

# Identifying obstacles and ranking common biological control research priorities for Europe to manage most economically important pests in arable, vegetable and perennial crops

Jay Ram Lamichhane,<sup>a,b\*</sup> Monika Bischoff-Schaefer,<sup>a,c</sup> Sylvia Bluemel,<sup>d</sup> Silke Dachbrodt-Saaydeh,<sup>c</sup> Laure Dreux,<sup>a</sup> Jean-Pierre Jansen,<sup>e</sup> Jozsef Kiss,<sup>f</sup> Jürgen Köhl,<sup>g</sup> Per Kudsk,<sup>h</sup> Thibaut Malausa,<sup>i</sup> Antoine Messéan,<sup>a</sup> Philippe C Nicot,<sup>b</sup> Pierre Ricci,<sup>i</sup> Jérôme Thibierge<sup>j</sup> and François Villeneuve<sup>k</sup>



## Abstract

EU agriculture is currently in transition from conventional crop protection to integrated pest management (IPM). Because biocontrol is a key component of IPM, many European countries recently have intensified their national efforts on biocontrol research and innovation (R&I), although such initiatives are often fragmented. The operational outputs of national efforts would benefit from closer collaboration among stakeholders via transnationally coordinated approaches, as most economically important pests are similar across Europe. This paper proposes a common European framework on biocontrol R&I. It identifies generic R&I bottlenecks and needs as well as priorities for three crop types (arable, vegetable and perennial crops). The existing gap between the market offers of biocontrol solutions and the demand of growers, the lengthy and expensive registration process for biocontrol solutions and their varying effectiveness due to variable climatic conditions and site-specific factors across Europe are key obstacles hindering the development and adoption of biocontrol solutions in Europe. Considering arable, vegetable and perennial crops, a dozen common target pests are identified for each type of crop and ranked by order of importance at European level. Such a ranked list indicates numerous topics on which future joint transnational efforts would be justified.

© 2016 Society of Chemical Industry

Supporting information may be found in the online version of this article.

**Keywords:** beneficials; biopesticides; biomolecules; European research networking; innovation; integrated pest management; semiochemicals; sustainable agriculture

## 1 INTRODUCTION

European agriculture is currently in transition from conventional crop protection, based on chemical pesticides, to integrated pest management (IPM) owing to changes in the European legislation which aims to protect human health and the environment.<sup>1</sup> The transition process requires increased knowledge and innovation to be generated and adapted to specific contexts, and new solutions to be effectively adopted by all actors involved in the crop protection sector. These needs have led to specific interest in the learning and training processes, with a focus on co-innovation dynamics involving a wide range of actors in the construction of innovations through strategic choices. Unlike the traditional crop protection model, where innovations were supplied as 'ready-to-use' tools, IPM is a dynamic system constantly modulated by end-users. To make any IPM system successful there is a need to put in place alternatives to conventional pesticides and plant protection measures that allow an effective management of crop pests (animal pests, pathogens and weeds). Biocontrol has the potential to become one of the main pillars of IPM systems

\* Correspondence to: JR Lamichhane, Eco-Innov Research Unit, INRA, 78850 Thiverval-Grignon, France. E-mail: jayram.lamichhane@gmail.com

a Eco-Innov Research Unit, INRA, Thiverval-Grignon, France

b Plant Pathology Research Unit, INRA, Montfavet, France

c Federal Research Centre for Cultivated Plants, Julius Kühn-Institut, Kleinmachnow, Germany

d Institute of Plant Health, Austrian Agency for Health and Food Safety (AGES), Vienna, Austria

e Life Science Department, Walloon Agricultural Research Centre, Gembloux, Belgium

f Plant Protection Institute, Szent Istvan University, Gödöllő, Hungary

g Wageningen University and Research Centre, Biointeractions and Plant Health, Wageningen, The Netherlands

h Department of Agroecology, Aarhus University, Slagelse, Denmark

and thus represents a key lever for a reduced reliance on conventional pesticides. Its principle is based on managing the balance of pest populations rather than eradicating them (pest management rather than pest control). In this paper, for biocontrol we refer to all methods/tools/measures/agents of plant protection that rely on the use of beneficial organisms<sup>2</sup> as well as their natural mechanisms and interactions which govern the relationship between biological species in the natural environment. Thus, this includes augmentative control, conservation biocontrol, but also the use of biopesticides, semiochemicals and plant defence stimulators.

Recent developments in the regulation of pesticides at European level – notably Regulation 1107/2009/EC<sup>3</sup> – have created favourable conditions for biocontrol R&I in Europe. This legal requirement on the authorisation and use of plant protection products has potential to promote biocontrol R&I in Europe. In particular, the classification of active ingredients into four groups (basic, low-risk and standard substances and candidates for substitution) would make it possible to place biocontrol agents within the low-risk category, making their registration easier and less expensive. Also, natural products of plant origin represent an important group of candidates to be included within the low-risk substances.<sup>4</sup> The EU has recently approved a first list of low-risk substances [e.g. *Isaria fumosorosea* (syn. *Paecilomyces fumosoroseus*), *Pepino mosaic virus*]. The need to have a fast approval process for low-risk substances and harmonisation of the assessment procedure within the EU member states was recently discussed in an international stakeholder meeting.<sup>5</sup> Data requirements for the approval of active substances and plant protection products needed at EU level are mainly adapted to conventional pesticides, and there is not yet a different approval and registration procedure for biocontrol solutions,<sup>6</sup> nor any registration procedure for biostimulants.<sup>7</sup> There are similar constraints when dealing with pesticide residue issues that are required to fulfil the European Regulation (EC) No. 1107/2009.<sup>8,9</sup>

Biocontrol R&I has become increasingly dynamic and involves a wide range of stakeholders from a variety of public institutions and companies (cooperatives and private companies). However, biocontrol R&I efforts are often carried out within national initiatives and in a fragmented fashion. Therefore, their operational outputs would benefit from closer collaboration between academia, the industry and the agricultural sectors on the one hand and from transnational cooperation on the other. In addition, a greater level of collaboration/knowledge-sharing is required to address key biocontrol needs and to pool biocontrol R&I efforts nationally and internationally on common pest priorities for a better biocontrol service provision.

Taking into account the particularly favourable current environment to address biocontrol R&I challenges in Europe, three networks concerned by biocontrol research organised a 'Joint International Workshop on Biocontrol' in Paris, France, on 27 and 28 January 2016. These networks are the French National Action Plan 'Ecophyto',<sup>10</sup> the European Research Area Network of Integrated Pest Management in Europe<sup>11</sup> and the West Palearctic Regional Section of the International Organisation for Biological and Integrated Control.<sup>12</sup> Fifty-three experts from 16 countries – including

scientists, governmental officials, policy makers, company representatives and agricultural advisors – met, discussed and ranked the most important and common pest problems in arable, vegetable (both indoor and outdoor) and perennial (orchards and vineyards) crops in Europe.

This paper aims to present the major outcomes of the workshop obtained by a questionnaire survey and a face-to-face group discussion. The questionnaire was designed and circulated in advance to all invited participants to receive their feedback on the most relevant biocontrol R&I issues in Europe. Additional responses were also received from experts who did not attend the workshop. The questionnaire included seven queries with multiple-choice answers and also provided the possibility for the respondents to express alternative opinions (Table 1; supporting information). The face-to-face group discussion was held during the workshop for each of the three crop groups mentioned above, and mainly focused on the sorting and ranking of the major pest problems and biological control priorities shared between European countries.

## 2 STATISTICS ON THE QUESTIONNAIRE SURVEY ON MAJOR BIOCONTROL RESEARCH AND IMPLEMENTATION BOTTLENECKS

Overall, 63 biocontrol experts from over 20 countries provided the completed questionnaire. The responses were analysed and the figures are presented in Table 1.

None of the respondents considered biocontrol as an independent approach to IPM. Because the efficacy of biocontrol methods is often considered as too limited to be relied upon singly for pest control, most participants emphasised that integrating biocontrol into IPM strategies, through the combination of different methods with partial effects, is particularly relevant to reduce reliance on conventional pesticides.

The opinions were divided concerning factors hindering the development of biocontrol in Europe. While for almost one-third of the respondents the main obstacle was the absence of a sufficiently large array of biocontrol solutions to enable the build-up of pest management strategies, others stated that the lack of projects aiming at integrating biocontrol solutions with other measures and limited funding for biocontrol research were the main impediments to biocontrol development. Some respondents provided other responses, including insufficient communication between research organisations in Europe, leading to an overlap of activities, insufficient biocontrol research demand owing to the availability of conventional pesticides, the lack of long-term funding schemes or the lack of multidisciplinary biocontrol research aiming at integrating biocontrol products with other measures (supporting information).

There was not a clear consensus on the potential factors hindering the implementation of biocontrol in Europe. The lack of commercially available biopesticides was the most frequent answer, followed by the lengthy and expensive registration process for biopesticides. Concerning the latter, the EU is supposed to come up with a proposal for a simplified dossier for the authorisation of low-risk substances. Such a new scenario will result in a reduced legislative burden, thereby favouring market availability of biocontrol solutions in Europe. Other responses included the varying effectiveness of biocontrol products/agents owing to very diverse and variable climatic conditions and site-specific factors across Europe, the reluctance of growers to take risks with methods

i INRA, Univ. Nice Sophia Antipolis, CNRS, UMR 1355-7254 Institut Sophia Agrobiotech, Sophia Antipolis, France

j In vivo AGRINOVEX, Ferme du Corbeau, Milly-la-Forêt, France

k Ctifi, Centre de Lanxade, Prignonieux, France

**Table 1.** Relevant questions and multiple answers related to biocontrol R&I asked through the questionnaire. The same respondent could provide more than one answer to the same question. In total, 63 experts responded to the questionnaire

Question	Multiple responses provided	Percentage
1. What is your opinion on biocontrol as a crop protection measure?	Biocontrol is an independent approach for crop protection	0
	Biocontrol is part of IPM	78
	Both	16
	Other (specify) <sup>a</sup>	5
	No response	0
2. What hinders the development of biocontrol measures in Europe?	Limited funding for biocontrol research (A)	10
	Lack of projects aiming at integrating biocontrol products to other measures (B)	6
	Insufficient range of biocontrol solutions to build up strategies (C)	14
	A + B	8
	B + C	16
	C + A	6
	All of them	16
	Other (specify) <sup>a</sup>	17
	No response	6
	3. What hinders the development and implementation of biocontrol in Europe?	Lengthy and expensive registration process for biopesticides (A)
Lack of commercially available biopesticides (B)		16
Low effectiveness of biopesticides owing to very diverse climatic conditions (C)		3
A + B		14
B + C		6
C + A		13
All of them		11
Other (specify) <sup>a</sup>		17
No response		5
4. What biocontrol research should focus on in Europe?		On the development of new biocontrol products
	On the optimisation of the effects of the biocontrol products	19
	Both	44
	Other (specify) <sup>a</sup>	17
	No response	0
5. What is/are the main factor/s to be considered while implementing biocontrol measures?	Tritrophic interactions (biocontrol agent/tool biotic and abiotic factors)	62
	The interactions between biocontrol – plant genetics	5
	Both	17
	Other (specify) <sup>a</sup>	16
	No response	0
6. What biocontrol solutions should focus on?	Single pest target	22
	Multiple pest target	32
	Both	24
	Other (specify) <sup>a</sup>	22
	No response	0
7. Which measure/s can enhance biocontrol during its application?	Strengthening the effectiveness of biocontrol by partial resistance	16
	Strengthening the effectiveness of biocontrol by other agronomic practices/DSS/strategies	65
	Other (specify) <sup>a</sup>	14
	No response	5

<sup>a</sup> Other responses that were different to those reported in the questionnaire are listed in the supporting information.

whose performances are perceived as uncertain, difficulty in evaluating the performance and impact of biocontrol methods posing particular problems linked to their partial effects, variable efficacy of biocontrol tools/measures compared with chemical solutions and growers' expectations that biocontrol solutions should be as quick and effective as conventional pesticides, constraints linked to the organisation of work and compatibility with other agronomic practices, lack of evidence showing successful strategies to integrate biocontrol into IPM, lack of knowledge on the unintentional effects of biocontrol products/agents, lack of methods to assess the benefits of biocontrol to human health and the environment and lack of public incentives for growers to use biocontrol (supporting information).

Opinions were equally split on whether biocontrol research in Europe should focus on the development of new biocontrol products, or on the optimisation of their efficacy, with a majority advocating the consideration of both objectives together. Many additional suggestions concerned the demonstration of efficacy of biocontrol at field level and the integration of biocontrol with other strategies, including conservation biocontrol, in the context of cropping system management (supporting information).

There was almost a clear consensus among the respondents about the major factor(s) to be considered while implementing biocontrol measures. Most of them emphasised the need to focus on multiple interactions, while only a few considered the interactions between biocontrol and plant genetics as more important. In addition, application techniques, formulation of the biocontrol products and instructions for growers or advisors were mentioned, as well as a number of socioeconomic factors (a biocontrol programme is in most cases more expensive than a chemical protection programme) influencing the uptake of biocontrol: the effects of market dynamics (the positioning of biocontrol products among inputs, the positioning of agricultural products from practices using biocontrol) and the role of incentives (quality labels or certification, financial incentives) from industries and public policy (supporting information).

The majority of the respondents indicated that biocontrol should focus on multiple pest targets rather than single pest species, especially when a biocontrol programme is composed of different biocontrol agents/products. Comments underlined the need to balance the practical benefits of biocontrol products having a broad range of actions with their risks in terms of unintentional effects on non-target organisms (supporting information).

Finally, most of the respondents stated that strengthening the effectiveness of biocontrol by other agronomic practices/strategies and decision support systems can promote biocontrol, although a few of them mentioned that partial plant resistance is the best way to this end. Adjustments to the ecosystem, precise knowledge of the pest densities and the actual status of the targeted stage of pests in the field to improve the timing of the application, the use of local biocontrol agents to get the best adaptation to the local conditions and recognition of the importance of biocontrol at growers' level as well as at society level were other measures stated as factors enhancing biocontrol during its application (supporting information).

### 3 RANKING OF BIOLOGICAL CONTROL RESEARCH PRIORITIES

During the individual discussion phase, the participants from each crop group were asked to provide the top-ten pest priorities to be tackled in their own country. While setting up such a priority list,

participants were requested to take the following into account: (i) the potential economic impact, in terms of yield loss and quality implications, associated with a given pest on a given crop; (ii) the possible lack of conventional control solutions, due either to the withdrawal from the market of previously available pesticides or to further restriction in their use. In some cases, the increased risk of resistance development to conventional pesticides was also taken into account. The overall objective was to identify all those economically important pests for which no or little sustainable pest management options, notably biocontrol solutions, are available. The discussion was followed by a sorting phase, during which common pest problems for each crop type were grouped, based on the number of countries sharing the same problem/s, followed by their ranking in order of importance.

#### 3.1 Arable crops

Arable crops comprise a wide variety of crops, including cereals, oilseed rape, peas and beans, sugar beet and potatoes. Although a number of conventional pesticides are available to manage most economically important pests of arable crops, growers suffer from the lack of effective management solutions for certain pests. Therefore, growers require more tools and consequently there is a strong need to develop biocontrol solutions to protect these crops.

A final list of 13 common-priority pest problems, sorted and ranked for arable crops, is reported in Table 2. Overall, it has emerged that few biocontrol solutions are available on the market for growers to manage these pests. Although some new biocontrol solutions are under development, there is a need to intensify research efforts, especially for the screening of new biocontrol agents for arable crops.

#### 3.2 Vegetable crops

Many vegetable crops fall under the category of 'minor or speciality crops' which acutely suffer from the lack of effective conventional pesticides.<sup>13</sup> Vegetable crops in Europe are characterised by a large diversity of species (more than 60), with marked differences in terms of the cultivated hectares for each crop (from less than 100 ha to several thousands). Further, for each crop there is an important diversity of production techniques adopted to supply products to the market all year round. Even when conventional pesticides are available, market acceptability driven by residues in food products is an issue for a number of vegetables as they are consumed fresh. Finally, the resistance of several important pests to pesticides and the sensitivity of pollinators to these products (e.g. bumblebees) call for an important adaptation of pest management methods. Therefore, biocontrol, along with other alternative measures to conventional pesticides, has an important role to play to protect this crop group. Another concern is that, while biocontrol in vegetable crops is widely practised in protected environments such as greenhouses,<sup>14,15</sup> its use under field conditions is still limited. This requires the biocontrol measures that are available and used in greenhouses to be adapted to field conditions, although this is not always feasible given that interacting factors in outdoor conditions are different to those in indoor conditions.

Table 3 presents a list of 12 common pest problems sorted and ranked in terms of immediate need for biocontrol solutions. Unlike the case of arable crops, there are many ongoing efforts in the development of biocontrol solutions for major vegetable crops, with a number of products already available on the market. Therefore, besides the need to develop new products, research should also address the issues of optimising, integrating and implementing already available products/measures.

**Table 2.** A final list of the most important common targets for new biocontrol products identified in arable crops across European countries. This list was sorted and ranked based on the 2 day discussion of the biocontrol workshop. The arable crop group focused on biocontrol solutions *sensu strictu*, which means that other alternative control options that form part of IPM (semiochemicals, fatty acids, botanicals, cultural practices, traps, etc.) were not explicitly listed. In total, 13 priority pests were identified, which were ranked into three classes: 1 = top priority, 2 = medium priority, 3 = low priority

Rank	Pest(s)	Crop(s)	Control solution under development	Available for use	Type of research needed
1	Wireworms	Potato, maize	Entomopathogenic fungi	No	Pest biology, screening of additional biocontrol solutions, proof of concept
1	Septoria <i>Fusarium</i> sp.	Wheat Cereals, maize	<i>Trichoderma</i> spp., <i>Bacillus</i> spp. Antagonist bacteria and fungi for ear treatment during flowering, crop residues, mycotoxin detoxification (e.g. degradation of deoxynivalenol), compounds produced by microorganisms	Laminarine (brown algae) <i>Polyversum (Pythium oligandrum)</i>	Screening for other solutions under field conditions, improving application strategies (for <i>Polyversum</i> ), additional biocontrol solutions, proof of concept of microbial crop residues and seed treatments, endophytes
2	Late blight	Potato	<i>Pseudomonas</i> spp. and <i>Bacillus</i> spp. antagonists, botanicals ( <i>Primula veris</i> )	No	Screening for other solutions, improvement of existing candidates and formulation
2	Soil-borne pests (e.g. <i>Macrophomina</i> sp., <i>Verticillium</i> sp., <i>Rhizoctonia</i> sp., <i>Plasmodiophora</i> sp., <i>Aphanomyces</i> sp., <i>Dickeya</i> sp., <i>Pectobacterium</i> sp., <i>Gaeumannomyces graminis</i> ) <i>Echinocha</i> sp., <i>Alopecurus</i> sp., <i>Apera</i> sp.	Arable crops	<i>Pseudomonas</i> spp. and <i>Bacillus</i> spp. antagonists, and many more	<i>Polyversum (Pythium oligandrum)</i> , <i>Trichoderma</i> spp., <i>Streptomyces</i> spp.	Improved application technology, supporting soil suppressiveness
2	<i>Cirsium</i> sp.	Arable crops	No	No	Screening of biocontrol agents (pathogens) and conservation biological strategies
Between 2 and 3	Pollen beetle	Oilseed rape	Rusts ( <i>Puccinia striiformis</i> , <i>Phoma</i> spp., <i>Sclerotinia</i> spp.), bacteria, flower-mining insects	Available in NZ (Phoma-based) but not in Europe	Combination of biocontrol agents with cultural practices (IPM)
Between 2 and 3	Weevils	Oilseed rape	Entomopathogenic fungi and nematodes ( <i>Beauveria</i> ) Parasitoids	No	Screening and optimisation of biocontrol agents
Between 2 and 3	Flea beetles	Oilseed rape	Entomopathogenic nematodes	No	Screening and development of biocontrol agents, conservation biocontrol
3	Sclerotinia rot	Oilseed rape, sunflower, soybean	<i>Trichoderma</i> spp., <i>Verticillium</i> spp., <i>Bacillus</i> sp.	Contains, <i>Bacillus pumilus</i> , <i>Pythium oligandrum</i>	Curative treatments, long-term IPM strategies
3	Seed-borne diseases (e.g. fusarium, <i>Tilletia</i> sp.)	Cereals	Yes	Mycostop ( <i>Streptomyces</i> sp.), Cedemon and Cerall ( <i>Pseudomonas</i> sp.)	Shelf-life of microbials on seeds (development of expertise for seed production and treatments)
3	Post-harvest pests (e.g. Lepidoptera, Coleoptera)	Cereals	Parasitoids, pheromones	<i>Trichogramma</i> sp., other wasps, predatory mites	No research need identified



**Table 3.** A final list of the most important common targets for new biocontrol products identified in vegetable crops (both indoor and outdoor) across European countries. This list was sorted and ranked based on the 2 day discussion of the biocontrol workshop. The discussion was mainly focused on field vegetables. Biocontrol solutions were considered *sensu latu*, taking into account other alternative control options that are part of IPM, such as semiochemicals, fatty acids, botanicals, cultural practices, traps, etc. In total, 12 priority pests were identified which were ranked from 1 to 12 in decreasing order of importance

Rank	Pest	Crop(s)	Control solution under development	Available for use	Type of research needed
1	Weeds	All	Rust, seed-eating beetles, <i>Alternaria</i> spp.	Research only	Screening
2	Root flies	Brassicacae, onions, radish, carrots, beans	Substrate management, PBMB, <sup>a</sup> attract and kill, conservative biocontrol, beneficials including nematodes and entomopathogenic fungi	Nematodes, rove beetles, predatory mites, fungi, plant extracts	Engineering and screening for finding new solutions, implementation
3	Powdery mildew	Tomatoes, carrots, cucurbits, cabbage	Green pesticides, induced resistance, elicitor, plant resistance, antagonists	Yes	Engineering and screening for finding new solutions, implementation
4	Thrips	Brassicacae, onions, leek, tomatoes, eggplant, pepper	Green pesticides, PBMB, beneficials, conservative biocontrol, endophytes, plant resistance	Yes	Screening, engineering
5	Aphids	Leafy vegetables, brassicacae, cucurbits, pepper, Solonaceae	Conservative biocontrol, entomopathogens, green pesticides, beneficials	Yes	Engineering, implementation, adoption
6	White flies	Tomatoes and other solanaceous vegetables, brassicacae, cucurbits	Beneficials, green pesticides, PBMB, conventional biocontrol	Yes	Screening, engineering
7	Downy mildew	Lettuce, onions, leafy vegetables, cucurbits, herbs	Green pesticides, induced resistance, elicitor, variety res., antagonists	Yes	Screening, engineering
8	<i>Fusarium</i> sp.	Onions, pepper, garlic, cucurbits, asparagus	Rootstocks, biofumigation, antagonists, endophytes, soil amendments, composts	Yes	Screening, engineering
9	Nematodes	Carrots, tomatoes, eggplant, pepper, onions, lettuce, melons	Biocontrol agents, green pesticides, trap plants	Several products	Engineering, screening, implementation
10	Lepidoptera	Brassicacae, tomatoes, pepper, leafy vegetables, beans	Green pesticides, beneficials, conservation biocontrol, microbials, PBMB	Yes	Engineering, implementation, adoption
11	<i>Botrytis</i> sp.	Leafy vegetables, onions, beans, tomatoes	Biocontrol, <i>Trichoderma</i> spp., green pesticides, induced resistance, elicitor	Yes	Screening and engineering for field, engineering for protected
12	Oomycetes ( <i>Phythium</i> , <i>Phytophthora</i> )	Solanaceae, carrots, lamb's lettuce	Variety resistance, green pesticides, biofumigation, soil amendment, forecasting, induced resistance, antagonists	Yes	Screening, engineering

<sup>a</sup> PBMB: pest behaviour manipulation for biocontrol, including sexual pheromones, repellents/attractants, visual or odour confusion for plant location or mating, lures, etc. All products and techniques that can contribute to biocontrol and have no direct lethal effects as insecticides or acaricides.

**Table 4.** A final list of the most important common targets for new biocontrol products identified in perennial crops (fruit crops and grapevines) across European countries. This was sorted and ranked from the initial list of 76 pest groups identified during the 2 day discussion of the biocontrol workshop. Biocontrol solutions were considered *sensu lato*, taking into account other alternative control options that are part of IPM, such as semiochemicals, fatty acids, botanicals, cultural practices, traps, etc. In total, 12 priority pests were identified which were ranked from 1 to 12 in decreasing order of importance. A: screening of new biocontrol agents; B: engineering of biocontrol products; C: integration of biocontrol agents into IPM strategies; D: adoption of biocontrol; bottlenecks and levers at the farm and supply chain levels

Rank	Pest	Crop(s)	Biocontrol solution under development	Available for use	Type of research needed
1	<i>Drosophila suzukii</i>	All stone and soft fruit, grapes	None	None	Biology of the pest, mass trapping, avoidance, parasitoids, repellants, pathogens, sterile insect technology
2	<i>Monilinia</i> sp. ( <i>laxa</i> , <i>fructicola</i> , <i>fructigena</i> )	All stone and soft fruit	None	None	A; then B; C would then be a priority (sanitation would be key – forecast models for timing of application); then D
3	<i>Venturia inaequalis</i>	Apple	None	None	A for overwintering inoculum; then B; C would then be a priority (R varieties, forecast models for timing of application; technology for spraying without tractor); then D
4	<i>Cydia pomonella</i>	Apple, pear, walnut	<i>Trichogramma</i> (national project in FR)	Mating disruption, granulosis virus, <i>Steinernema carpocapse</i> , sterile insect technique (Canada)	A (e.g. new virus strains), B, C and D (sterile insect technology, physical methods, landscape management and conservation biocontrol)
5	<i>Psylla</i> complex	Apple and pear	Kaolin; not widely used	Conservation biocontrol for <i>Psylla pyri</i>	A (against vector and endophytes against the phytolasma); C (repellents/attractants, conservation biocontrol and landscape management)
6	<i>Rhagoletis cerasi</i> + fruit flies	Peach, cherry, walnut, apple, citrus, olive	None	None	A (e.g. for attract and infect/kill; attractants); C and D (SIT, multispecies traps; IP with existing parasitoids, <i>Beauveria</i> , physical protection)
7	<i>Phytophthora</i> complex	Strawberry, cane fruit	None	None	A; then B; C (biofumigation + 'cleaning crops'; detection method for sanitation soil/cuttings)
8	<i>Verticillium</i> complex	Strawberry, hops, cane fruit	None	None	A; then B; C (biofumigation + 'cleaning crops'; detection method for sanitation soil/cuttings)
9	Powdery mildews	Strawberry, cane fruit, grapes	None	None	A; B (improve existing BCAs); C
10	<i>Scaphoideus titanus</i> (grapevine flavescence dorée)	Grapes	None	None	A (against the vector and gdf, e.g. endophytes); C (combine BCAs with physical methods – vibration, mating disruption, repellants, avoidance techniques, trapping)
11	<i>Plasmopara viticola</i>	Grapes	None	None	A, B, C and D (test with predictive models)
12	<i>Halyomorpha halys</i>	All stone fruit, apple, grapes	None	None	Pest biology; A (parasitoids); C (mass trapping, repellents/attractants)

### 3.3 Perennial crops

The perennial crops considered covered grapevine and different fruit crops, most of which are 'minor crops'. Consequently, the requirement of biocontrol R&I for this crop group is important for the same reason as described above. Although biocontrol is increasingly applied in perennial crops,<sup>16,17</sup> there are still a number of important pest problems for which no biocontrol solution is available or even under development.

This is illustrated by Table 4 which lists 12 common pest problems on perennial crops that urgently require biocontrol solutions. Consequently, a wide range of needed research actions is advocated, firstly in the screening of new agents but also in integrating and adopting new biocontrol solutions.

## 4 CONCLUSIONS AND PERSPECTIVES

This survey highlights the considerable gap between the current offer in biocontrol solutions and what growers would need to manage important pest problems. The primary requirement of R&I is to enlarge the range of biocontrol solutions through screening for new biocontrol agents suitable for commercial use<sup>18</sup> and engineering new methods.

Contributors to the survey have further identified diverse factors currently impeding the development of biocontrol and suggested research approaches to help raise these constraints. These suggestions can be summarised in the following recommendations: (1) invest in the appropriate assessment of biocontrol methods, including both the consideration of their potential unintentional effects and the identification of the contextual factors that determine their performance, in order to improve growers' guidance on the proper use of biocontrol; (2) devise strategies combining biocontrol methods with other pest management tactics, in the context of IPM or even cropping system management, to help growers integrate biocontrol into their practices; (3) enlarge the scope of biocontrol research to the socioeconomic factors influencing biocontrol adoption, which calls for the development of multidisciplinary projects involving diverse actors throughout the value chain of agriculture.

Compared to fruit or vegetables, arable crops are in a markedly different situation: a lower input/cost per hectare and lower consumer concern about pesticide residues reduce the incentive to introduce biocontrol. Additional efforts are needed to raise awareness about the positive environmental effects expected from biocontrol in arable crops because of their huge acreages. Conservation biocontrol could be an interesting approach in this context, which might be fostered by recent EU agri-environmental funding schemes aimed at promoting farmland.<sup>19</sup>

These recommendations issued by a large panel of experts represent a valuable contribution to the definition of priorities in biocontrol research and attractive opportunities for joint transnational initiatives.

## ACKNOWLEDGEMENTS

The authors thank the anonymous reviewers for providing a number of valuable comments on the earlier version of the paper and all participants of the workshop for their active and valuable contribution to the discussion, as well as those who did not attend but provided feedback on the questionnaire. The ERA-Net C-IPM

is funded by the EU under the 7th framework programme (Grant agreement number 618110).

## SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

## REFERENCES

- Lamichhane JR, Dachbrodt-Saaydeh S, Kudsk P and Messéan A, Towards a reduced reliance on conventional pesticides in European agriculture. *Plant Dis* **100**:10–24 (2016).
- Eilenberg J, Hajek A and Lomer C, Suggestions for unifying the terminology in biological control. *BioControl* **46**:387–400 (2001).
- Regulation (EC) No. 1107/2009 of the European Parliament and of the Council of 21 October 2009 concerning the placing of plant protection products on the market and repealing Council Directives 79/117/EEC and 91/414/EEC. European Commission, Brussels, Belgium (2009).
- Villaverde JJ, Sandin-España P, Sevilla-Morán B, López-Goti C and Alonso-Prados JL, Biopesticides from natural products: current development, legislative framework, and future needs. *BioResources* **11**:5618–5640 (2016).
- Customised Approach to Assess the Efficacy of Low-risk Plant Protection Products*. [Online]. Available: <http://www.ctgb.nl/en/news/news-items/2016/04/08/customised-approach-to-assess-the-efficacy-of-low-risk-plant-protection-products> [13 June 2016].
- Villaverde JJ, Sevilla-Morán B, Sandín-España P, López-Goti C and Alonso-Prados JL, Biopesticides in the framework of the European Pesticide Regulation (EC) No. 1107/2009. *Pest Manag Sci* **70**:2–5 (2014).
- Matyjaszyk E, Products containing microorganisms as a tool in integrated pest management and the rules of their market placement in the European Union. *Pest Manag Sci* **71**:1201–1206 (2015).
- Villaverde JJ, Sevilla-Morán B, López-Goti C, Alonso-Prados JL and Sandín-España P, Trends in analysis of pesticide residues to fulfil the European Regulation (EC) No. 1107/2009. *Trends Anal Chem* **80**:568–580 (2016).
- European Commission (EC) Guidance document SANCO/12571/2013 rev. 0 on analytical quality control and validation procedures for pesticide residues analysis in food and feed. European Commission, Brussels, Belgium, pp. 1–48 (2013).
- The French National Action Plan 'Ecophyto'*. [Online]. Available: <http://agriculture.gouv.fr/ecophyto-kesako-0> [17 July 2016].
- The European Research Area Network on Integrated Pest Management*. [Online]. Available: <http://c-ipm.org/> [8 July 2016].
- The West Palearctic Regional Section of the International Organization for Biological and Integrated Control*. [Online]. Available: <http://www.iobc-wprs.org> [8 July 2016].
- Lamichhane JR, Arendse W, Dachbrodt-Saaydeh S, Kudsk K, Roman JC, van Bijsterveldt-Gels JEM *et al.*, Challenges and opportunities for integrated pest management in Europe: a telling example of minor uses. *Crop Prot* **74**:42–47 (2015).
- Bale JS, van Lenteren JC and Bigler F, Biological control and sustainable food production. *Phil Trans R Soc Lond B Biol Sci* **363**:761–776 (2008).
- Calvo JC, Biological control of insect and mite pests in greenhouse solanaceous crops. *BioControl* **2**:125–144 (2008).
- Gabarra R, Riudavets J, Rodríguez GA, Pujade-Villar J and Arnó J, Prospects for the biological control of *Drosophila suzukii*. *BioControl* **60**:331–339 (2015).
- Cazorla FM and Mercado-Blanco J, Biological control of tree and woody plant diseases: an impossible task? *BioControl* **61**:233–242 (2016).
- Köhl J, Postma J, Nicot P, Ruocco M and Blum B, Stepwise screening of microorganisms for commercial use in biological control of plant-pathogenic fungi and bacteria. *BiolControl* **57**:1–12 (2011).
- Holland JM, Bianchi FJJA, Entling MH, Moonen A-C, Smith BM and Jeanneret P, Structure, function and management of semi-natural habitats for conservation biological control: a review of European studies. *Pest Manag Sci* DOI: 10.1002/ps.4318 (2016).