impact Assessment of Australian Weed Biological Control. CRC for Australian Weed Management.

Pupo, A., 2016. Evolution of Vegetation and Natural Landscape of Madeira Island. PhD Thesis. University of Madeira.

Ravel, D., 1999. Hurdles and bottlenecks on the road to biocontrol of plant pathogens. Australas. Plant Pathol. 28, 53. https://doi.org/10.1071/AP99007.

Reeder, R.H., Bacon, E.T.G., Caiden, M.J., et al., 2018. Effect of population density of the Azolla weevil (Stenopelmus rufinasus) on the surface cover of the water fern (Azolla filiculoides) in the UK. BioControl 63, 185–192.

Schwarzländer, M., Hinz, H.L., Winston, R.L., Day, M.D., 2018a. Biological control of weeds: an analysis of introductions, rates of establishment and estimates of success, worldwide. BioControl 63, 319–331. https://doi.org/10.1007/s10526-018-9890-8.

Schwarzländer, M., Moran, V.C., Raghu, S., 2018b. Constraints in weed biological control: contrasting responses by implementing nations. BioControl 63, 313–317. https://doi.org/10.1007/s10526-018-9888-2.

Sforza, R., 2021. The diversity of biological control agents. In: Mason, P. (Ed.), Biological Control: Global Impacts, Challenges and Future Directions of Pest Management. CSIRO Publishing, Canberra, Australia.

Shackleton, C.M., Shackleton, R.T., 2016. Knowledge, perceptions and willingness to control designated invasive tree species in urban household gardens in South Africa. Biol. Invasions 18, 1599–1609. https://doi.org/10.1007/s10530-016-1104-7.

Sharpe, L.M., 2014. Public perspectives on genetic biocontrol technologies for controlling invasive fish. Biol. Invasions 16, 1241–1256. https://doi.org/10.1007/s10530-013-0545-5.

Shaw, R., Marchante, E., Lommen, S., et al., 2017. Why so little biocontrol of plant invasions in Europe: what are the real issues? In: Máguas, C., Crous, C., Costa, C. (Eds.), EMAPI 2017 - Ecology and Management of Alien Plant Invasions - Syntheses, Challenges and New Opportunities. Centre for Ecology, Evolution and Environmental Changes - cE3c, Lisboa, Portugal, p. 27.

Shaw, R., Schaffner, U., Marchante, E., 2016. The regulation of biological control of weeds in Europe - an evolving landscape. EPPO Bull. 46, 254–258. https://doi.org/10.1111/epp.12308.

Shaw, R.H., Ellison, C.A., Marchante, H., et al., 2018. Weed biological control in the European Union: from serendipity to strategy. BioControl 63, 333–347. https://doi.org/10.1007/s10526-017-9844-6.

Sheppard, A., Shaw, R.H., Sforza, R., 2006. Top 20 environmental weeds for classical biological control in Europe: a review of opportunities. Top 20 environmental weeds for classical biological control in Europe : a review of opportunities , regulations and other barriers to adoption. https://doi.org/10.1111/j.1365-3180.2006.00497.x. Weed Research 93–117.

Suckling, D.M., Sforza, R.F.H., 2014. What magnitude are observed non-target impacts from weed biocontrol? PLoS One 9. https://doi.org/10.1371/journal.pone.0084847.

Sun, Y., Müller-Schärer, H., Schaffner, U., 2022. Fighting neobiota with neobiota: consider it more often and do it more rigorously. Biol. Conserv. 268.

Tanner, R.A., Ellison, C.A., Seier, M.K., et al., 2015. Puccinia komarovii var. glanduliferae var. nov.: a fungal agent for the biological control of Himalayan balsam (Impatiens glandulifera). Eur. J. Plant Pathol. 141, 247–266. https://doi.org/10.1007/s10658-014-0539-x.

Thomas, M.B., Willis, A.J., 1998. Biocontrol—risky but necessary? Trends Ecol. Evol. 13, 325–329. https://doi.org/10.1016/S0169-5347(98)01417-7.

Tryon, H., 1910. The wild cochineal insect, with reference to its injurious action on prickly pear (Opuntia spp.) in India, etc., and to its availability for the subjugation of this plant in Queensland and elsewhere. Qld. Agric. J. 25, 188–197.

van, Lenteren JC., Cock, M.J.W., Hoffmeister, T.S., Sands, D.P.A., 2006. Host specificity in arthropod biological control, methods for testing and interpretation of the data. In: Bigler, F., Babendreier, D., Kuhlmann, U. (Eds.), Environmental Impact of Invertebrates for Biological Control of Arthropods: Methods and Risk Assessment. CABI, Wallingford, pp. 38–63.

van, Wilgen BW., de, Wit MP., Anderson, H.J., et al., 2004. Costs and benefits of biological control of invasive alien plants: case studies from South Africa. South Afr. J. Sci. 100, 113–122.

Varia, S., Wood, S.V., Allen, R.M.S., Murphy, S.T., 2022. Assessment of the host-range and impact of the mite, *Aculus crassulae*, a potential biological control agent for Australian swamp stonecrop, *Crassula helmsii*. Biol. Control 167, 104854.
Varia, S., Wood, S., Pratt, C., et al., 2018. A "mitey" solution for Australian swamp stonecrop in the UK. In: XV International Symposium on Biological Control of Weeds. CAB International, Engelberg, Switzerland, p. 168.
Vieira, R., 2002. Flora da Madeira: plantas Vasculares Naturalizadas No Arquipélago da Madeira (Boletim do Museu Municipal do Funchal: história Natural). Departamento de Ciência da Câmara Municipal do Funchal, Funchal, Madeira.
Vurro, M., Evans, H.C., 2008. Opportunities and constraints for the biological control of weeds in Europe. In: Proceedings of the XII International Symposium on Biological Control of Weeds, La Grande Motte, France, 22-27 April, 2007. CABI, Wallingford, pp. 455–462.
Warner, K.D., 2012. Fighting pathophobia: how to construct constructive public engagement with biocontrol for nature without augmenting public fears. BioControl 57, 307–317. https://doi.org/10.1007/s10526-011-9419-x.
Warner, K.D., McNeil, J.N., Getz, C., 2009. What every biocontrol researcher should know about the public. In: Julien, M., Sforza, R., Bon, M., et al. (Eds.), XII International Symposium on Biological Control of Weeds. CAB International, Wallingford, UK, pp. 398–402. La Grande Motte, France.
Weisberg, D.S., Landrum, A.R., Metz, S.E., Weisberg, M., 2018. No missing link: knowledge predicts acceptance of evolution in the United States. Bioscience 68, 212–222.
Wilkinson, R., Fitzgerald, G., 1997. Public Perceptions of Biological Control of Rabbits in New Zealand: Some Ethical and Practical Issues. Kluwer Academic Publishers.
Winston, R.L., Schwarzländer, M., Hinz, H.L., et al., 2014. Biological Control of Weeds: A World Catalogue of Agents and Their Target Weeds. USDA Forest Service. https://doi.org/10.1146/annurev.ento.43.1.369. Forest Health Technology Enterprise Team 5th editio:1–848.
Zimmermann, H.G., Moran, V.C., Hoffmann, J.H., 2001. The renowned cactus moth, Cactoblastis cactorum (Lepidoptera: Pyralidae): its natural history and threat to native Opuntia floras in Mexico and the United States of America. Fla. Entomol. 543–551.