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1 Lack of evidence for a decrease in synthetic pesticide use on the main arable crops in France

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8 **Abstract**

9 The frequent, widespread use of pesticides in agriculture adversely affects biodiversity,
10 human health, and water quality. In 2008, the French government adopted an environmental
11 policy plan, “Ecophyto 2018”, to halve pesticide use within 10 years. Trends in synthetic
12 pesticide sales and use in France were described, through three different indicators: the
13 number of unit doses (NUD), the quantity of active ingredient (QAI), and the treatment
14 frequency index (TFI). Changes in pesticide use on seven of the principal arable crops in
15 France since the implementation of this policy plan were analyzed, together with the impact
16 of changes in pesticide use on water quality. No evidence was found for a decrease in
17 pesticide sales at national level between 2008 and 2013. In terms of the TFI values for
18 individual crops, the only decrease in pesticide use observed since 2001 was for soft wheat.
19 This decrease was very slight, and pesticide use did not decline more rapidly after 2006 than
20 before. Changes in pesticide use differed between French regions and crops. Water pollution
21 did not decrease during the period studied. Possible explanations for the lack of effectiveness
22 of the French environmental plan are considered in the context of European legislation.

23 **Keywords**

24 Agricultural policy, pesticide indicators, crop, impact, water pollution

25 **Highlights**

- 26 - Trends in pesticide use on arable crops in France between 2001 and 2014 were described.
- 27 - No change in pesticide sales was observed at the national scale.
- 28 - Pesticide use has not decreased more rapidly since the adoption of the environmental plan.
- 29 - Water pollution did not decrease.

30 **1. Introduction**

31 Europe has been the leading consumer of synthetic pesticides worldwide since 2004 (based on
32 pesticide sales; McDougall LTD, 2013), accounting for about 45% of total pesticide use
33 (calculated by weight; De *et al.*, 2014). In France, agriculture uses an average of 4.1 t of
34 active ingredients per 1000 ha per year, close to the European (EU-15) average of 5.1 t
35 (Eurostat, 2014). This intensive use of synthetic pesticides has serious consequences for the
36 environment and human health (e.g., Elbaz *et al.*, 2009; INSERM, 2013). Several common
37 pesticides were classified as ‘probable’ or ‘possible’ carcinogenic by international agencies
38 (i.e., glyphosate in 2015 (IARC, 2016) and metolachlor in 1998 (EPA, 2016), respectively).
39 Pesticides can contaminate surface water through leaching (e.g., Gilliom, 2007), with
40 deleterious effects on non-target organisms, such as fish populations (e.g., Carriger *et al.*,
41 2008; Shinn *et al.*, 2015). Intensive pesticide use also generates costs associated with the
42 treatment of pesticide damage, and these costs may be high enough to drive associated total
43 costs beyond benefits (Bourguet and Guillemaud, 2016).

44 Synthetic pesticides have been detected in 93% of French watercourses (SoeS, 2013). In
45 2011, pesticide concentrations exceeded the limit allowed for drinking water ($0.5 \mu\text{g l}^{-1}$ in
46 Council Directive 98/83/EC, 1998) in about 4% of groundwater and 30% of rivers (SoeS,
47 2013). Water containing more than $5 \mu\text{g l}^{-1}$ pesticides cannot legally be used to produce
48 drinking water in Europe, and water containing between 0.5 and $5 \mu\text{g l}^{-1}$ pesticides must be

49 treated before use (Council Directive 98/83/EC, 1998). Every year in France, about 45% of
50 the volume withdrawn for drinking water is treated to remove pesticides (Bommelaer and
51 Devaux, 2011). The spatial distribution of pesticide-contaminated water is uneven over
52 France, with higher levels of contamination for agricultural zones specializing in cereal
53 production and vineyards (SoeS, 2015). The cost of eliminating 1 kg of pesticide from water
54 ranges from €60,000 to €200,000 (Bommelaer and Devaux, 2011). The extra processing costs
55 for drinking water due to pesticide contamination have been estimated at between 260 and
56 360 M€ annually in France (Bommelaer and Devaux, 2011). These costs are of a similar
57 magnitude to the 120-360 M€ estimated for nitrate treatment each year (Bommelaer and
58 Devaux, 2011). Between 1998 and 2008, 372 French water catchments were abandoned due
59 to high levels of pesticide concentration (State Secretariat for Health, 2012).

60 In 2009, the European Parliament established a framework to “achieve the sustainable use of
61 pesticides” through Directive 2009/128/EC (2009). According to this directive, each Member
62 State is required to adopt a national action plan laying down quantitative objectives,
63 indicators, and a schedule to “reduce risks and impacts of pesticide use on human health and
64 the environment”. The general objectives of this directive include (1) promoting integrated
65 pest management (IPM) and the use of alternative techniques, to limit pesticide applications,
66 (2) monitoring the use of plant protection products and setting targets for its reduction, and (3)
67 training and informing professional users and the general public, and raising awareness about
68 the hazards and risks associated with pesticides (Directive 2009/128/EC, 2009).

69 France adopted an ambitious environmental policy, including quantitative objectives in 2008,
70 to comply with this directive. This environmental policy, “Ecophyto 2018”, was designed to
71 halve agricultural and non-agricultural pesticide use within 10 years, but included no mid-
72 term objective. This policy included four main actions designed to promote changes in the
73 behavior of farmers in terms of pesticide use. One of these actions was the provision of better

74 information for farmers concerning the real threats posed to crops, through the reinforcement
75 of pest surveillance networks. Another focused on the identification and promotion of
76 agricultural practices less dependent on pesticides (IPM, biocontrol), notably through the
77 support of innovations in crop management practices and the development of cropping
78 systems with lower levels of pesticide input. The third action was the establishment of a
79 network of experimental farms. These farms were intended to have a pedagogical role,
80 showing farmers how to achieve good results by using pesticides differently or at lower doses.
81 The training of agricultural professionals in the safe use of smaller amounts of pesticides was
82 also planned (Plan Ecophyto 2018, 2008). In addition to Ecophyto 2018, some pesticides with
83 particularly dangerous active ingredients were banned. Substantial investment was dedicated
84 to the Ecophyto 2018 plan, with an average annual budget of €100 million for the 2010-2012
85 period (*Commission des affaires économiques sur le projet de loi de finances pour 2013,*
86 *2012*). This funding comes from three main sources: the French State (€130 million for the
87 2010-2012 period), a Pigovian tax (“fee for diffuse pollution”; €150 million for the 2010-
88 2012 period), and other public institutions, including the European Union (*Commission des*
89 *affaires économiques sur le projet de loi de finances pour 2013, 2012*). The Pigovian tax for
90 pollution (Law no. 2006-1772, 2006) was initiated in January 2008, and is based on the
91 “polluter pays” principle. Substances containing active pesticides are taxed according to their
92 level of toxicity, and pesticide distributors pay these taxes.

93 This study provides a detailed compilation and analysis of data for pesticide use and water
94 quality in France. It also aims to assess the mid-term effects of the Ecophyto 2018 plan. It
95 focuses on synthetic pesticides for agricultural use, which accounted for 88-93% of pesticide
96 sales from 2008 through 2013 (calculations based on *Ecophyto-Note de suivi 2014, 2015*).
97 Official French data on pesticide sales and use, and on water quality, between 2001 and 2014,
98 were obtained.

100 **2. Materials and Methods**

101 **2.1. Indicators of pesticide use**

102 This analysis was based on the three indicators selected by the French Ministry of Agriculture
103 for the monitoring of pesticide sales and use at the national scale and for evaluations of the
104 impact of its environmental policy (Plan Ecophyto 2018, 2008). These indicators include only
105 synthetic pesticides and do not take biocides into account.

106 The first indicator is based on yearly pesticide sales at national level: the number of unit doses
107 (NUD) per hectare. The NUD is an indicator created to monitor trends in pesticide use
108 following the implementation of Ecophyto 2018. As the official indicator for the assessment
109 of the Ecophyto 2018 plan, it was designed to prevent an artificial reduction of sales figures
110 linked to the replacement of one active ingredient by another ingredient effective at a lower
111 dose (Ecophyto-Le NODU, 2012). NUD is the total number of treatments performed annually
112 on all the agricultural land throughout France. Its division by the total acreage of agricultural
113 land (accessed in Agreste, 2016), yields to the mean number of treatments per hectare of
114 agricultural land. The NUD characterizes the annual intensity of pesticide use, based on the
115 total amounts of active ingredients sold, national crop acreages and the crop-specific doses
116 recommended for each active ingredient (Figure 1). Firstly, for each crop and each active
117 ingredient, a specific “unit dose” is determined from the maximum dose recommended for the
118 crop and active ingredient considered. Secondly, a unique unit dose is defined for each active
119 ingredient, by weighting the crop-specific unit dose by crop acreage. Thirdly, the NUD is
120 calculated by summing, for all active ingredients, the amount of active ingredients sold,
121 divided by their previously defined unique unit dose (Figure 1). The NUD was calculated for
122 all types of synthetic pesticides together (total NUD) and for individual types of pesticide
123 (fungicides, herbicides and insecticides). NUD data were reported for each year between 2008

124 and 2013, in the annual reports on pesticide use of the French Ministry of Agriculture
125 (*Ecophyto-Note de suivi 2014, 2015*). The Ministry made use of a national database to
126 calculate the NUD, assuming that all the products purchased were used in same year. This
127 database was compiled from sales balance sheets transmitted by pesticide dealers to state
128 agencies and water offices, as part of their mandatory statements on diffuse pollution for
129 calculation of the Pigovian tax (*Ecophyto-Note de suivi 2014, 2015*).

130 The second indicator used is the quantity of active ingredient (QAI, in t), which is the
131 quantity of active ingredients annually sold in France (Figure 1). The Ministry calculates this
132 indicator from the same database used for NUD calculation. The different types of pesticide
133 are not dealt with separately in the calculation of QAI, due to a lack of detailed data. The QAI
134 values obtained are reported in the same official annual reports on pesticide use than for
135 NUD. Like NUD, QAI is calculated on a yearly basis (Figure 1).

136 The third indicator is the treatment frequency index (TFI, unitless), which is also calculated
137 on a yearly basis. The official reports list the TFI values obtained for each crop and for each
138 administrative region separately. This index was calculated from data collected during the
139 national surveys of agricultural practices performed in 2001, 2006, 2011 and 2014. TFI was
140 determined for all types of pesticides together, and, in some cases, separately for herbicides
141 (all crops) and fungicides (all crops except durum wheat and sunflower). No TFI data for
142 insecticides were available for 2011 and 2014, because there were too few observations. Only
143 crops and regions for which data were available for 2001, 2006, 2011 and 2014 were
144 considered in our analysis. Only crops surveyed in at least four regions were analyzed: soft
145 wheat (*Triticum aestivum* L.), durum wheat (*Triticum durum* L.), barley (*Hordeum vulgare*
146 L.), rapeseed (*Brassica napus* L.), sunflower (*Helianthus annuus* L.), pea (*Pisum sativum* L.)
147 and sugar beet (*Beta vulgaris* L.) (Appendix A).

148 TFI (total, herbicides and fungicides) data were extracted from two published reports

149 (*Agreste-Enquête Pratiques culturales 2006, 2010, Agreste-Enquête Pratiques culturales*
150 *2011, 2013 and Agreste-Enquête Pratiques culturales 2014, 2016*) presenting data collected
151 during surveys conducted in 2006, 2011 and 2014, and from an unpublished report (L.
152 Guichard, pers. comm) presenting data collected during the 2001 survey. TFI data were
153 calculated in the same way and over the same scale in these three reports. TFI data are
154 available at the aggregated NUTS 2 regional level (NUTS 2 units correspond to
155 administrative divisions, each with a population of 0.8-3 million inhabitants; Eurostat, 2011).
156 For each crop, the TFI data were aggregated at national level (TFI_{cn}) by weighting the NUTS
157 2 TFI (TFI_{cr}) data by their respective acreages (Figure 1). The doses of pesticides
158 recommended and actually applied were used to calculate the TFI (Figure 1). The French
159 Ministry of Agriculture extracted data on applied pesticide doses from representative samples
160 of fields selected during national surveys. Recommended doses were extracted from the
161 National Plant Protection Database (Ephy website, 2014).

162

163 # Figure 1 approximately here #

164

165 **2.2. Indicators of surface water quality**

166 Two indicators were used to characterize surface water quality with regard to pesticides. The
167 first was the proportion of surface water measurements for which pesticide concentration
168 exceeded the acceptability threshold for drinking water of 0.5 µg l⁻¹ fixed by European
169 Council Directive 98/83/EC (1998). Between 2007 and 2012, the French Ministry of Ecology
170 reported this indicator annually, at both the NUTS 2 regional level and national level (Eider
171 database, 2016) (See Appendix B for the limitations of this measurement from 2008 and
172 2010). This indicator was derived from measurements taken at stations on French

173 watercourses (Eider database, 2016). Each value is the average of at least four yearly
174 measurements (with a few exceptions, see Appendix B). Values of pesticide concentrations
175 were classified into five categories (no detection, concentration below $0.1 \mu\text{g l}^{-1}$, between 0.1
176 and $0.5 \mu\text{g l}^{-1}$, between 0.5 and $5 \mu\text{g l}^{-1}$, and above $5 \mu\text{g l}^{-1}$) for each NUTS 2 region and at
177 national level.

178 The second indicator was the rate of detection of several dangerous chemical ingredients
179 (glyphosate, metolachlor, atrazine, diuron, chlortoluron and isoproturon) and their metabolites
180 in water samples nationally, expressed as a percentage. This analysis focused on active
181 ingredients quantified for at least two years after 2008 (all herbicides). Detection rate data
182 were obtained from two national reports on pesticides in aquatic environments published by
183 the Ministry of Ecology (data 1997-2007 in Soes, 2010 and data 2009-2013 in Soes, 2015).
184 Measurements were available for the 2009-2013 period, for all the active ingredients
185 considered. Measurements for most active ingredients were available for 1997 through 2007,
186 but, for AMPA and 2-hydroxy atrazine, data were available only from 1999 and 2000
187 onwards, respectively (see frequency of testing in Appendix C).

188

189 **2.3. Statistical analyses**

190 Linear regression models were fitted to the data to estimate trends for QAI and NUD
191 (herbicides, fungicides, insecticides, and total) over time. The estimated regression
192 coefficients were used to study the trends in pesticide use over time in France. The
193 significance of the regression coefficient estimates was assessed in Student's *t* tests
194 (difference of the coefficient from zero). A similar statistical approach was used to determine
195 the significance of trends over time for the TFI for each individual crop at national level.

196 The change in NUTS 2 TFI (herbicides, fungicides, and total) was characterized by the use of
197 a linear mixed-effect model to estimate the time trend for each type of TFI for each individual
198 crop, with region treated as a random effect on both the intercept and the slope. Linear models
199 were used to determine the relationship between TFI and year and between TFI and region,
200 for a variance analysis to quantify the relative effects of year and NUTS 2 region on TFI
201 variability.

202 The proportion of surface water samples containing more than $0.5 \mu\text{g l}^{-1}$ pesticides was
203 calculated for the 2007-2008 and 2009-2012 periods. Chi-squared tests were used to assess
204 the significance of differences in proportion. This analysis was performed separately at
205 national level and at the level of each individual region.

206 Finally, trends in the rates of detection of active ingredients in surface water over time, at
207 national level, were fitted by linear regression, and the significance of the estimated
208 regression coefficients was assessed in Student's *t* tests.

209 All statistical analyses were performed with R software (R Development Core Team, 2013),
210 and all the data are provided in the Supporting Information for this article.

211

212 **3. Results**

213 **3.1. Changes in pesticide sales and use**

214 The total number of unit doses (NUD) and the quantity of active ingredients (QAI) followed
215 similar trends nationally over the 2008-2013 period (Figure 2). The total NUD increased
216 during this period, with a significant positive estimated linear trend ($p < 0.05$) of about +0.074
217 unit doses per year and per hectare of agricultural land (+2.07 unit doses for the total surface
218 area under agriculture in France, Figure 2). The NUD for herbicides increased significantly
219 over the same period, by about +1.47 unit doses per year over the entire area under agriculture

220 in France. The NUDs for fungicides and insecticides remained stable ($p>0.05$) during the
221 2008-2013 period (Figure 2). The QAI remained stable over this period, the coefficient for the
222 trend not differing significantly from zero ($p>0.05$).

223

224 # Figure 2 approximately here #

225

226 TFI trends between 2001 and 2014 differed between crops (Figure 3). The lowest TFI values
227 were obtained for sunflower (median values of about 2) and the highest were obtained for
228 rapeseed (median values of about 5.8). For the other principal crops, median TFI values
229 ranged from 2.5 to 4.5 (Figure 3). The median TFI values of most crops decreased between
230 2001 and 2014, but these decreases were significant only for soft wheat ($p<0.001$, see Table
231 1). An annual decrease of about 4% would be required to half TFI of 2006 for soft wheat by
232 2018. This decrease rate is largely above the observed decrease of 1% (Table 1). Median TFI
233 remained stable between 2001 and 2014 for sugar beet. It even increased during this period
234 for barley and rapeseed (Figure 3). However, these trends were significant for barley only
235 ($p<0.05$; Table 1). The effect of NUTS 2 region on TFI was significant ($p=0.05$) for soft
236 wheat, barley, durum wheat and rapeseed. NUTS 2 region had a stronger effect than year for
237 barley, durum wheat and rapeseed (Appendix D).

238 TFI-fungicides was more variable between NUTS 2 regions than TFI-herbicides (Figure 3).
239 TFI-herbicides increased significantly between 2001 and 2014 for all crops but durum wheat
240 and sunflower. TFI-herbicides remained stable for these two crops (Table 1). A significant
241 effect of NUTS 2 region on TFI-herbicides was found for all crops except sunflower and
242 sugar beet ($p=0.05$). The NUTS 2 effect was larger than the year effect on TFI-herbicides for
243 soft wheat and durum wheat (Appendix D). TFI-fungicides significantly decreased ($p=0.05$)

244 for barley and pea only (missing data for durum wheat and sunflower; Table 1). The NUTS 2
245 region effect on TFI-fungicides was significant for all crops but pea. This effect was larger
246 than the year effect for rapeseed and sugar beet (Appendix D).

247 At the national scale, the trends for TFI highlighted a significant decrease for soft wheat
248 between 2001 and 2014 ($p < 0.05$, Table 2). TFI-herbicides significantly increased for sugar
249 beet, and TFI-fungicides showed a significantly decreasing trend for barley between 2001 and
250 2014 (Table 2). All other trends were not significant.

251

252 # Figure 3 around here #

253 # Table 1 around here #

254 # Table 2 around here #

255

256 The changes in TFI from 2001-2006 and from 2006-2011 differed considerably between
257 regions, for all crops (Figure 3). Regional TFI values revealed a decrease in pesticide use in
258 38 of 57 crop-region combinations between 2001 and 2006, in 37 of 57 crop-region
259 combinations between 2006 and 2011, and in only 17 crop-region combinations between
260 2011 and 2014. Over the whole period, 33 out of 57 crop-region combinations showed a
261 decrease in TFI between 2001 and 2014 (i.e., about 58% of all the crop-region combinations).
262 Only 5 of the 33 crop-region combinations displaying a decrease in TFI between 2001 and
263 2014 had a larger decrease in TFI between 2011 and 2014 than between 2001 and 2006, and
264 this difference remained small.

265 **3.2. Changes in water quality**

266 At the national scale, the proportion of river stations at which no pesticide was detected varied
267 from 6.6 to 11.2% between 2007 and 2012 (Figure 4). The proportion of water samples with

268 pesticide contents exceeding $0.5 \mu\text{g l}^{-1}$ (the threshold of acceptability for drinking water)
269 varied from 15.4 to 36.8% over this period. The mean proportion of surface water samples
270 considered unsuitable for use as drinking water was equal to 26.1% for both the 2007-2008
271 and 2009-2012 periods (Table 3).

272 Some regions had proportions of water samples with pesticide contents exceeding $0.5 \mu\text{g l}^{-1}$
273 well above the national average. For instance, during the 2007-2012 period, 60-84% of river
274 samples in Ile-de-France and 42-74% in Nord-Pas-de-Calais (Figure 5) were considered to be
275 of low quality (pesticide levels above the acceptability threshold for drinking water). The
276 proportion of low-quality water samples was lower in 2009-2012 than in 2007-2008 in only
277 one region (Aquitaine, Table 3, Appendix E). Indeed, this proportion actually increased
278 significantly in three NUTS 2 regions between these two periods ($p=0.05$, Table 3).

279

280 # Figure 4 approximately here #

281 # Table 3 approximately here #

282 # Figure 5 approximately here #

283 The active ingredients atrazine and metolachlor were banned in 2003. The detection rates for
284 these two ingredients and their metabolites (desethyl atrazine and 2-hydroxy atrazine)
285 decreased significantly between 1997 and 2007 ($p<0.05$; Figure 8, Appendix G). Between
286 2009 and 2013, the rates of detection of metolachlor and de-ethylated atrazine remained
287 stable, whereas those of atrazine and 2-hydroxyatrazine increased significantly (Figure 6,
288 Appendix G). Despite its prohibition in 2008, the rate of diuron detection in water samples
289 did not decrease significantly, either before or after 2008 ($p>0.05$; Appendix F). The rate of
290 glyphosate detection in surface water samples decreased significantly in the years leading up

291 to 2008, by about 4.2% per year, subsequently increasing by about 3.8% per year (Appendix
292 F).

293

294 # Figure 6 approximately here #

295

296 **4. Discussion**

297 **4.1 Ecophyto 2018 actions to decrease pesticide use and the results achieved**

298 In this study, pesticide use trends in France were characterized with three indicators
299 determined at the national and regional levels. QAI and NUD values showed that there was no
300 significant decrease in pesticide sales ($p>0.05$) at the national scale between the establishment
301 of the Ecophyto plan in 2008 and the most recent statistics analyzed here, those for 2013
302 (Table 4). The only significant decrease observed for (total) TFI was that for soft wheat (a
303 major crop grown on about 5,000,000 ha in France in 2014 (Agreste, 2016)) between 2001
304 and 2014 (Table 4).

305

306 # Table 4 approximately here #

307

308 The public policy on pesticide use established after 2006 did not accelerate the decrease in
309 pesticide use. The largest decreases in pesticide use observed between 2006 and 2011 were
310 for pea crop, and they amounted to only about 8% of the 2006 TFI value, far from the goal of
311 a 50% decrease in pesticide use by 2018 established in the Ecophyto 2018 plan. For
312 comparison, the quantity of active ingredient decreased by about 30% in France between 1998
313 and 2008 (108,700 and 78,600 t, respectively; UIPP, 2012). Moreover, the TFI remained
314 stable or even increased for other crops after 2006. The decrease in pesticide use may not be

315 linear, because the volume and frequency of applications (especially for insecticides and
316 fungicides) depend on pest pressure and weather conditions (e.g., Miraglia et al., 2009).
317 Detailed information about pest pressure for each crop remain scarce, but annual assessments
318 of Ecophyto 2018 at national level suggests that pest pressure in the 2009-2013 period was
319 similar to that in 2008 (Ecophyto-Note de suivi (2010); Ecophyto-Note de suivi 2012 (2013);
320 Ecophyto-Note de suivi 2013 (2013); and Ecophyto-Note de suivi 2014 (2015)). At the
321 national scale, pesticide sales could also be influenced by land use changes. However, Urruty
322 et al. (2016) showed that changes in agricultural land use had nearly no impact on total
323 pesticide use at national scale from 1989 to 2013. During this period, the substitution of
324 intensive systems (e.g., vineyards) by low pesticide systems (annual crops) were balanced by
325 land use changes leading to an increased pesticide use (e.g., replacement of set-aside lands by
326 arable crops) (Urruty et al., 2016).

327 The economic context may also influence pesticide use. Market prices for most cereals have
328 been high in recent years, especially in 2008, 2010 and 2011 (AGPB, 2013). Strong market
329 prices may affect decision-making, and encourage some farmers to over-protect their crops
330 with “precautionary” applications intended to maximize yield (e.g., Pannell *et al.*, 1991;
331 Pedersen *et al.*, 2012). For example, halving pesticide use may reduce soft wheat yields by
332 5% to 13% (Hossard *et al.*, 2014). This loss may not be compensated by the savings from
333 lower pesticide costs if cereal prices are high (Hossard *et al.*, 2014). Some studies have
334 reported an absence of correlation between pesticide use, productivity and profitability
335 (Lechenet *et al.*, 2014), but other studies have reported lower gross margins for integrated
336 pest management (IPM) strategies. In these last studies, the difference relative to conventional
337 systems was larger for advanced IPM (11-60%) than for intermediate IPM (2-44%)
338 (Dachbrodt-Saaydeh *et al.*, 2015). Intermediate IPM strategies attempt to control pests
339 individually, whereas advanced IPM includes other agronomic practices, such as the use of

340 mulches and varietal mixtures, to reduce pesticide use further (Dachbrodt-Saaydeh *et al.*,
341 2015). Under IPM strategies, synthetic pesticides may be replaced by biocides based on
342 natural products and living organisms (Villaverde *et al.*, 2014). However, many of these
343 bioproducts have narrower spectra of activity, shorter lifespans, and are less effective and
344 more expensive than regular pesticides (Chandler *et al.*, 2011; Glare *et al.*, 2012).

345 Previous studies (Butault *et al.*, 2010; Jacquet *et al.*, 2011) estimated that halving pesticide
346 use in France would require radical changes in current systems (e.g., crop rotations). By
347 contrast, these studies suggested that a 10% to 30% decrease with no loss of profitability
348 would be possible if low-input techniques were practiced on a large scale. It has been claimed
349 that IPM strategies are common in orchard and greenhouse production systems, but ‘largely
350 marginal’ in arable crop systems in Europe (Lefebvre *et al.*, 2015). However, no data are
351 currently available concerning the areas managed by such practices.

352 In line with the objectives of the Ecophyto 2018 plan, several active ingredients of
353 considerable concern were withdrawn from the market in 2008 (e.g., diuron) or earlier (e.g.,
354 atrazine and metolachlor in 2003). However, detection rates for these molecules continued to
355 increase after 2008. This may reflect a potential time lag between the application of pesticides
356 and their transfer to water. These transfers are influenced by the pedoclimatic conditions
357 driving soil processes, such as runoff, leaching, and the sorption of pesticides to soil and
358 sediments (e.g., Borggaard *et al.*, 2008; Gevaio *et al.*, 2000; Dollinger *et al.*, 2015). For
359 atrazine and metolachlor, this time lag may also reflect temporary binding to sediment in
360 surface water (Rice *et al.*, 2004).

361

362 **4.2 Limitations of pesticide use indicators and related data**

363 NUD and QAI are based on pesticide sales, whereas TFI describes levels of pesticide use. TFI
364 has two key advantages over NUD and QAI: (1) it is calculated for individual crops, and (2) it
365 is based on actual cropping practices (real use). However, TFI calculation requires large
366 amounts of data that are very time-consuming to collect at national level. As a result, this
367 index was available only for the principal arable crops, and only for the years 2001, 2006,
368 2011 and 2014. TFI data are based on field surveys, where sampling should be representative
369 of the crop at the NUTS 2 regional scale. The regions surveyed differ from year to year. For
370 example, surveys were performed in six more NUTS 2 regions in 2011 than in 2006 (*Agreste*
371 *- Enquête Pratiques culturales 2011, 2013*). We included only NUTS 2 regions surveyed in
372 each of the four years, 2001, 2006, 2011, and 2014, for our calculation. The doses applied
373 were calculated according to the recommended application rate. TFI thus provides
374 information about the intensity of pesticide use. This indicator also accounts for all active
375 molecules included in commercial products. However, it does not reflect the effect of
376 pesticides on the environment.

377 In our analysis of TFI, the start time for the implementation of the Ecophyto 2018 policy was
378 approximated by using 2006 as the reference year, rather than 2008, due to the dates of the
379 surveys used to collect the data (2001, 2006, 2011 and 2014). This indicator was calculated
380 using a database different from that used by for QAI and NUD calculations for Ecophyto
381 2018. The use of 2006 rather than 2008 as the reference year may have resulted in an
382 underestimate of pesticide use before the introduction of Ecophyto 2018, particularly given
383 that pesticide sales were high in 2008. According to the Union of Crop Protection Industries
384 (UIPP), the total quantity of active ingredients sold was 71,600 t in 2006 and 78,600 t in 2008
385 (UIPP, 2012). However, the total quantity of active ingredients sold was much higher in 2001
386 (99,600 t), and it remained stable from 2003 to 2008 (UIPP, 2012). Moreover, QAI is
387 determined on the basis of sales rather than use and is highly dependent on product

388 composition. In terms of the total quantity of active ingredients reported by UIPP (UIPP,
389 2012), sales decreased strongly between 2008 and 2009 (from 78,600 t to 63,700 t),
390 subsequently remaining stable until 2011 (61,900 t in 2010, and 62,700 t in 2011). The
391 database used for the NUD and QAI calculations was different from that used by UIPP.
392 According to the 2013 Ecophyto 2018 assessment (*Ecophyto-Note de suivi 2013*, 2013), the
393 national pesticide sales database may be incomplete for 2008, which would have resulted in
394 pesticide sales being underestimated in 2008. A comparison of the two databases showed that
395 they overlapped for 76% of 2008 sales, and 91% of 2009 sales (*Ecophyto-Note de suivi 2013*,
396 2013). This implies that the NUD and QAI values should have been higher for 2008, but
397 correction of the values would not modify our conclusions, as the QAI value would still be
398 lower in 2008 than in 2013.

399

400 **4.3 Prospects for future?**

401 Fruit production and horticulture were excluded from national surveys until 2012 and 2014,
402 respectively (Agreste, 2016), despite their high levels of pesticide use. For example, the TFI
403 for table apples was about 36.5 in 2006 (Butault *et al.*, 2011). Horticulture and fruit
404 production accounted for 4.7% and 5.2% of pesticide use in France, and 0.8% of the total
405 cultivated area. Arable crops accounted for 67.6% of the country's pesticide use and 45.7% of
406 the land area cultivated (INRA calculations based on Agreste, MAAPRAT and SSP data,
407 cited by Butault *et al.*, 2011). Newer pesticides tend to be more selective than older
408 molecules, and are, therefore, generally less toxic to non-target organisms (Casida *et al.*,
409 1998). However, one recent study suggested that 90% of the total impact of pesticides on
410 health in Europe was due to only 13 active substances applied on vegetables, fruit trees and
411 grapes (Fantke *et al.*, 2012). Surveys on pesticide use were performed in 2012 for fruit
412 production, and in 2014 for horticulture. Similar surveys will be conducted in 2016 and 2017,

413 respectively (Agreste, 2016). It will then be possible to analyze trends in pesticide use for
414 fruit and horticultural crops, using an approach similar to that used here for arable crops.

415 In 2015, the French Ministry of Agriculture adopted a second environmental plan,
416 Ecophyto – II (French Ministry of Agriculture, Food Industry and Forestry, 2015). The
417 objective is still to decrease pesticide use by 50%, but with a target date of 2025 rather than
418 2018 as in the first Ecophyto plan (Plan Ecophyto 2018, 2008). The updated plan also
419 specifies a mid-term objective of a 25% decrease in pesticide use by 2020. This 25% decrease
420 should be achieved by generalizing and optimizing existing agricultural management
421 techniques (e.g., IPM), which was already the primary means of action for Ecophyto 2018. A
422 certificate of pesticide savings included in the new plan (JORF n°0238, 2014) should favor
423 the spread of these techniques. This certificate will require dealers of pesticides for
424 professional use to take (or favor) actions designed to reduce their use (Ordonnance n°2015-
425 1244, 2015). Financial penalties will be applied in 2021 by the government (French Ministry
426 of Agriculture, Food Industry and Forestry, 2016). The 2025 objective should be achieved
427 through significant changes in both production systems and agricultural chains, supported by
428 political determinants in the medium and long term and by advances in science and
429 techniques. The 2025 plan thus relies on a combination of technical advices, training and
430 taxes/fines. One of the key hypotheses underlying this approach was that providing farmers
431 with information about the health status of crops, the safe use of pesticides and low-pesticide
432 techniques and systems would encourage farmers to reduce pesticide uses. Our findings
433 indicate that these measures have not been effective in the short term as no real decrease in
434 pesticide use was observed so far. One reason might be that the Pigovian tax used in France
435 remained much lower than that applied in other countries, such as Denmark (*Commission des*
436 *affaires économiques sur le projet de loi de finances pour 2013*, 2012). The Danish action
437 plan included a high tax on pesticides (34-54% of sale price), which resulted in a decrease in

438 pesticide use by about one third over 10 years (TFI of 3.1 in 1990-1993 vs. TFI of 2.1 in
439 2001-2003; Neumeister, 2007; Nielsen, 2005). This tax had a direct short-term impact
440 resulting in a 5-10% decrease in pesticide sales, and it also rendered other pest control
441 measures more competitive (Neumeister, 2007). Switzerland adopted a compensatory system
442 rather than a tax-based approach; Swiss farms receive ecology payments for implementing
443 specific practices, such as crop rotation or the limited use of some pesticides (e.g.,
444 insecticides, pre-emergence herbicides; Neumeister, 2007). The payment depends on the
445 degree to which such practices are applied. For example, larger amounts are paid for
446 extensive production (no insecticide, fungicide, or growth regulator), and premium prices are
447 applied to products produced in accordance with the guidelines of an integrated production
448 label (Jacquet *et al.*, 2011). No precise statistics for pesticide use are available in Switzerland,
449 but total pesticide sales decreased by about 12% between 2000 and 2005, mostly due to a
450 decrease in insecticide and fungicide sales (Neumeister, 2007). Both the Danish and the Swiss
451 plans combine an efficient technical advisory system and strong market mechanisms (i.e.,
452 pesticide taxation and financial incentives, respectively).

453

454 **5. Conclusion**

455 We found no evidence of a decrease in pesticide sales at national level between 2008 and
456 2013. Similarly, pesticide use did not decrease for most arable crops between 2006 and 2014
457 in France. No mid-term objective was included in the Ecophyto 2018 policy, but the absence
458 of a decrease over this period suggests that the objective of a 50% decrease in pesticide use on
459 arable fields is unlikely to be attained by 2018. A significant decrease in pesticide use was
460 observed between 2001 and 2014 for soft wheat only. For this crop, the rate of decrease
461 represents only one fourth of the level required to half pesticide use by 2018. The
462 concentration of some active ingredients considered ‘possibly’ or ‘probably’ carcinogenic

463 increased after 2009. Our results thus suggest that the actions undertaken within the Ecophyto
464 2018 policy were not successful, and this policy should be revised. An international
465 assessment of modes of action for decreasing pesticide use, and their impacts, would facilitate
466 the design of effective public policies in this domain.

467

468 **6. Acknowledgments**

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472 their comments on earlier versions of this manuscript.

473

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613

1 Table 1. Estimated NUTS 2 total TFI, TFI herbicide and fungicide trends between 2001 and 2014. TFI_{cr} is the TFI calculated for each NUTS 2
 2 region and for each crop (see Figure 1).
 3

Crop	Time trend for TFI _{cr} (absolute)		Time trend for TFI _{cr} (relative)		TFI _{cr} herbicides		TFI _{cr} fungicides	
	Slope (TFI unit per year)	p-value	Mean TFI ₂₀₀₆	Relative slope (% of TFI ₂₀₀₆ per year)	Slope (TFI unit per year)	p-value	Slope (TFI unit per year)	p-value
Soft wheat	-0.036	<0.001	3.714	-0.967 %	0.011	0.003	-0.008	0.061
Durum wheat	-0.003	0.907	-	-	0.002	0.767	NA	NA
Barley	0.023	0.032	-	-	0.031	<0.001	-0.013	<0.001
Rapeseed	0.015	0.247	-	-	0.022	<0.001	0.004	0.340
Sunflower	-0.017	0.106	-	-	-0.002	0.711	NA	NA
Pea	-0.017	0.386	-	-	0.018	<0.001	-0.025	0.031
Sugarbeet	0.005	0.765	-	-	0.079	<0.001	-0.007	0.287

4 *** : p<0.001 ; **: p<0.01 ; * : p<0.05 ; NS : not significant at p=0.05 ; NA: data not available

5

6 Table 2. Estimated total TFI, TFI herbicides and TFI fungicides trends between 2001 and
7 2014 at the national level. TFIcn is the TFI calculated for a given crop at the national scale
8 (see Figure 1 and §2.1 for details).

Crop	TFIcn		TFIcn herbicides		TFIcn fungicides	
	slope	p-value	slope	p-value	slope	p-value
Soft wheat	-0.044	0.023	-0.013	0.402	-0.011	0.472
Durum wheat	0.011	0.741	0.006	0.582	NA	NA
Barley	0.018	0.280	0.031	0.069	-0.018	0.026
Rapeseed	-0.005	0.781	0.017	0.236	0.003	0.796
Sunflower	-0.021	0.336	-0.004	0.715	NA	NA
Pea	-0.033	0.246	0.016	0.074	-0.026	0.389
Sugarbeet	<0.001	0.982	0.082	0.031	-0.008	0.522

Table 3. Change in the proportion of stations with total pesticide concentrations exceeding 0.5 $\mu\text{g l}^{-1}$ and associated χ^2 tests.

Scale	Proportion of stations (%) with Total concentration of pesticides > 0.5 $\mu\text{g l}^{-1}$		
	mean 2007-2008	mean 2009-2012	p-value
France	26.107	26.066	0.995
Alsace ^a	8.750	32.971	<0.001
Aquitaine	41.954	22.688	0.017
Auvergne	0	26.015	<0.001
Lower Normandy	4.375	6.851	0.460
Burgundy	19.327	23.069	0.565
Brittany	22.685	26.484	0.588
Centre	11.486	35.014	<0.001
Champagne-Ardenne	32.663	20.730	0.102
Franche-Comté	13.031	14.675	0.755
Upper Normandy	11.127	11.628	0.916
Ile-de-France	72.534	68.498	0.734
Languedoc-Roussillon	17.905	15.823	0.720
Lorraine	24.375	29.202	0.510
Midi-Pyrénées	22.132	25.252	0.650
Nord-Pas-de-Calais	57.949	59.519	0.885
Pays-de-la-Loire	45.629	49.906	0.662
Picardy	37.792	32.064	0.493
Poitou-Charentes	15.951	11.602	0.407
Provence-Alpes-Côte-d'Azur	14.16	11.668	0.624
Rhône-Alpes	15.896	15.484	0.941

^a only one measure was realized in Alsace in 2008.

1 Table 4. Summary of changes in pesticide use for the three indicators QSA, NUD and TFI at
 2 national level.

3

Indicator	Crop	Period of time	National trend	Regional trend
QSA	All	2008-2013	NS	NA
NUD-total		2008-2013	↗	NA
NUD-herbicides		2008-2013	↗	NA
NUD-fungicides		2008-2013	NS	NA
NUD-insecticides		2008-2013	NS	NA
TFI-total	Soft wheat	2001-2014	↘	↘
TFI-herbicides		2001-2014	NS	↗
TFI-fungicides		2001-2014	NS	NS
TFI-total	Durum wheat	2001-2014	NS	NS
TFI-herbicides		2001-2014	NS	NS
TFI-total	Barley	2001-2014	NS	↗
TFI-herbicides		2001-2014	NS	↗
TFI-fungicides		2001-2014	↘	↘
TFI-total	Rapeseed	2001-2014	NS	NS
TFI-herbicides		2001-2014	NS	↗
TFI-fungicides		2001-2014	NS	NS
TFI-total	Sunflower	2001-2014	NS	NS
TFI-herbicides		2001-2014	NS	NS
TFI-total	Pea	2001-2014	NS	NS
TFI-herbicides		2001-2014	NS	↗
TFI-fungicides		2001-2014	NS	↘
TFI-total	Sugarbeet	2001-2014	NS	NS
TFI-herbicides		2001-2014	↗	↗
TFI-fungicides		2001-2014	NS	NS

4 NS : not significant ($p > 0.05$) ; ↗ : significant increase ($p < 0.05$) ; ↘ : significant decrease
 5 ($p < 0.05$) ; NA : missing data.

6

Figure captions

Figure 1. Data and methods for calculating the three pesticide use indicators: number of unit doses (NUD), quantity of active substances (QAI) and treatment frequency index (TFI). These indicators are calculated on a yearly basis, for the years in which the necessary information is available. Adapted from Baschet and Pingault, 2009 ; Pingault *et al.*, 2012.

Figure 2. Pesticide use trends shown by the national indicators quantity of active ingredients (QAI, in black), number of unit doses (NUD, red diamonds), and number of unit doses for herbicides (NUD_h, red upward triangles), fungicides (NUD_f, red dots) and insecticides (NUD_i, red downward triangles) for the total surface area under agriculture in France. Dashed lines indicate the fitted regressions.

The legend indicates the estimated value of the slope of the regression line (a) and the associated p-value (p). NS: not significant ($p > 0.05$) ; * : significant at $p = 0.05$.

Figure 3. Distribution of total TFI (A) and TFI for herbicides only (B) or fungicides only (C) for the seven crops and the three four surveyed. The boxplot indicates the minimum, 1st quartile, median, 3rd quartile, and maximum value across French regions. No data were available for fungicides use on durum wheat and sunflower.

Figure 4. Proportion of pesticide measurements in each of five concentration classes between 2007 and 2012 for samples taken from French rivers.

The number of stations at which measurements were made is indicated at the top of the bar for each year. Water with a total pesticide content exceeding $0.5 \mu\text{g l}^{-1}$ is considered unfit for drinking, according to European Union regulations (Council Directive 98/83/EC, 1998).

Figure 5. Proportion of pesticide measurements in each of five concentration classes, for samples from the rivers of the NUTS 2 regions Ile de France and Nord Pas de Calais, between 2007 and 2012. The number of stations at which measurements were made is indicated at the top of the bar for each year.

Stations: Points along watercourses at which measurements were made.

Figure 6. Evolution of the detection rate of six chemical ingredients and their metabolites in French rivers, at the national scale.

Solid lines correspond to significant slopes ($p = 0.05$) ; dashed lines correspond to not-significant slopes ($p = 0.05$) – see appendix E for more details on model parameters. For the chemicals that were forbidden within the considered time frame, the year of their interdiction is indicated by a ‘o’ on the x-axis.

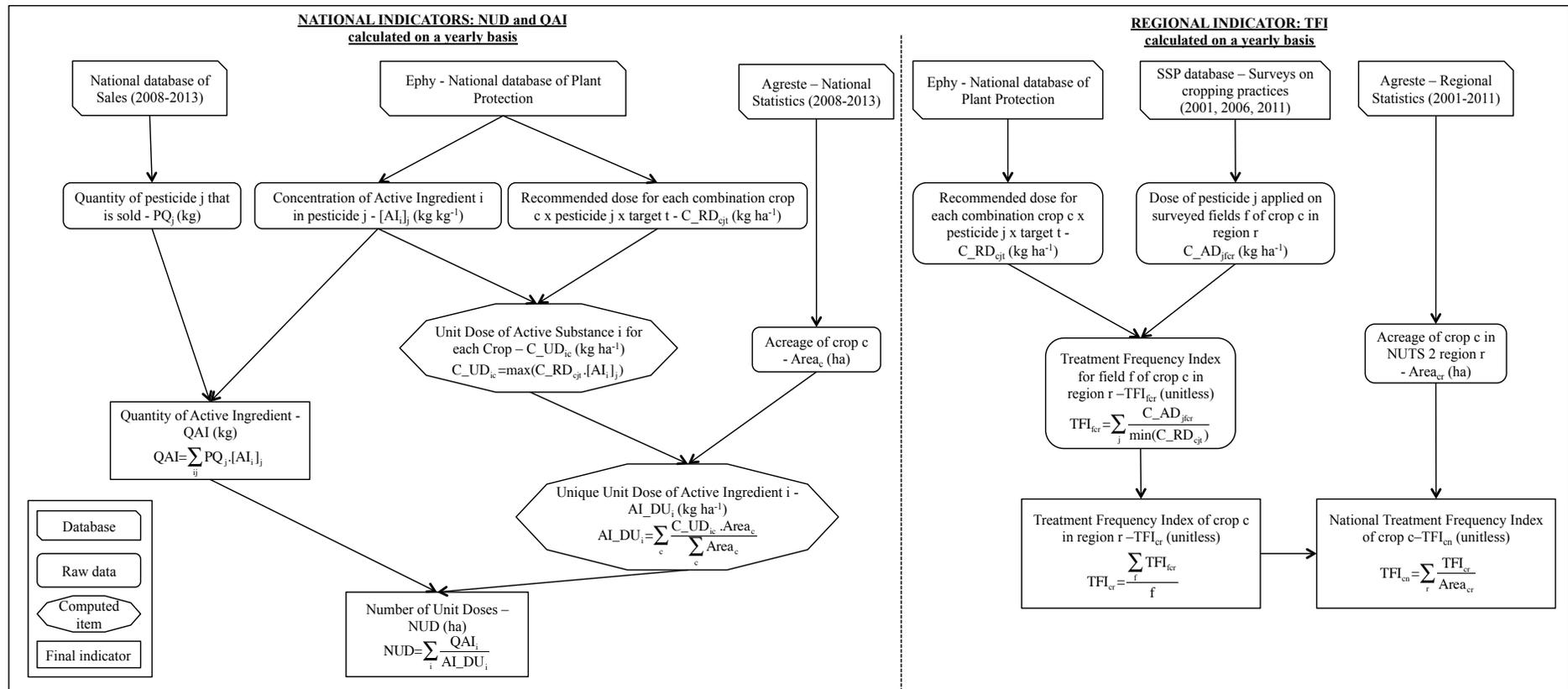


Figure 1. Data and methods for calculating the three pesticide use indicators: number of unit doses (NUD), quantity of active substances (QAI) and treatment frequency index (TFI). These indicators are calculated on a yearly basis, for the years in which the necessary information is available. Adapted from Baschet and Pingault, 2009 ; Pingault et al., 2012

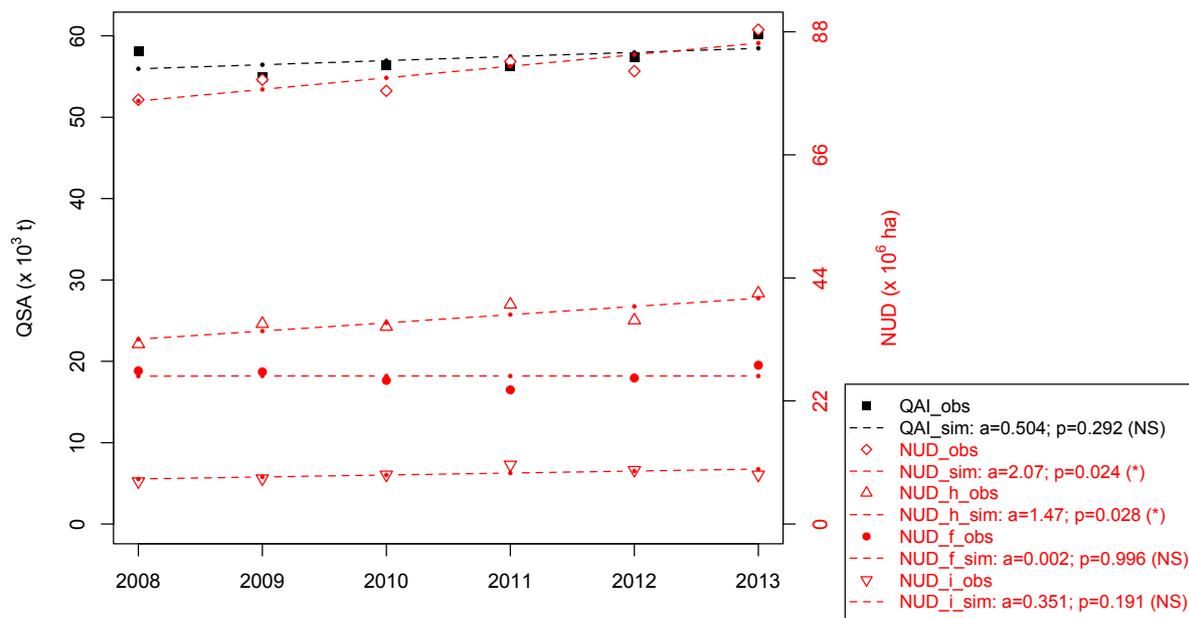


Figure 2. Pesticide use trends shown by the national indicators quantity of active ingredients (QAI, in black), number of unit doses (NUD, red diamonds), and number of unit doses for herbicides (NUD_h, red upward triangles), fungicides (NUD_f, red dots) and insecticides (NUD_i, red downward triangles) for the total surface area under agriculture in France.

Dashed lines indicate the fitted regressions.

The legend indicates the estimated value of the slope of the regression line (a) and the associated p-value (p). NS: not significant ($p>0.05$) ; * : significant at $p=0.05$.

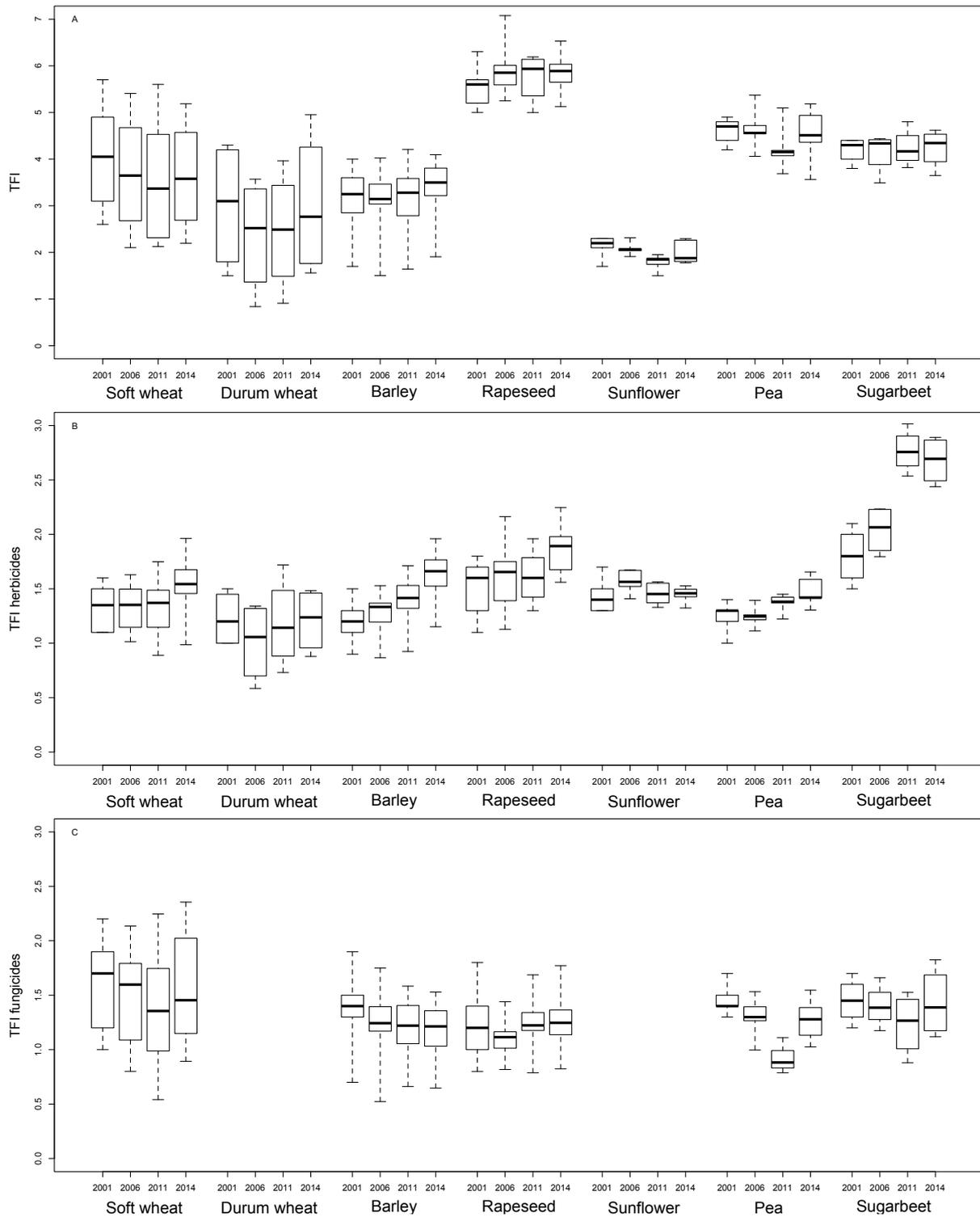


Figure 3. Distribution of total TFI (A) and TFI for herbicides only (B) or fungicides only (C) for the seven crops and the four years surveyed. The boxplot indicates the minimum, 1st quartile, median, 3rd quartile, and maximum value across French regions. No data were available for fungicide use on durum wheat and sunflower.

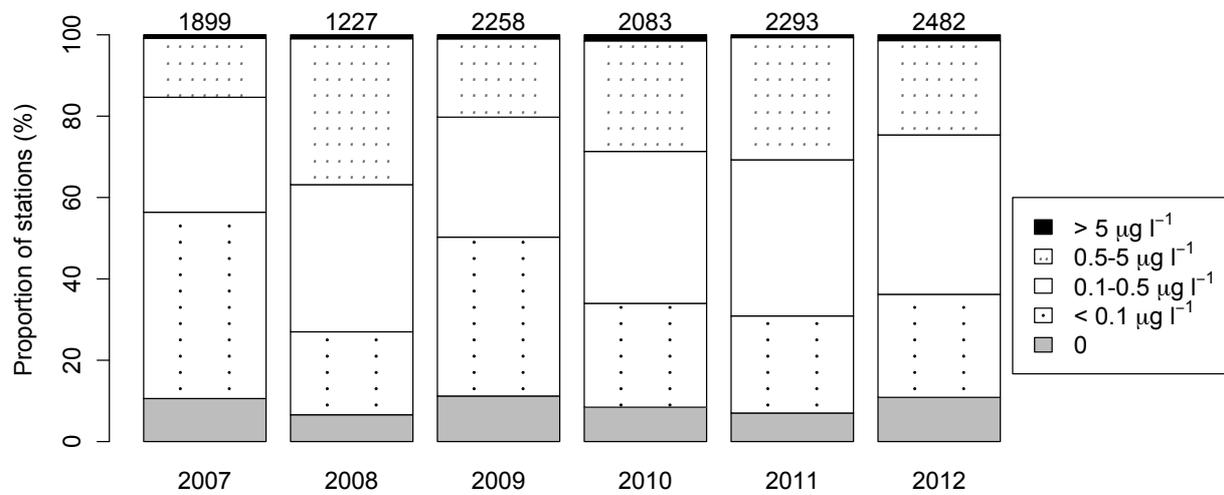


Figure 4. Proportion of pesticide measurements in each of five concentration classes between 2007 and 2012 for samples taken from French rivers.

The number of stations at which measurements were made is indicated at the top of the bar for each year. Water with a total pesticide content exceeding $0.5 \mu\text{g l}^{-1}$ is considered unfit for drinking, according to European Union regulations (Council Directive 98/83/EC, 1998).

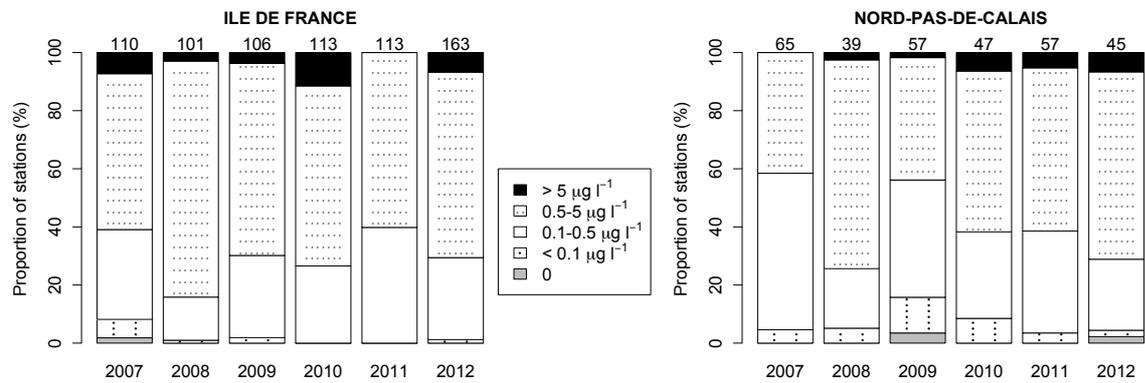


Figure 5. Proportion of pesticide measurements in each of five concentration classes, for samples from the rivers of the NUTS 2 regions Ile de France and Nord Pas de Calais, between 2007 and 2012. The number of stations at which measurements were made is indicated at the top of the bar for each year.

Stations: Points along watercourses at which measurements were made.

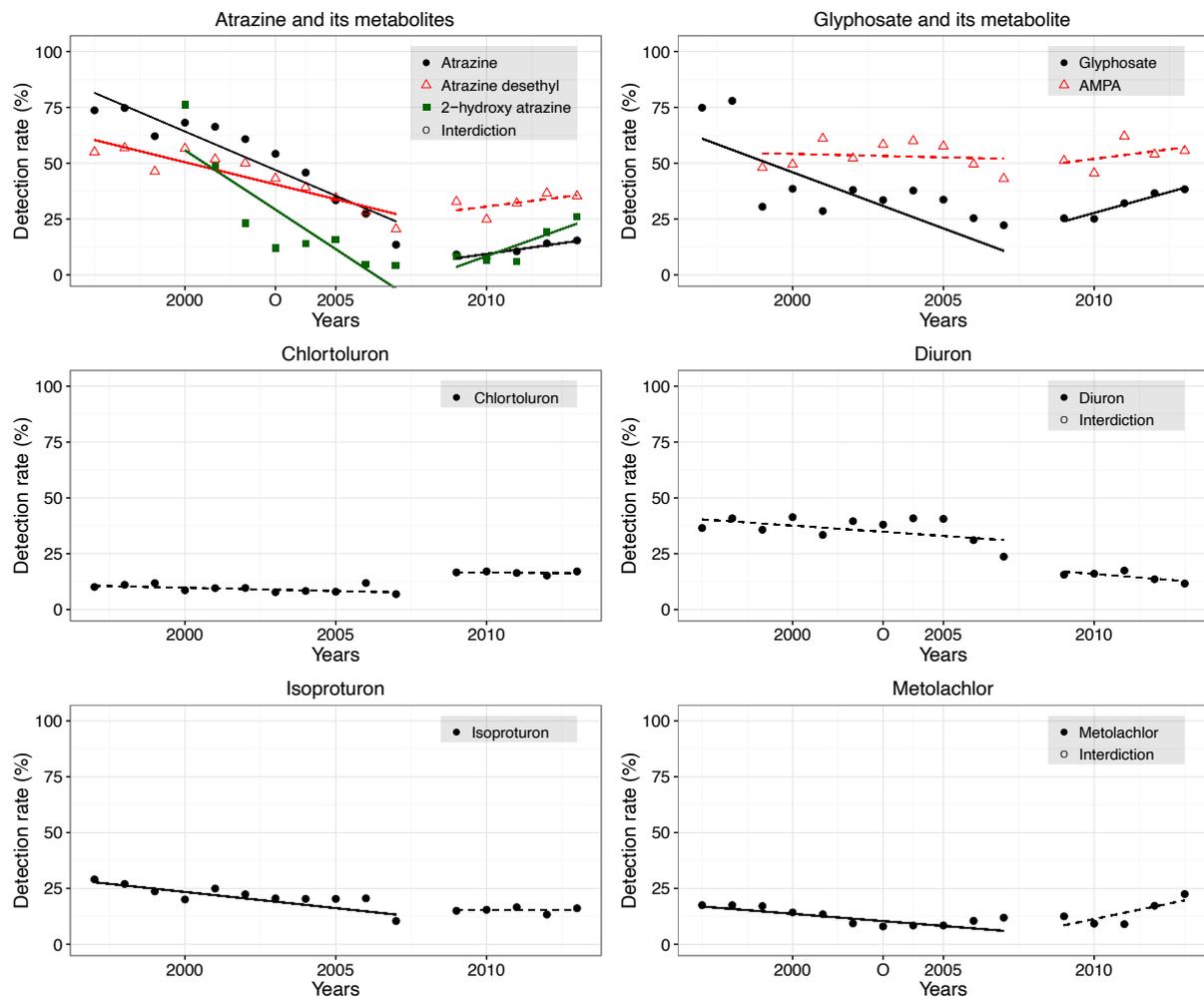


Figure 6. Evolution of the detection rate of six chemical ingredients and their metabolites in French rivers, at the national scale. Solid lines correspond to significant slopes ($p = 0.05$) ; dashed lines correspond to not-significant slopes ($p = 0.05$) – see appendix E for more details on model parameters. For the chemicals that were forbidden within the considered time frame, the year of their interdiction is indicated by a ‘o’ on the x-axis.