Monitoring systems for resistance to plant protection products across the world: Between redundancy and complementarity

Short running title: Monitoring systems for resistance to plant protection products across the world

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Abstract:

BACKGROUND: Monitoring resistance to Plant Protection Products (PPPs) is crucial for understanding the evolution of resistances in bioagressors, thereby allowing scientists to design sound bioagressor management strategies. Globally, resistance monitoring is implemented by a wide range of actors that fall into three distinct categories: academic, governmental, and private. The purpose of this study was to investigate worldwide diversity in PPP resistance monitoring systems, and to shed light on their different facets. RESULTS: A large survey involving 162 experts from 48 countries made it possible to identify and analyze 250 resistance monitoring systems. Through an in-depth analysis, the features of the different monitoring systems were identified. The main factor differentiating monitoring systems was essentially the capabilities (funding, manpower, technology, etc.) of the actors involved in each system. In most countries, and especially in those with a high Human Development Index, academic, governmental, and private monitoring systems coexist. Overall, systems focus far more on monitoring established resistances than on the detection of emerging resistances. Governmental and private resistance monitoring systems generally have considerable capacities to generate data, whereas academic resistance monitoring systems are more specialized. Governmental actors federate and enrol a wider variety of stakeholders. CONCLUSION: These results suggest that the efficacy of PPP resistance monitoring could be enhanced if the different actors involved in resistance monitoring could pool resources and increase collaborative efforts.

Keywords: pesticide resistance management; insecticide; herbicide; fungicide; institutional analysis and development; surveillance

55 # 1. Introduction & background

56 Plant Protection Products (PPPs) are active ingredients or organisms used to kill, alter the
57 development of, or mitigating the deleterious effects of plant bioagressors such as animals,
58 pathogens, and weeds. In agriculture, PPPs can select resistant bioagressor genotypes that have the
59 inheritable ability to survive PPP concentrations that kill or inhibit the development of sensitive
60 genotypes of the same species. Resistance is generally selected from bioagressor standing genetic
61 variation or from *de novo* mutations (Hawkins et al., 2019; R4P, 2016). When the proportion of
62 resistant genotypes in one bioagressor population is high enough, resistance leads to a visible
63 decrease in the efficacy of PPP applications in the field. This is "resistance in practice", which is
64 considered a side effect of PPP use. It may lead farmers to carry out additional applications of higher
65 doses of the PPP concerned, or of other PPPs with possibly less favorable ecotoxicological profiles.
66 Bioagressor resistance has considerable economic consequences worldwide in terms of additional
67 PPP use, compensatory agronomic practices, food production losses, and environmental pollution
68 (Palumbi, 2001). A recent study conducted in the United Kingdom estimated that herbicide
69 resistance can double the economic costs of weed management (Hicks et al., 2018). Other studies
70 concluded that weed management costs could increase by between USD 85 and USD 138.ha^{-1} when
71 herbicide resistance is present (Lambert et al., 2017; Zhou et al., 2015). Therefore, managing the
72 evolution of resistance is a major challenge in crop protection, in line with the increasing social
73 pressure towards agriculture that is less dependent on chemical inputs (Jørgensen et al., 2020).
74 Social pressure is increasingly taken into account by stakeholders and has been translated into law,
75 especially in the European Union, including the development of specific regulations (Box 1) and of
76 dedicated PPP risk indicators (Box 2).

77 Efficient resistance management relies: (i) on the use of bioagressor control practices not resorting to
78 PPP (e.g. resistant cultivars, prophylaxis, agricultural practices, etc.), and (ii) if needed, the judicious
79 application of PPPs following anti-resistance strategies, namely alternating PPPs, using mixtures,

80 applying spatial mosaic practices, or dose modulation, so as to maximize the heterogeneity of
81 selection applied on bioagressor genotypes (Délye et al., 2013; Jørgensen et al., 2017;
82 REX_Consortium, 2013; van den Bosch et al., 2014). While the relative efficacies of the different
83 strategies in impeding resistance development are still debated, probably because they closely
84 depend on bioagressor biology and resistance genetics, there is a consensus that the management of
85 resistance at the earliest stages of its development is a prerequisite for the sustainability of PPP
86 efficacy. Designing efficient strategies for PPP resistance management requires knowledge of the
87 resistance status and resistance mechanisms of a given bioagressor to one or several PPPs, and
88 therefore depends on information obtained from PPP resistance monitoring and academic research
89 (see an example in Box 3).

90 PPP resistance monitoring involves regular collection of data on the occurrence, frequency, and/or
91 location of bioagressor genotypes with phenotypic and genetic characteristics making them resistant
92 to PPPs. Resistance monitoring is used across the world to assess and curb the incidence of resistant
93 human pathogens (Broekmans et al., 2002; Mölstad et al., 2017; Zignol et al., 2018) or animal
94 pathogens (Werner et al., 2018), or for food safety (Mc Nulty et al., 2016; Pruden et al., 2018). In
95 many countries, resistance monitoring is a prerequisite for PPP authorization and a key component
96 of the post-authorization phase, and therefore falls within the jurisdiction of governmental and
97 regulatory authorities. It also enables forecasting of in-field PPP efficacy and makes it possible to put
98 forward preventive measures against the development of resistance. In addition, resistance
99 monitoring is instrumental in further adapting stakeholder strategies and in preventing crop
100 protection impasses. Resistance monitoring helps to optimize the efficiency of PPP applications and
101 maintain efficacy, and guides commercial and R&D strategies in the plant protection product
102 industry. Consequently, there is a market for PPP resistance monitoring data, which attracts private
103 organizations. On a different level, preventing the use of inefficient PPPs by adequate resistance
104 monitoring contributes to the public interest objective of limiting the overall amount of PPPs used in
105 a country and is therefore the purview of public institutions. Moreover, PPP resistance monitoring is

106 also of interest for academic scientists studying the evolution of bioagressors. Clearly, PPP resistance
107 constitutes a textbook example of an evolutionary process that can be observed at contemporary
108 scales (e.g. (Blake et al., 2018; Garnault et al., 2019; Hicks et al., 2018; Labbé et al., 2007). PPP
109 resistance monitoring is therefore implemented by a variety of actors who fall into three main
110 categories: academic, governmental, and private. Despite the importance and the diversity of the
111 issues associated with PPP resistance monitoring, no quantitative or qualitative information had
112 previously been published at a worldwide level on the organization of PPP resistance monitoring.
113 Furthermore, the handful of studies that have investigated the organization of PPP resistance
114 monitoring all focused on a specific topic and/or considered a limited number of countries. Examples
115 include a public-private partnership for insecticide resistance management of the diamondback moth
116 in Hawaii (Krell et al., 2016), a public-private consortium to study fungicide resistance in Septoria leaf
117 blotch and rusts on wheat in Europe (Jørgensen et al., 2018), institutional organization of monitoring
118 approaches for resistance to transgenic *Bacillus thuringiensis* (Bt)-crops in four countries (Carriere et
119 al., 2019), and an overview on herbicide resistance management across the world with few details on
120 monitoring (Peterson et al., 2018).

121 This study aimed to describe the diversity of actors and features of PPP resistance monitoring within
122 and among countries, to explore the factors underlying this diversity, and to identify possible
123 synergies. Our general hypothesis was that functional complementarities between the coexisting
124 actors in a given country may explain the diversity of monitoring systems observed around the world.
125 To test this assumption, we used a multilevel case study questionnaire methodology (Eisenhardt,
126 1989; Yin, 2003), and more precisely, an embedded, multiple-case research design (Yin, 2003). The
127 most important level we considered was the Resistance Monitoring System (RMS), which is an
128 organization with its own objectives, resources, and rationales that produces and organizes PPP
129 resistance monitoring (**Figure 1**). An RMS produces Resistance Monitoring Information Products
130 (RMIPs), deliverables that enable actors to visualize and track the development of resistance,
131 whether these products are publicly shared or not. An RMS may produce several different

132 information products. At a higher level, in a given country, the coexisting RMSs shape a National
133 Resistance Monitoring Landscape (NRML). Based on this multilevel design, we: (i) described the
134 diversity of RMSs around the world, and tested whether the NRML could be related to country's
135 Human Development Index (HDI), (ii) described similarities and differences regarding the various
136 RMSs, and (iii) characterized the interplay between actors that implement different RMSs.

137

138 ## 2. Methods

139 ### 2.1. Questionnaire design

140 Based on a preliminary investigation, we defined three categories of RMS, based on the type and
141 funding of the organization in charge: Academic, Governmental, and Private. An Academic RMS is a
142 monitoring initiative carried out by academic actors, where the main aim is the scientific study of
143 resistance evolution. A Governmental RMS is an initiative aimed at producing publicly available
144 information for agricultural extension services and state services for PPP evaluation and
145 authorization, and to address PPP regulation questions (e.g. non-intentional effects of PPPs such as
146 the selection for resistances). A Private RMS is a resistance monitoring initiative carried out by
147 private actors, where the main aim is to detect and track the spread of resistance, with the aim of
148 supporting R&D and PPP stewardship, as well as PPP evaluation by the authorities.

149 The questionnaire was composed of a series of 75 directive and 35 non-directive questions
150 (Supporting Information 3). Both directive and non-directive questions explored the reasons and
151 rationales of the RMS by addressing various features (informant details, country, etc.). The
152 respondents were asked to list all the existing RMSs they were aware of in their country, as well as
153 the reasons and rationales for each of them. One respondent could describe up to one RMS
154 belonging to each category (maximum 3 RMS per respondent). The questionnaire also asked for
155 details on each RMS listed by the respondent (e.g. category, objectives, spatial and temporal scales,
156 methodology, funding, links with registration and regulation, communication of results, etc.). The last
157 part of the questionnaire explored the collection and availability of data on PPP use throughout the
158 respondents' countries, (through sales data and/or survey). These data are useful for resistance
159 monitoring in order to select PPPs of interest and to focus resources on regions where selection
160 pressure toward resistance is high (see Box 2 for a detailed example). When the question was
161 directive (multiple-choice), a free response insert was available to add an option or make a

162 comment. Hence, several of these responses and options were re-encoded for the analysis to create
163 groups, when relevant.

164 **2.2. Data collection**

165 The experts contacted in a preliminary phase were chosen for their ability to identify the PPP
166 resistance monitoring initiatives and/or their own participation in such monitoring programs in their
167 country. In addition, we tried to balance the number of experts in each major category of pesticides
168 by sending the questionnaire to a similar number of experts in insecticide, fungicide and herbicide
169 resistance. In a second phase, we used a snowball sampling technique: the initial respondents were
170 invited to recruit new respondents meeting the eligibility criteria mentioned above. This sampling
171 technique was used because of the difficulty in identifying resistance monitoring experts
172 internationally (Heckathorn, 1997). The questionnaire was sent via a *Sphinx* software internet link
173 from October 3, 2016 to November 22, 2017.

174

175 **2.3. Data analysis**

176 For each country, responses concerning RMSs were aggregated to generate comprehensive
177 information on its NRML. Countries with one or few respondents were not excluded from the
178 analysis. However, this criterion was taken into account when interpreting the data and comparing
179 countries. For countries with several respondents, such as European Union countries, Australia and
180 the United States, answers about the NRML were consistent among respondents. Similarly, for each
181 RMS described, we asked which resistance topics were monitored (one topic = one triplet: crop ×
182 bioagressor × PPP active ingredient). These topics were then grouped according to bioagressor types
183 (fungi, insects, weeds, and combinations of these three types). These answers where compiled for
184 each country.
185 To analyze whether countries with a higher development level were characterized by a more diverse
186 NRML, we used the 2016 Human Development Index (HDI (UNDP, 2016)), a composite statistical

value of life expectancy, education, and per capita income indicators (Anand & Sen, 1994)). The influence of the HDI on the presence of each RMS category and the influence of the HDI on the type of collection of PPP use data in each country were tested using generalized linear regressions with a binomial distribution of errors and logit link function.

The effect of the category of RMS on the number of actor types participating in the choice of the monitored topics, or in the resistance data analysis, were tested using a non-parametric Kruskal–Wallis rank-sum test. All other tests of relationships between different qualitative variables were conducted by chi-squared (χ^2) tests of independence. When the number of replicates was too small for a χ^2 test, we used a χ^2 test with Monte-Carlo simulations using 2,000 replicates to compute *p*-values, or opted for a qualitative comparative analysis (Greckhamer et al., 2008; Livne-Tarandach et al., 2015). All statistical analyses were carried out using the statistical software R 3.6.1 (R Core Team, 2019). The data and code are available in a Zenodo online repository (http://doi.org/10.5281/zenodo.3723898).

202 # 3. Results and discussion

203 The questionnaire was sent to 554 experts on PPP resistance monitoring from 74 countries, including
204 283 experts in Europe and 271 outside Europe. A total of 162 experts (29 %) from 48 countries (65 %)
205 responded to the questionnaire. The countries with the highest number of respondents were mainly
206 located in Europe and North America (**Figure 2A**). Europeans represented 64 % of the respondents
207 (103 experts), despite our efforts to collect data from a wide range of countries. The main group of
208 respondents was academic experts (66 % of the respondents). The other groups identified were
209 executives in government organizations (20 %), experts from private companies (10 %), and
210 extension services and agricultural consulting companies (4 %). The area of expertise of most
211 respondents was herbicide or fungicide resistance (32 % and 30 %, respectively), followed by
212 insecticide resistance (18 %), and generalist experts (more than one area of expertise, representing
213 20 %) (**Figure 2B**). With our questionnaire approach, we inventoried 250 RMSs worldwide, relatively
214 well balanced among countries and among the categories defined for this study, i.e Academic,
215 Governmental, and Private (**Figures 2C and 2D**).

216 ## 3.1. Diversity of NRMLs around the world

217 ### 3.1.1. All categories of RMSs coexist in most of the respondent countries

218 The most frequent situation (44 % of the countries surveyed) was the coexistence of the three
219 categories of RMS (namely Academic, Governmental, and Private). The two most frequent situations
220 were the existence of Academic RMSs only and coexistence of Academic and Private RMSs (17 % of
221 the countries surveyed each). All other situations represented less than 4 % each. The NRML was
222 reported to be coexistence between Governmental and Private RMSs in a single country, with one
223 respondent. Four other countries reported no RMS. However, it should be noted that for each of
224 these five cases, the information was provided by a single respondent, thereby limiting its reliability.

225 ### 3.1.2. The HDI value influences NRML diversity and collection of PPP use data

226 The three categories of RMS were present in 83 % of the countries with an HDI > 0.9, in 45 % of the
227 countries with an HDI between 0.8 and 0.9, and in 17 % of the countries with an HDI < 0.8
228 (**Figure 3A**). Importantly, countries with an HDI < 0.8 had the least diversified NRMLs, with an
229 overrepresentation of Academic RMSs (10 out of 12 had Academic RMSs, including five with only
230 Academic RMSs). Consistently, the presence of Governmental RMSs was significantly more likely in
231 countries with a high HDI ($p = 0.018$, **Figure S1.1**, supporting information). By contrast, the
232 occurrence of Academic and Private RMSs did not significantly correlate with HDI ($p = 0.429$ and
233 0.746, respectively, **Figure S1.1**, supporting information).

234 PPP use was monitored through records of sales data from PPP distributors (53 %), through
235 consumer surveys on PPP use (8 %), or through a combination of both (23 %). Data on PPP sales were
236 collected mainly at the national and regional scales (47 % and 33 %, respectively), while surveys on
237 PPP use were conducted at more local geographic scales (22 % at the field level, 42 % at a regional
238 scale, and 17 % at the national scale). The procedure to collect data on PPP use differed according to
239 the HDI: the higher the HDI, the more exhaustive the collection of data on PPP use in a given country
240 (**Figure 3B**). Consistently, countries with high HDIs were more likely to use data on PPP based on
241 'sales' and 'survey data' to adapt their monitoring systems ($p = 0.019$ and 0.058, respectively,
242 **Figure S1.2**, supporting information).

243 Interestingly, the more comprehensive the collection of data on PPP use, the more diverse the NRML
244 (**Figure 3C**, $\chi^2 = 10.6$, Monte-Carlo $p = 0.008$). In the three countries where no collection of data on
245 PPP use was reported, the NRML relied on only one category of RMS. Conversely, 87 % of the
246 countries monitoring PPP use through both sales and surveys had the three RMS categories. This
247 association may be found primarily in countries where governmental policies are being implemented,
248 in particular to mitigate the environmental impact of agriculture.

249

250

251 **3.2. Features of RMSs**

252 **3.2.1. Governmental and Private RMSs are generalists, while Academic RMSs are more**
253 **specialized**

254 Regardless of their category, 46 % of the RMSs considered a maximum of five topics per year and
255 43 % considered from 5 to 20 topics per year. Only 11 % of the RMSs managed more than 20 topics
256 per year. Private RMSs were the most involved in managing a high number of topics (47 % of the
257 RMSs surveying more than 20 topics were Private).

258 Among the RMSs identified, 38 % produced RMIPs on herbicides, 29 % on fungicides, 20 % on
259 insecticides, and 12 % on at least two bioagressor types (**Figure 4A**). Most RMSs were dedicated to a
260 single bioagressor type, regardless of the RMS category. The proportion of RMSs investigating more
261 than one type of bioagressor was significantly higher in Governmental RMSs (24 %), compared to
262 Private (13 %) and Academic (3 %) ones (**Figure 4B**) (χ^2 = 12.3, Monte-Carlo p = 0.002).
263 Governmental RMSs specialized in fungi only were proportionally less apparent. Academic RMSs
264 appeared to be more specialized, i.e. focused on a limited number of bioagressors, the biology of
265 which they master. This is most likely because Academic RMSs are usually part of broader research
266 programs aimed at understanding the mechanisms and processes involved in the selection of
267 resistance, and to predict the evolution of resistances or the associated risks. By contrast,
268 governmental and private actors are mostly interested in obtaining an accurate picture of the
269 resistance status for management or regulation purposes.

270 **3.2.2. All RMSs address emerging and established resistances, but focus mainly on loss of**
271 **PPP efficacy**

272 RMSs aim either at detecting emerging resistances (for preventive actions) or at assessing the extent
273 of established resistances (for curative actions). Irrespective of their category, the vast majority of
274 RMSs had both objectives (71 %), whereas 16 % and 13 % of the RMSs focused exclusively on

275 established resistances or emerging resistances, respectively. We did not detect a significant
276 correlation between the number of RMS objectives and the number of RMS categories in the NRML
277 (χ^2 = 4.68, Monte-Carlo p = 0.319). However, for countries with a single category of RMS, the
278 proportion of RMSs with both objectives tended to be slightly lower (60 %) than in the countries
279 where two or three categories of RMSs coexisted (64 % or 74 %, respectively).

280 The sampling procedure tended to differ between RMS categories (χ^2_2 = 5.82, p = 0.054). Regardless
281 of the RMS, the most frequent cause for field sampling was a reduction or disruption of treatment
282 efficacy represented by 42 %, 42 %, and 49 % of responses in Academic, Governmental and Private
283 RMSs, respectively (**Figure 4C**). Regarding the second sampling procedure, Academic and
284 Governmental RMSs tended to use more random sampling than Private RMSs (32 % and 29 % *vs.*
285 21 %, respectively), while Private RMS sampling procedures were more often based on selection
286 pressure, i.e. on data on PPP use (31 %). Altogether, these results were expected since the scope of
287 the different RMS categories is generally different. Private actors may focus on ensuring the
288 durability of their active ingredients, while adapting recommendations to local resistance status. By
289 contrast, academic actors may be more interested in describing unbiased patterns of in-field
290 resistance distribution.

291 **3.2.3. Data collection methods and analytical techniques are similar among RMSs**

292 Collecting relevant metadata associated with the history of the fields sampled (crop, GPS
293 coordinates, bioagressor intensity, and history of PPP used) is an important part of resistance
294 monitoring. These data can also be used for statistical and modelling analyses, which are necessary
295 to assist the development of management strategies. We therefore surveyed how metadata were
296 collected: on paper, digitally, or both. Using paper forms only was the most represented data
297 collection methods in all RMS categories (56 %). A small trend was found for exclusively digital
298 metadata collection that was more widespread in Academic RMSs than in the others.

299 Analytical techniques, including bioassays, biomolecular methods, or biochemical approaches, differ
300 in cost, sensitivity, and specificity (R4P, 2016). There were no differences in the respective use of
301 these different techniques for resistance detection among RMS categories (χ^2 = 11.1, Monte-Carlo
302 p = 0.550), despite different financial constraints between RMS categories, and despite the need for
303 different technological expertise. Bioassay was the most frequently used technique in all RMSs
304 (95 %), while 77 % and 34 % of the RMSs used biomolecular and biochemical tests, respectively. The
305 use of two different analytical techniques in the same RMS was the most frequent (46 % of the
306 RMSs), with almost exclusively a combination of bioassays and biomolecular techniques. RMSs using
307 only one technique (24 % of the RMSs) used bioassays in the vast majority of cases (83 %). Lastly,
308 30 % of the RMSs, especially those investigating herbicide and insecticide resistances, combined the
309 three techniques. Interestingly, non-target site resistance due to detoxication enzymes is more
310 frequent in these types of bioagressors and the analysis of this resistance requires a multiscale
311 approach (Hawkins et al., 2019).
312

313 **3.2.4. Diffusion and publication of the RMIPs vary according to the category of RMS**

314 Publishing clear, up-to-date, and relevant RMIPs is important to assist growers and stakeholders in
315 implementing efficient actions to manage resistance. RMIP publication significantly differed among
316 RMS categories (χ^2 = 50.1, Monte-Carlo p < 0.001, **Figure 4D**). The vast majority of the RMIPs were
317 published (87 %). Nearly all unpublished RMIPs (92 %) were from Private RMSs. Unpublished RMIPs
318 might be used in post-authorization reports, which are not considered formal publications and are
319 restricted to official authorities. Alternatively, RMIPs may be considered strategic and fall under
320 corporate proprietary information for private stakeholders. By contrast, Governmental RMSs
321 systematically published RMIPs, usually on an annual basis (57 %), which probably aimed at assisting
322 resistance management. Academic RMSs published RMIPs on a less regular basis, in line with their
323 main objective of publishing scientific articles in peer-reviewed journals, which implies combining

324 multi-year monitoring data for population studies, resistance evolution assessments, or
325 investigations of resistance mechanisms (Blake et al., 2018; Garnault et al., 2019; Hicks et al., 2018;
326 Labbé et al., 2007).

327

328 **3.3. Complementarities and interplays between RMSs and actors**

329 **3.3.1. RMS funding**

330 Private actors such as agrochemical companies or PPP retailers (grower cooperatives, vendors) were
331 the main funders of RMSs (**Figure 5A**). They were the sole funding source for 32 % of the RMSs
332 identified, and one of the funding sources for 30 % of the RMSs. The strong implication of private
333 actors in RMS funding likely reflects the strategic impact of PPP resistance on their business,
334 regulatory obligations, and their interest in PPP durability and in the evolution of agricultural
335 bioagressor landscapes to inform their search for new products. All funding combinations were
336 represented, but single-source funding dominated the picture (66 %, **Figure 5A**). However, different
337 situations were observed according to the RMS category when considering self-funding (χ^2 = 52.5,
338 Monte-Carlo $p < 0.001$). Most Private RMSs were funded by private funds only (81 %), while private
339 funding also supported Academic and Governmental RMSs. By contrast, Academic RMSs mixed all
340 possible funding sources and academic funding supported almost exclusively Academic RMSs
341 (**Figure 5A**). We suggest that the overall lower academic funding dedicated to resistance monitoring
342 has two main causes: firstly, academic endowments are generally insufficient to support extensive or
343 continued monitoring, and secondly, resistance monitoring is needed on a less regular basis for
344 resistance research. Surprisingly, one out of 48 Private RMSs was entirely financed by governmental
345 funds and 4 out of 53 Governmental RMSs were entirely financed by private funds. Overall, co-
346 funding from two or three sources was reported for 35 % of the RMSs (28 % and 7 %, respectively).
347 Co-funding was more frequent for Governmental RMSs (49 %) than for Academic (36 %) or Private
348 ones (17 %), suggesting better integration when monitoring involves official authorities.

349 **3.3.2. Officially-standardized protocols are more conducive to public decision-making**

350 RMIPs can be used to authorize, improve, or ban PPP use. In countries where there is official
351 standardization of the resistance monitoring protocol (recognized as "official" by the stakeholders),
352 changes in PPP authorization or in recommendations of PPP use is more frequent following
353 resistance detection ($\chi_1^2 = 5.00$, $p = 0.025$). This result suggests that standardization of the
354 monitoring protocol is an important issue to assist public decision-making for the management of
355 PPP use.

356 **3.3.3. Governmental actors appear to be the most able to federate and enroll a wide**
357 **variety of stakeholders**

358 The choice of the topics monitored by Governmental RMSs involved a wider range of actors (public
359 administration, academics, companies, and others) than other RMS categories (Kruskal–Wallis
360 $\chi_2^2 = 33.7$, $p < 0.001$, **Figure 5B**). Twice as many partners were involved in Governmental RMSs
361 compared to Academic and Private ones. Our results suggest that the existence of a legal obligation
362 to monitor PPP resistance (in the EU and some other countries) may lead to the involvement of a
363 greater number of partners. Alternatively, Governmental RMSs may be more trustworthy in the eyes
364 of other actors. Regardless of the reason, involvement of governments may foster participation by
365 others stakeholders because public involvement legitimizes the collective action. This observation
366 supports the relevance of generalized involvement of governments and/or their representatives in
367 the monitoring systems (Fuglie & Toole, 2014; Krell et al., 2016; Wang et al., 2013). Including a
368 broader range of partners seems to be beneficial as it combines the interests of the general public,
369 producers, and markets, while promoting multi-actor synergies (Pinkse & Kolk, 2012).

370 **3.3.4. Academic actors are the major providers of capabilities and knowledge in the**
371 **analysis and interpretation of monitoring data**

372 Data analysis is another important aspect of PPP resistance monitoring. It requires specific
373 knowledge adapted to the sampling design and the analysis methods used to detect and/or quantify
374 resistance. Regardless of the RMS, the number of types of experts who analyze data is the same (ca.
375 1.5 persons; Kruskal–Wallis χ^2_2 = 4.90, p = 0.080). When considering all RMSs together, academics
376 represent more than half of the experts involved in data analysis (52 %, **Figure 5C**). This observation
377 strongly suggests that most expertise resides in research centers and universities.

378 The type of experts in charge of data analysis and interpretation differed according to the RMS
379 categories (χ^2 = 50.7, Monte-Carlo p < 0.001). Data from Private RMSs were mostly analyzed by
380 private actors (61 %, **Figure 5C),** but academics were also substantially involved in the analysis of
381 Private RMS data (30 %). The vast majority of data from Academic and Governmental RMSs was
382 analyzed by academic actors (72 % and 50 %, respectively). Because PPP resistance data can have an
383 impact on sales and market shares, they can be considered strategic by private stakeholders, from an
384 economic point of view. This may explain why, despite the expertise of academics, the majority of
385 the analyses of Private RMS data were conducted by the private stakeholders themselves.
386 Conversely, Governmental RMSs may lack analytical skills and/or wish to avoid conflicts of interests,
387 which may explain why they rely on academic rather than on private researchers for assistance with
388 data analysis when external expertise is needed (DeAngelis, 2000; Robinson et al., 2013).

389 **3.3.5. Coexistence of different RMSs in a country increases the diversity of the types of**
390 **bioagressors surveyed**

391 One of the greatest challenges in monitoring PPP resistances is the diversity of the topics to be
392 considered, which implies dealing with a wide range of bioagressors, each with its own biological and
393 genetic specificities. Eighty percent of the countries with the three categories of RMS (representing
394 40 % of all countries with respondents) had the three types of bioagressors surveyed (**Figure 5D**).
395 Below three RMSs, no specific NRML composition was associated with a higher number of types of
396 bioagressors surveyed. NRMLs were more often incomplete (not monitoring the three types of

397 bioagressors) when only one or two categories of RMS coexisted in the country (only 33 % and 27 %
398 monitored the three types of bioagressors, respectively). As a result, a diversified NRML seems to be
399 correlated with more diverse and broader bioagressor monitoring. In diversified NRMLs, RMS
400 activities may overlap and produce redundancy, such as surveying the same topics. However, our
401 results suggest that each category of RMS carries a specific advantage and has specific added-value in
402 the NRML, leading to synergies in the combination of academic, governmental, and private actors.

403

404 4. General discussion

405 Monitoring PPP resistance is pivotal for implementing integrated and sustainable bioagressor
406 management. This is the first study of this magnitude investigating the diversity of the RMSs
407 throughout the world. Our study contains unavoidable bias, prominent among which is an over-
408 representation of European Union and academic respondents (64 % and 66 %, respectively), while
409 they represented 51 % and 65 % of the experts to whom the questionnaire was sent, respectively.
410 This might be a collateral effect of our "snowball" sampling strategy, with most respondents being
411 academics. Our work nevertheless reveals contrasted NRMLs, possibly driven by variable incentives
412 (Box 1). We identified the (co)existence of three categories of key actors: academic, governmental,
413 and private organizations that support three different categories of RMSs. The distinction between
414 Academic and Governmental RMS categories could be questioned, as the two categories usually
415 benefit largely from public funding. However, in some countries, academic actors such as universities
416 might be private and, beyond funding, the results of our study support our initial distinction as the
417 three RMS categories differ in many respects, including organization, capacities, and purposes.
418 All three categories of RMSs generate RMIPs that differ in many ways: their degree of independence
419 towards their funding sources, their intended use, the possibility for their public release, and their
420 frequency of publication when published. For example, Governmental RMIPs are generally published
421 on an annual basis and are intended to inform a broad audience. By contrast, Private RMIPs are

422 generally not published and are intended for internal use only (fulfilment of post-authorization
423 procedures, commercial and R&D strategies, etc.). Academic RMIPs are generally published
424 irregularly, as they are often used for the production of academic papers with a broader scope than
425 merely monitoring. However, the three categories of RMSs also present many similarities. While
426 84 % of the RMSs claim to focus on emerging resistances, only 28 % use sampling protocols that may
427 effectively identify emerging resistances, i.e. sampling "hot spots" based on PPP use data (Box 2).
428 This suggests that RMSs in fact target established resistances via targeted or random samplings. This
429 argues in favor of directing more effort toward promoting sampling protocols enabling the detection
430 of emerging resistances, as early implementation of resistance management is most efficient.
431
432 We also investigated the interplay between private, academic and governmental actors. When a
433 Governmental RMS is present in a country, especially a country with a high HDI, the diversity of types
434 of surveyed bioagressors is higher, twice as many actor types are involved in the choice of topics, and
435 data on PPP use are more comprehensive. This may be due to legal requirements for post-
436 authorization procedures, a governmental prerogative. In addition, Governmental RMSs appear to be
437 best at fostering co-funding from several actor types, though Academic RMSs gather more funding
438 from other actor types. Our study quantified assets that are intuitively associated with each actor, as
439 reported in the literature (Hurley & Frisvold, 2016; Krell et al., 2016). The results suggest that private
440 actors have a strong funding capacity and are typically active in major agricultural regions, academic
441 actors focus on few cases and are best in data analysis capacity and scientific knowledge, and
442 governmental actors have a major focus on resistance dissemination and show more inclusiveness
443 with an ability to bring various stakeholders together. As a result, beyond co-funding, there are some
444 obvious synergies in combining academic, governmental and private capacities in joint RMSs, as put
445 forward during the Worldwide Insecticide-resistance Network Workshop in Brazil (Corbel et al.,
446 2017), or in a recent study on co-evolutionary governance of resistance monitoring (Jørgensen et al.,
447 2020). Our suggestion is similar to those made recently by Carrière et al (2019) on the monitoring of

448 insect resistance to transgenic Bt crops. The proposed type of joint RMS was not found in our survey,
449 possibly because of the design of our questionnaire that included an *a priori* separation between
450 Academic, Governmental and Private RMSs. However, given that the questionnaire included non-
451 directive questions, the existence of joint RMSs would likely have emerged if it had been a frequent
452 occurrence. Beyond potential direct synergies in joint RMSs, there are indirect synergies when
453 Academic, Governmental and Private RMSs coexist in the same NRML (see example in Box 3). On the
454 one hand, this cohabitation might generate redundancy in resistance topics surveyed. On the other,
455 cohabitation increases the diversity of types of bioagressors surveyed in the country, and thereby
456 generates mutual benefits by increasing the performance of monitoring programs. This might be due
457 to emulation and competition among actor types, in particular for emerging resistance of significant
458 economic interest.
459
460 Surveying changes in national RMSs and NRMLs over time should make it possible to identify
461 additional complementarities, synergies, or tensions between RMSs. For example, Private and
462 Governmental RMSs may clearly have antagonistic interests regarding data publication or
463 transparency. Additional, more focused investigations could also reveal more complex NRMLs than
464 inventoried here, in particular for regions of the world that are less represented in our survey, such
465 as Africa or Oceania. Importantly, our study investigated only RMSs and the production of RMIPs. A
466 step forward would be to include the effective impact of the RMIPs (e.g., to adapt strategies for PPP
467 use) on their final recipients, with each recipient category acting at their own geographical scale (e.g.,
468 growers, salespersons, technical consultants, and scientists). It would be interesting to identify the
469 category or type of organization of RMSs that effectively prompts the final recipients to adapt or
470 change their practices on the basis of the RMIPs. The highest utility of an RMS is no doubt reached
471 when farmers effectively take into account the information provided by RMIPs when designing their
472 bioagressor control tactics (Givens et al., 2011; Johnson & Gibson, 2006; Leach et al., 2019; Llewellyn
473 et al., 2007; Ulber & Rissel, 2018). The potential impact of RMIPs depends on four characteristics:

474 transparency, pedagogy, regular updates, and broad diffusion (via extension services, agricultural
475 newspapers, and journals or websites). National and international groups that review and diffuse
476 RMIPs could be key actors alongside RMSs (see examples in SI 2).
477 Our survey described a large number of features, but did not evaluate RMS quality. RMS quality may
478 vary depending on financial constraints, on the expertise of the actors involved, and on the
479 operational constraints related to the bioagressors monitored (Ambec & Desquilbet, 2012; Guedes,
480 2017). Based on our results, approaches could be implemented to evaluate RMS quality with regard
481 to their objectives, and assess the quality of their output RMIPs. One such approach is the OASIS
482 method (Hendrikx et al., 2011), which enables an in-depth analysis of the implementation and the
483 quality of an epidemiological surveillance system, and the identification of recommendations for
484 improvement.
485

486 ## 5. Conclusion

487 Studying the worldwide diversity of organizations monitoring PPP resistance was a methodological
488 challenge, and our study, although explorative and not without some unavoidable bias, is therefore
489 an innovative and seminal research on an unexplored aspect of this crucial global issue. Charles
490 Darwin wrote "In the long history of humankind (and animal kind, too), those who learned to
491 collaborate and improvise most effectively have prevailed" (Darwin, 1859). Our survey revealed a
492 diversity of RMSs with, in most countries, different categories of RMSs coexisting. Why and how
493 could this "functional redundancy" be maintained? And why did the most effective RMS not prevail
494 and lead the others to disappear? An analysis of the distinctive resources and the related outcome
495 advantages of each RMS category suggests that better than mere coexistence, there is
496 complementarity among them. The overall efficiency of an NRML could be improved if the different
497 RMSs in different categories were merged, or better, moved towards open and transparent
498 collaboration, and the different actors' capabilities were pooled. This is where our study joins
499 Darwin's quotation. However, the benefits of RMS collaboration across categories have only been

500 broached by the results of our explorative study, and need to be tested and studied more closely.
501 The antagonisms and synergisms between the different types of monitoring need to be investigated
502 more in depth, as well as the expected benefits of collaboration. As a result, templates for multi-
503 actor structures may be proposed to build efficient and comprehensive RMSs generating quality data
504 and having a tangible impact on agricultural practices.

505

506 ## 6. Acknowledgments

507 We would like to thank all the respondents who kindly participated in this survey. The original idea
508 for this study came from a meeting of the EPPO 'resistance panel'. This project was partly funded and
509 supported by the French Agency for Food, Environmental and Occupational Health & Safety (ANSES)
510 via the tax on sales of plant protection products. The proceeds of this tax are assigned to ANSES to
511 finance the establishment of the system for monitoring the adverse effects of plant protection
512 products, called 'phytopharmacovigilance' (PPV), established by the French Act on the future of
513 agriculture dated October 13, 2014.

514
515

7. Glossary (optional)

Bioagressor: a living organism detrimental to crop production that can be an animal (arthropod, rodent, etc.), a plant (weed), or a phytopathogenic microorganism (bacterium, fungus, etc.).

Emerging resistance: early phase of resistance evolution, when resistant bioagressor genotypes are present at very low frequencies in one bioagressor population.

Established resistance: later phase of resistance evolution, when resistance disrupts bioagressor control in the field because the frequency of resistant bioagressor genotypes in the bioagressor population is sufficiently high.

HDI: Human Development Index, a composite statistical value of life expectancy, education, and per capita income indicators.

Hot spot: any area or place of known high levels of diversity or quantity of PPP use.

NRML: National Resistance Monitoring Landscape. At the country level, all existing resistance monitoring systems (RMSs) and their interactions.

PPP: Plant Protection Product. Active ingredients or organisms used to kill, alter development of, or mitigate the deleterious effects of plant bioagressors (animals, pathogens, weeds).

PPP Resistance: (i) Natural, inheritable ability of a bioagressor genotype (mutant, resistant genotype) to survive PPP concentrations that kill or inhibit the development of wild-type genotypes of the same species (sensitive genotypes); (ii) outcome of the adaptive evolution of bioagressors as a result of the selection pressure for less-PPP-sensitive genotypes exerted by PPPs.

Resistant genotype: bioagressor genotype having PPP resistance.

Resistance monitoring: regular collection of data on the occurrence, frequency, and/or location of resistant bioagressor genotypes.

Resistance topic: Crop × Bioagressor x PPP (or active ingredient)

RMIP: Resistance Monitoring Information Product. A deliverable that enables actors to visualize and track the development of resistance, whether or not shared publicly.

RMS: Resistance Monitoring System. An organization or a group of organizations with their own objectives and resources (financial, technical and human) and rationales that organize PPP resistance monitoring and produce Resistance Monitoring Information Products (RMIPs). An RMS may produce several different information products. In this study, we defined three categories of RMS, based on the type of organization and their funding, namely

--Academic RMS: a resistance monitoring initiative carried out by academic actors, where the main aim is the scientific study of evolution of PPP resistance of bioagressors.

--Governmental RMS: a resistance monitoring initiative carried out by governmental actors, aimed at producing publicly available information for agricultural extension services and state services for PPP

550 evaluation and authorization, and to address PPP regulation questions (e.g. non-intentional effects of
551 PPPs such as the selection for resistances).
552 **--Joint RMS:** an ideal RMS that combines several types of actors (academic, governmental or/and
553 private) managing the objectives and resources of resistance monitoring together.
554 **--Private RMS:** a resistance monitoring initiative carried out by private actors, where the main aim is
555 to detect and track the spread of resistance, with the aim of supporting R&D and PPP stewardship, as
556 well as PPP evaluation by the authorities.
557

558 ## 8. Boxes

559 **Box 1: Rationales for resistance monitoring across the world**

560 NRMLs with the three RMS categories were more frequent in countries in the highest HDI classes
561 (see Figure 3A). Beyond important differences in national wealth, one reason for this unequal pattern
562 of resistance monitoring organization is that countries may have different incentives when
563 authorizing PPPs. Safety for users and the environment is a common basic incentive for all countries.
564 Efficacy is another crucial incentive when authorizing PPPs. Some countries consider that resistance-
565 concerned PPPs will mechanically disappear from the market because of decreasing efficacy (e.g.
566 resistance risk assessment is not a requirement in the US Pesticide Registration Improvement
567 Extension Act PRIA 4, nor in New Zealand or Japan (resources in SI2)). In this way, it is considered a
568 company responsibility to anticipate the resistance risk, to market sustainable products, and to
569 recommend good practices. Other countries are more concerned about the selection of resistance
570 and its impact on PPP efficacy. In fact, the rapid build-up of resistance that led to historical dramatic
571 loss of efficacy in some situations (e.g. resistance to benzimidazoles or QoIs in many pathogens,
572 resistance to diamide insecticides in Lepidopteran pests, resistance to ACCase inhibitors in grass
573 weeds) certainly helped convince authorities of the importance of resistance prevention and
574 management strategies to support farmers with appropriate information on resistance. The social
575 pressure towards an agricultural model that is less dependent on chemical inputs may also have
576 strengthened this concern, as resistance management implies substituting PPPs by alternative
577 control methods and prevents inefficient spraying. This has been translated into law, especially in the
578 European Union (e.g. Directive 2009/128/EC, (Parliament, 2009)), with the development of specific
579 regulations (e.g. the "plan Écophyto" in France, which promotes integrated bioagressor management
580 and non-chemical bioagressor control to reduce pesticide consumption). Resistance risk assessment
581 is also a recommendation of the Food and Agriculture Organization of the United Nations (FAO) in its
582 guidelines for the authorization of PPPs (resources in SI2). The requirement for resistance
583 management is included in authorization dossiers in Australia (resources in SI2) and in EU countries.
584 In fact, the systematic evaluation of resistance in marketing authorization dossiers for PPPs has been
585 carried out in some EU countries for years, before EU regulations came into force. Then, resistance
586 risk assessment was generalized at the European level in 1993 via Directive 91/414/EEC, then in 2011
587 via Regulation (EC) No. 1107/2009, which is applied by all EU members states as a whole. The pre-
588 marketing assessment makes it possible to take into account resistance phenomena and to anticipate
589 problems, in particular concerning certain active ingredients that are subject to a high risk of
590 resistance development. Some limitations on PPP use can be issued after evaluation of the marketing
591 authorization application. Dossier requirements include sensitivity baselines, potential risk of target

resistance development, a cross-resistance analysis, population status for resistance and efficacy, and recommendations for resistance management. Similarly, China recently levelled up its requirements on resistance risk assessment (Regulation on the Administration of Pesticides – Decree 677, resources in SI2), which in time may change the overall picture of resistance monitoring internationally.

Box 2: Spray intensity maps provide potential information on hot spots for resistance development

It is generally accepted that the higher the spray intensity with PPPs with the same mode of action, the higher the risk of resistance selection. Based on this, resistance monitoring would be focused on areas with the highest, temporally and spatially homogeneous use of PPPs.

In Europe, as part of EU regulations, all farmers are required to keep a record of PPP use on each of their fields. These data can be checked during inspection, but are only kept at the farm level and therefore do not provide an overall picture of the PPP use patterns. In Denmark, the farmers' records are compiled in a national database, with the overall aim of obtaining an accurate picture of PPP use across the country (known as "Pesticide Load", (Kudsk et al., 2018). According to the Danish Public Administration Act, information from the Danish database is publicly available. It is compulsory for farmers to upload information on crop area and PPP use by crop. Based on the collected information, hot spots of PPP use can be identified where the potential for resistance development can be expected to be high, as illustrated for a group of insecticides, fungicides and herbicides (Figure 6). The detailed information on PPP use available in the database allows for very detailed analyses of PPP use patterns, for instance over time, or by crop and regions (Jørgensen et al., 2019). The information can also be used to find hot spots for potential environmental impact and undesirable PPP effects, such as leaching (Kudsk et al., 2018), or for further investigations on the impact of specific crop rotations on the intensity of PPP use (Jørgensen et al., 2019). To our knowledge, Denmark is so far the only country with such a detailed system for recording the use of PPP.

The Danish Environmental Protection Agency (DEPA) uses data on annual PPP sales and usage. Until now, the data have not been used as background information for resistance monitoring, although this is feasible. Monitoring for PPP resistance in Denmark is mainly organized by academic institutions like Aarhus University, in collaboration with agrochemical companies and advisory services (SEGES), which help to organize the collection of samples across the country. An extensive partnership involving academic, governmental, and private actors addressing fungicide resistance monitoring is led by NorBaRAG, an international Nordic Baltic resistance action group (Kudsk, 2010). This has resulted in several papers providing an overall picture of the resistance situation (Heick et al., 2017).

632 **Box 3: Knowing the resistance status as a prerequisite for smart resistance management**

633 Gathering information on resistance to PPPs requires resources, field-oriented networks of
634 stakeholders, and multi-scale organization within a country. RMS aims can be the detection of
635 emerging resistance and the assessment of the prevalence of resistance in bioagressor populations.
636 This information is crucial for the evaluation of the impact of anti-resistance strategies. In situations
637 where the risk for resistance evolution is high, PPP users are expected to benefit from coordination
638 fostered by sharing RMIPs, but this gain may be at the expense of agrochemical companies that may
639 consequently face lower PPP demand (Lemarié & Marcoul, 2018). This makes information on
640 resistance strategic, and may explain why different RMSs or types of RMSs coexist in the same
641 country.

642 Resistance is also a hot topic for plant protection, because of growing social pressure towards
643 agriculture that is less dependent on chemical inputs. Consequently, this may also lead to more
644 complex NRMLs including complementary RMSs. In our questionnaire, we identified some initiatives
645 trying to structure resistance monitoring at a national level and centralizing RMIPs (see SI2). As an
646 example, we detail here the case of France, which is best known by the authors. Other countries may
647 of course have equivalent or more comprehensive organizations.

648 Up to 5 RMSs can be distinguished in France. (1) Monitoring is achieved by agrochemical companies
649 and their contractors (i.e. Private RMSs) to provide data for authorization dossiers, pre- and post-
650 authorization, as required by European and French regulations. This information is used for
651 marketing authorization, issued by the public agency in charge of PPP approvals. (2) Agrochemical
652 companies, but also cooperatives, retailers, and extension services, represented by crop-specialized
653 technical institutes, (i.e. Private RMSs) may also carry out more specific monitoring to accompany
654 PPP development and offer use recommendations throughout the lifespan of the PPP. Such
655 information is used for internal purposes or targeted publication towards stakeholders, and is in part
656 summarized by Resistance Action Committees (RACs) on their websites. (3) Public research institutes
657 also collect and analyze samples, often in collaboration with extension services, for basic research on
658 resistance evolution, management, and mechanisms (i.e. Academic RMSs), which can be used for
659 recommendations on resistance management, together with other stakeholders. (4) The French
660 Ministry of Agriculture funds a national resistance monitoring plan (i.e. a Governmental RMS) aimed
661 at detecting emerging resistances, with situations prioritized by field practitioners and experts. This is
662 legitimated by the Écophyto national regulation that includes the monitoring of non-intended effects
663 of PPP use. Samples are collected via a large range of partners, some being organized in networks.
664 PPP sensitivity assays are achieved by a dedicated public laboratory and by research institutes.
665 Results are used to inform public decision-making. (5) Phytopharmacovigilance (i.e. a Governmental
666 RMS) is organized by the French Ministries of Agriculture, Human Health, and the Environment and

request the official declaration of resistance cases by any stakeholders. It relies on the previous RMSs described and encourages all stakeholders to feed back information to identify early signs of resistance. Its data are considered for post-authorization.

Finally, in addition to manufacturer use recommendations, available information from these various RMSs is summarized by representatives of agricultural sectors and general experts in collaborative notes freely available on the internet, in addition to resistance reports (www.r4p-inra.fr). Lists of resistance cases are also regularly updated and reflect agriculture in France today, and its history of PPP use (**Table 1**). They also orient further research and monitoring on resistance, as well as PPP evaluation.

Table 1: Details on resistance cases detected in France (1978 – 2019).

Criteria	***Fungicides***	***Insecticides-Miticides***	***Herbicides***	***Total***
Number of resistance cases[1]	83	53	77	213
Number of bioagressors	32	25	34	91
Top 3 bioagressors	*Botrytis cinerea* *Erysiphe graminis* f. sp. *tritici* *Plasmopara viticola (ex aequo)*	*Cydia pomonella* *Myzus persicae* *Aphis gossypii*	*Lolium* sp. *Alopecurus myosuroides* *Papaver rhoeas*	
Number of PPP modes of action[3](chemical group)	21	13	5	39
Top 3 modes of action	Anti-microtubules (Benzimidazoles) Inhibitors of cytochrome b, Qo site (QoIs-P) Inhibitors of succinate dehydrogenase (SDHIs)	Voltage-gated sodium channel disruption (Pyrethroids) GABA-gated chloride channel disruption (Organochlorides) Acetylcholine esterase inhibitors (Organophosphates) *(ex aequo)*	ALS inhibitors (Sulfonylureas) PsbA inhibitors (Triazines) ACCase inhibitors	
Number of crops	19	27	14	38
Top 3 crops	Wheat Grapevine Barley	Apple Oilseed rape Peach	Winter cereals Maize Sunflower	

[1] Number of resistance cases listed as the number of triplets (crop x bioagressor x PPP mode of action).

[2] Number of bioagressors distinguished according to their EPPO code.

[3] Number of PPP modes of action distinguished according to their codes in the R4P unified classification (https://osf.io/UBHR5). Includes legacy PPPs no longer authorized.

Update December 2019. Full list available at https://osf.io/byv62/ or from https://www.r4p-inra.fr.

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841

842

843 **FIGURE LEGENDS**

844 **Figure 1:** The three levels of investigation: the National Resistance Monitoring Landscape (NRML),
845 the Resistance Monitoring System (RMS), and the Resistance Monitoring Information Product (RMIP).

846

847 **Figure 2:** Profile of questionnaire responses: number of questionnaire respondents (A) across the
848 world, and (B) according to their area of expertise in PPP resistance by bioagressor type. (C) Number
849 of RMSs per RMS category described by the respondents (one respondent could describe up to one
850 RMS belonging to each category), and (D) number of countries with at least one described RMS for
851 each category of RMS.

852

853 **Figure 3**: Resistance monitoring at the country level: (A) relationship between the Human
854 Development Index (HDI) of the countries surveyed and the composition of their National Resistance
855 Monitoring Landscape (NRML), (B) relationship between the HDI and the source of data on PPP use,
856 (C) relationship between the sources of data on PPP use in the countries surveyed and their NRML.

857

858 **Figure 4**: Characteristics of the different Resistance Monitoring System (RMS) categories: (A) number
859 of RMSs and bioagressor types monitored (178 out of the 250 described RMSs included information
860 on the type of bioagressor monitored); (B) proportions of the types of bioagressor monitored
861 according to the RMS categories; (C) orientation of the field sampling protocol according to the RMS
862 categories (200 out of the 250 described RMSs included information on the orientation of the
863 sampling protocol); (D) timing and frequency of publication of Resistance Monitoring Information
864 Products (RMIPs) according to the RMS categories (200 out of the 250 described RMSs included
865 information on the timing of publication).

866

867 **Figure 5**: Complementarities of Resistance Monitoring Systems (RMS) and actors: (A) distribution of
868 RMS funding sources, for all RMS categories taken together, for Academic RMSs, for Governmental
869 RMSs, and for Private RMSs (174 out of the 250 described RMSs included information on funding);
870 (B) number of actor types participating in the choice of topics for each RMS category (227 out of the
871 250 described RMSs included information on the actor types participating in the choice of topics); (C)
872 type of experts in charge of data analysis and interpretation depending on RMS categories (219 out
873 of the 250 described RMSs included information on the type of experts in charge of data analysis);
874 (D) influence of the number of RMS categories in the country and the National Resistance Monitoring
875 Landscape (NRML, in color) on the number of surveyed bioagressor types in the country. Circle size is
876 proportionate to the number of countries (stipulated in the middle).

877

878 **Figure 6:** Maps of the intensity of pesticide use (TFI) in Denmark, as an average of four growing
879 seasons (2011-2014). The maps cover three groups of active ingredients: pyrethroids, triazoles, and
880 glyphosate. The maps can provide useful guidance on where the risks for specific resistance problems
881 are higher. Coloring on the maps represents the distribution of calculated values. Blue represents the
882 8.33% lowest values, and red the 8.33% highest, while the ten color codes in between depict a linear
883 scale with each color code representing 8.33% of the interval between the lowest and highest values.

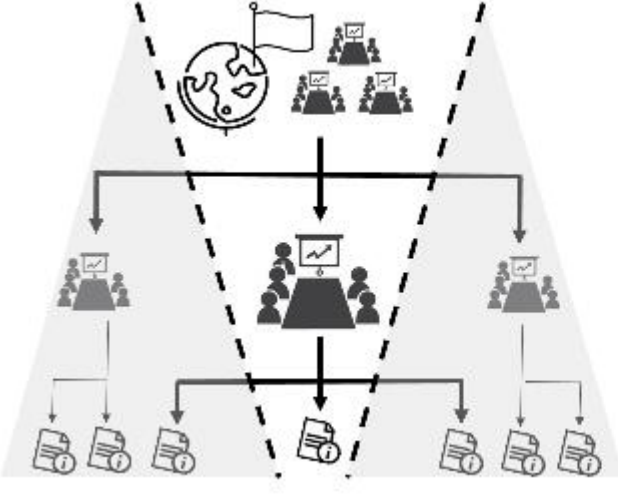
884

885 **Figure S1.1:** Probability of presence of one RMS category in a country depending on the Human
886 Development Index (HDI) of the country. A) Probability of an Academic RMS in the country (non-
887 significant correlation, $Z = 0.79$, $p = 0.429$), B) Probability of a Governmental RMS in the country
888 (significant correlation, $Z = 2.37$, $p = 0.018$), C) Probability of a Private RMS in the country (non-
889 significant correlation, $Z = 0.32$, $p = 0.746$). Logistic regression model prediction (solid line) and 95 %
890 CI (grey band) are presented.

891

892 **Figure S1.2:** Probability of presence of one type of source for monitoring of PPP use data in a country
893 depending on the Human Development Index (HDI) of the country. A) Probability of PPP use data
894 monitored by PPP sales in the country (significant correlation, Z = 2.34, p = 0.019), B) Probability of
895 PPP use data monitored by PPP survey in the country (marginally significant correlation, Z = 1.90,
896 p = 0.058). Logistic regression model prediction (solid line) and 95 % CI (grey band) are presented.

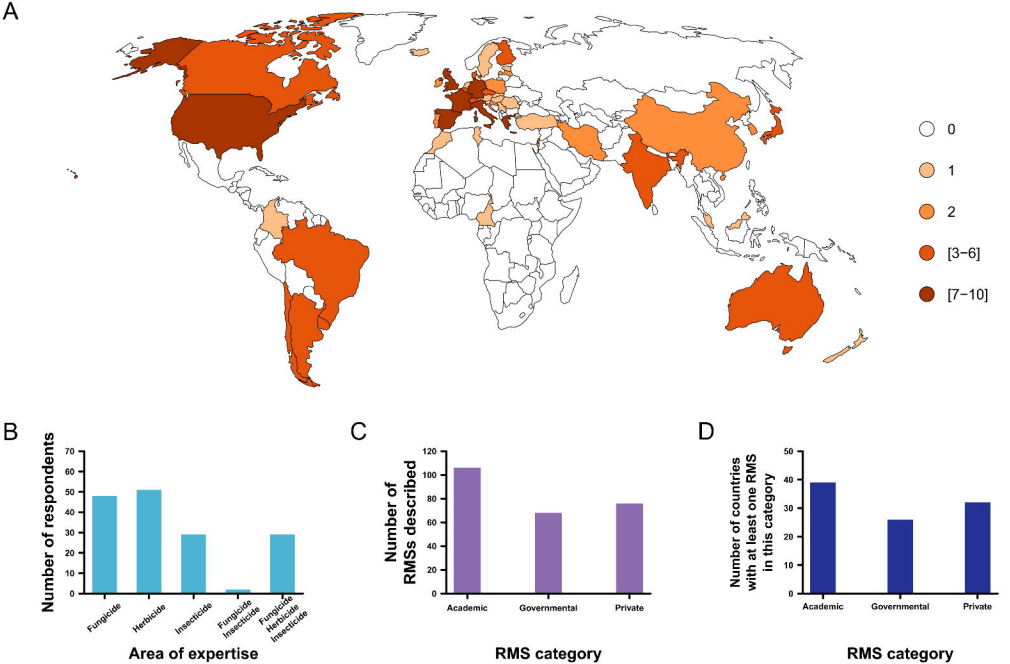
897

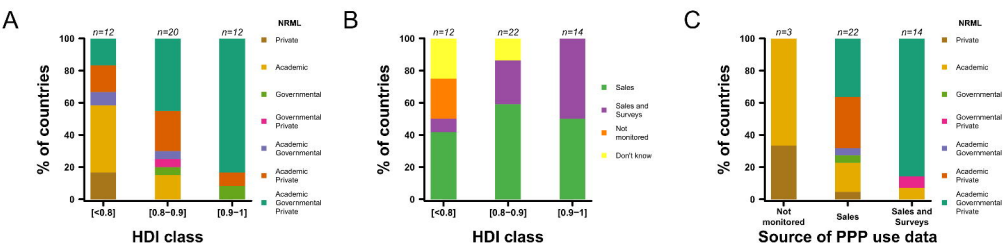


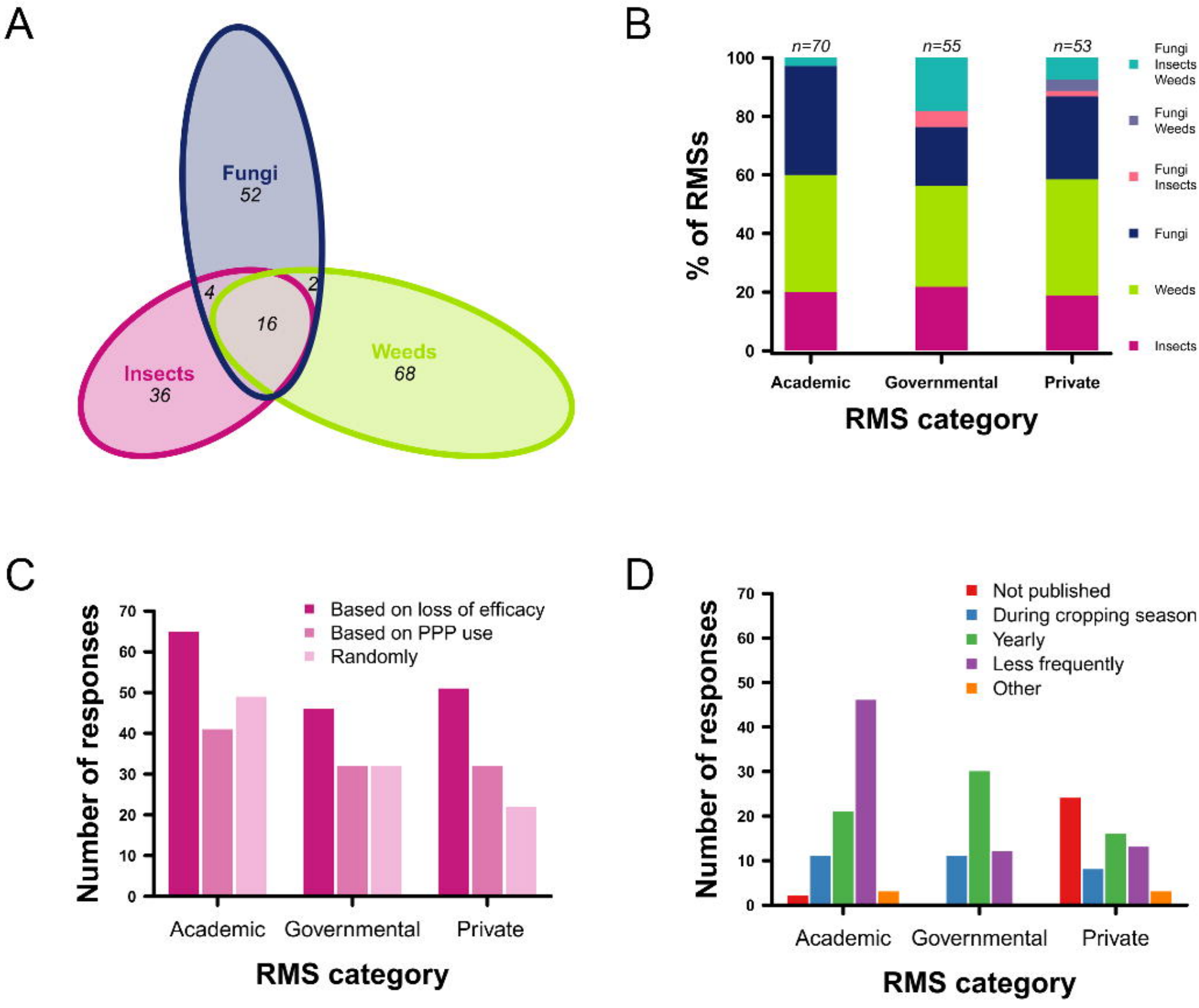
The National Resistance Monitoring Landscape (NRML) level:
At the country level, all existing resistance monitoring systems (RMSs) and their interactions.

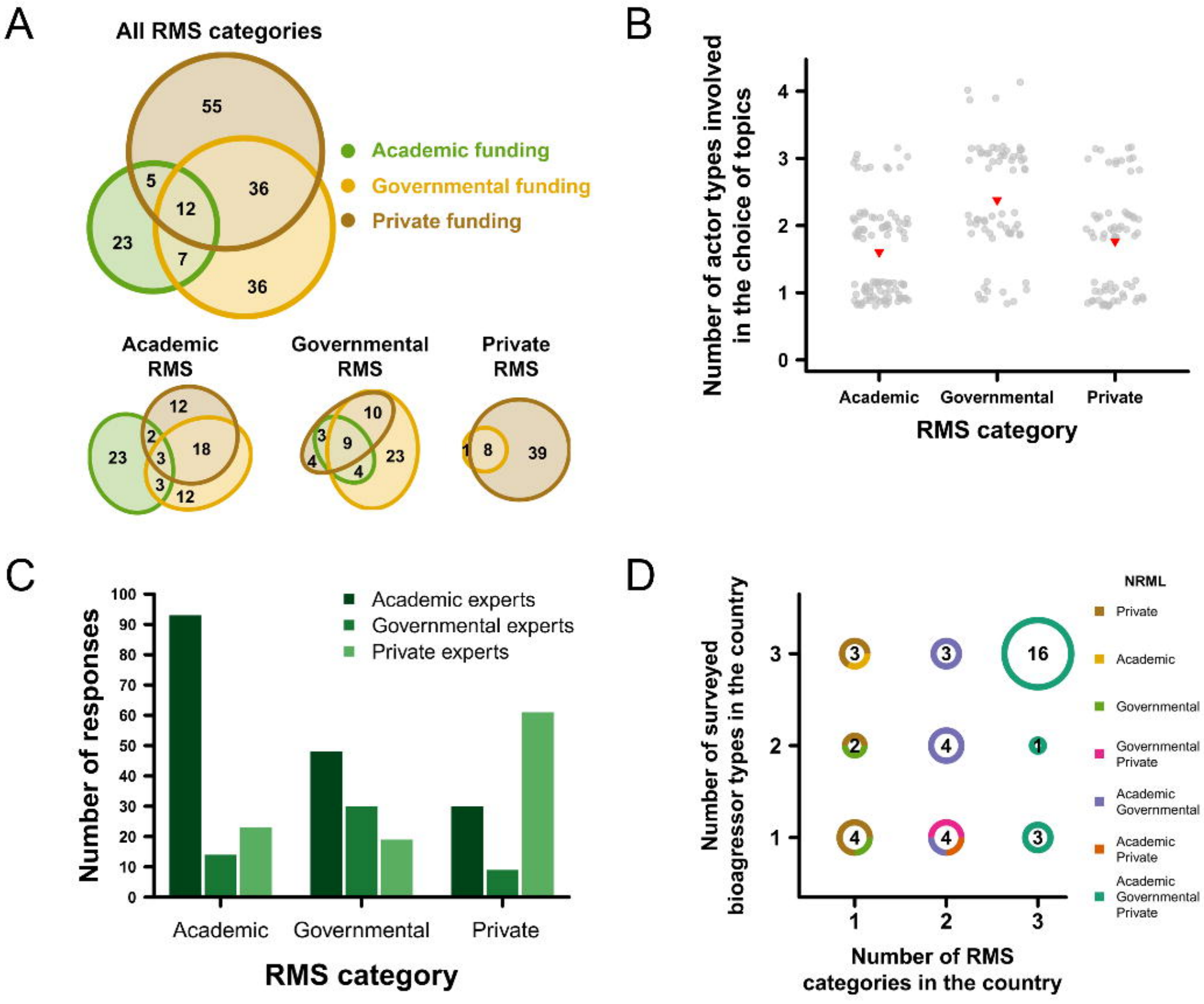
The Resistance Monitoring System (RMS) level:
An organization or a group of organizations with their own objectives and resources (financial, technical and human) and rationales that organize PPP resistance monitoring and produce Resistance Monitoring Information Products (RMIPs). An RMS may produce several different information products.

The Resistance Monitoring Information Product (RMIP) level:
A deliverable that enables actors to visualize and track the development of resistance, whether or not shared publicly.

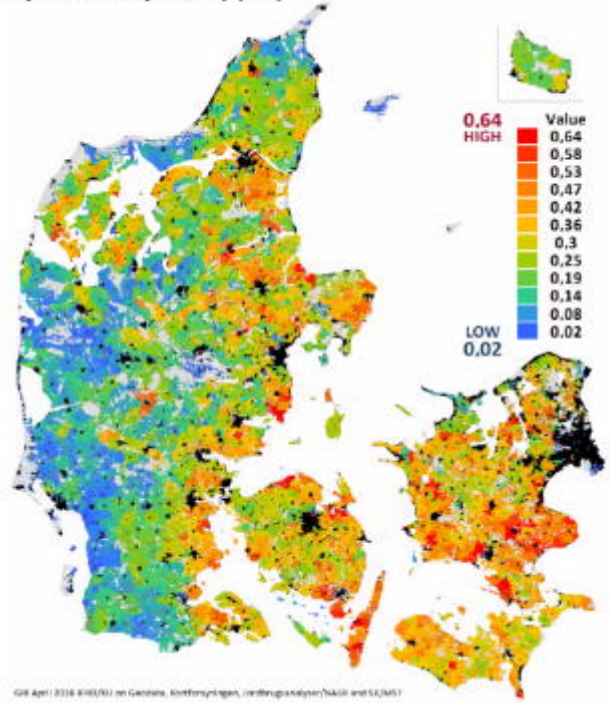

A
0
1
2
[3−6]
[7−10]
B
Number of respondents
70
60
50
40
30
20
10
0
Fungicide
Herbicide
Insecticide
Fungicide Insecticide
Fungicide Herbicide Insecticide
Area of expertise
C
Number of RMSs described
120
100
80
60
40
20
0
Academic
Governmental
Private
RMS category
D
Number of countries with at least one RMS in this category
50
40
30
20
10
0
Academic
Governmental
Private
RMS category


A
n=12
n=20
n=12
% of countries
100
80
60
40
20
0
[<0.8]
[0.8–0.9]
[0.9–1]
HDI class
NRML
Private
Academic
Governmental
Governmental Private
Academic Governmental
Academic Private
Academic Governmental Private
B
n=12
n=22
n=14
% of countries
100
80
60
40
20
0
[<0.8]
[0.8–0.9]
[0.9–1]
HDI class
Sales
Sales and Surveys
Not monitored
Don't know
C
n=3
n=22
n=14
% of countries
100
80
60
40
20
0
Not monitored
Sales
Sales and Surveys
Source of PPP use data
NRML
Private
Academic
Governmental
Governmental Private
Academic Governmental
Academic Private
Academic Governmental Private

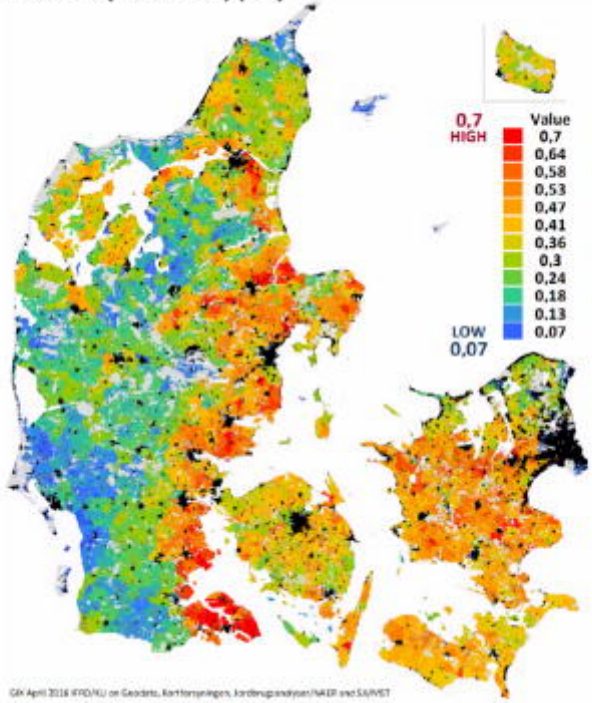
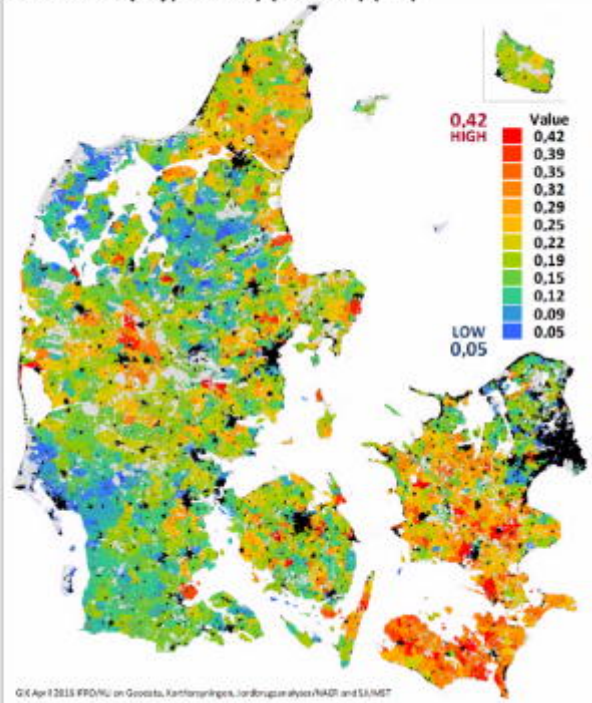

A
Fungi
52
Insects
36
Weeds
68
4
2
16
B
n=70
n=55
n=53
% of RMSs
100
80
60
40
20
0
Academic
Governmental
Private
RMS category
Fungi Insects Weeds
Fungi Weeds
Fungi Insects
Fungi
Weeds
Insects
C
Number of responses
70
60
50
40
30
20
10
0
Based on loss of efficacy
Based on PPP use
Randomly
Academic
Governmental
Private
RMS category
D
Number of responses
70
60
50
40
30
20
10
0
Not published
During cropping season
Yearly
Less frequently
Other
Academic
Governmental
Private
RMS category


A
All RMS categories
55
5
36
12
23
7
36
Academic funding
Governmental funding
Private funding
Academic RMS
12
2
18
23
3
3
12
Governmental RMS
10
3
9
23
4
4
Private RMS
1
8
39
B
Number of actor types involved in the choice of topics
0
1
2
3
4
Academic
Governmental
Private
RMS category
C
Number of responses
0
10
20
30
40
50
60
70
80
90
100
Academic experts
Governmental experts
Private experts
Academic
Governmental
Private
RMS category
D
Number of surveyed bioagressor types in the country
1
2
3
3
3
16
2
4
1
4
4
3
1
2
3
Number of RMS categories in the country
NRML
Private
Academic
Governmental
Governmental Private
Academic Governmental
Academic Private
Academic Governmental Private

Pyrethroids (IRAC 3) (TFI)



Triazoles (FRAC G1 3) (TFI)



EPSP inhib (Glyphosate) (HRAC G) (TFI)