



**HAL**  
open science

## **Incidence of four genera of fungi in organic and low-input farming conditions in/on the grain of bread wheat over a 13-year period in France**

Bernard Rolland, Denise Deffains, Patrick Delarue, Stephane Gilles, Antonin Le Campion, Alain Monnier, None Jean-Yves-Morlais, H el ene Navier, Alexandre Pichard, Patrice Walczak, et al.

### ► **To cite this version:**

Bernard Rolland, Denise Deffains, Patrick Delarue, Stephane Gilles, Antonin Le Campion, et al.. Incidence of four genera of fungi in organic and low-input farming conditions in/on the grain of bread wheat over a 13-year period in France. *Organic Agriculture*, 2023, *Organic Agriculture*, 3 (4), pp.503-511. 10.1007/s13165-023-00443-4 . hal-04305725

**HAL Id: hal-04305725**

**<https://hal.science/hal-04305725>**

Submitted on 4 Jan 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destin ee au d ep ot et  a la diffusion de documents scientifiques de niveau recherche, publi es ou non,  emanant des  tablissements d'enseignement et de recherche fran ais ou  trangers, des laboratoires publics ou priv es.

1 Title:  
2 Incidence of four genera of fungi in organic and low-input farming conditions in/on the grain  
3 of bread wheat over a 13-year period in France  
4

5 Author information:

6 Bernard Rolland<sup>\*,1</sup>, Denise Deffains<sup>1</sup>, Patrick Delarue<sup>1</sup>, Stéphane Gilles<sup>2</sup>, Antonin Le  
7 Champion<sup>1</sup>, Alain Monnier<sup>1</sup>, Jean-Yves-Morlais<sup>1</sup>, Hélène Navier<sup>1</sup>, Alexandre Pichard<sup>2</sup>, Patrice  
8 Walczak<sup>3</sup>, Rémi Perronne<sup>\*,1</sup>

9 <sup>1</sup> INRAE, Agrocampus Ouest, Université de Rennes, IGEPP, F-35650 Le Rheu, France

10 <sup>2</sup> Agri-Obtentions, Ferme de Gauvilliers, 78660 Orsonville, France

11 <sup>3</sup> INRAE, UE FERLUS 1373, Fourrages Environnement Ruminants Lusignan, 150 route le  
12 Chêne, CS 80006, 86600 Lusignan, France

13 \*co-first authors  
14

15 Corresponding author:

16 Rémi Perronne

17 [remi.perronne@inrae.fr](mailto:remi.perronne@inrae.fr)  
18

19 ORCID number of authors:

20 Rémi Perronne: 0000-0002-5089-0510  
21  
22

23 **Abstract** Bread wheat can be infected and/or contaminated by several genera of mycotoxin-  
24 producing fungi. In the European Union, several mycotoxins are subject to defined limits for  
25 human consumption. Speculation has arisen about the potential higher contamination level of  
26 mycotoxins produced by *Fusarium* species in organic compared to conventional production  
27 systems. So far, many studies have focused on the level of mycotoxins, highlighting comparable  
28 levels in organic and conventional farming. In this long-term study, we monitored, each year  
29 over a 13-year period in several sites in France and for a set of bread wheat genotypes, the  
30 incidence of four fungal genera on bread wheat grains from both conventional low-input and  
31 organic farming. During this long period of monitoring, we used the same morphological  
32 characterization of fungal colonies. The results obtained highlighted two general trends. First,  
33 the incidence of the genus *Fusarium* in grains was generally lower than or equal to 1% in more  
34 than 60% of ‘year × site’ combinations, both in low-input and organic farming conditions. In  
35 contrast, the genus *Alternaria* was dominant in the vast majority of combinations. Second, the  
36 main explanatory factors of the incidence of fungus on grains, independently of the genus and  
37 the farming conditions, were the year and the ‘year × site’ interaction, suggesting the dominant  
38 influence of the environmental conditions of the year and the site on the relative development  
39 of the fungal genera in/on grains. According to these results, organic or low-input production  
40 of bread wheat does not represent a significant risk for the development of *Fusarium* head blight  
41 in France.  
42

43 **Keywords** Fungal incidence . Morphological identification . *Fusarium* . *Alternaria* . *Epicoccum*  
44 . *Microdochium*  
45

46 **Acknowledgements** The authors acknowledge the teams from Institut national de la recherche  
47 agronomique (INRA, currently INRAE) experimental units of Auzeville, Lusignan, Le Moulon,  
48 Le Rheu, as well as the team of Agri-Obtentions for their involvement in these experiments.  
49 Our work has been supported for 14 years by French Technical Institute for Organic farming  
50 (Laurence Fontaine ITAB) and InterBio Bretagne as part of the State-Region (Brittany) Project

51 Contract (CPER). We would like to thank organic farmers who received INRA on-farm trials  
52 in Brittany (GAEC La Mandardière), Poitou-Charentes (MM. Pinelli and Ingrandes) and Ile-  
53 de-France (F. Chevalier) regions for 13 years, and for sharing their knowledge and perspectives  
54 on agricultural practices. The publication is in memory of Maxime Trottet who developed the  
55 procedure, initiated by Laurent Saur, of morphological characterization of fungal colonies in  
56 INRA Le Rheu. We thank the editor and the three anonymous reviewers who helped to improve  
57 the manuscript.

58

59 **Competing interests** The authors declare no competing interests.

60

61 **Author contribution** BR conceive and design the study. Material preparation and data  
62 collection were performed by DD, PD, SG, ALC, AM, JYM, HN, AP and PW. Morphological  
63 characterization of fungal colonies were performed by DD, PD and JYM. Statistical analyses  
64 were performed by RP. The first draft of the manuscript was written by RP and all authors  
65 commented on previous versions of the manuscript. All authors read and approved the final  
66 manuscript.

67

68 **Data availability** The datasets and metadata will be accessible on the publicly available Data  
69 INRAE repository at <https://entrepot.recherche.data.gouv.fr/dataverse/inrae>

70

#### 71 **Supplementary Information**

72 **Online Resource 1** Coordinates of the sampling locations in conventional low-input and  
73 organic farming systems

74 **Online Resource 2** List of bread wheat genotypes retained for the statistical analyses in  
75 conventional low-input and organic farming systems

## 76 Introduction

77  
78 The agricultural intensive production model is currently questioned because of agronomic,  
79 environmental, public health and sometimes socio-economic issues (van der Werf 1996; Loyce  
80 et al. 2012; Bourguet and Guillemaud 2016). In this context, reducing the reliance of agriculture  
81 on external inputs constitutes a priority to achieve more sustainable models of production.  
82 However, an alternative model such as organic farming has been questioned for several decades  
83 about its ability to ensure food safety (Magkos et al. 2006; Lairon 2010; Garcia and Teixeira  
84 2017). Currently, organic farming is characterized by an increasing consumer demand, which  
85 requires paying attention to the sanitary quality of food production, including mycotoxin  
86 contamination (Brodal et al. 2016).

87 This is particularly the case for bread wheat for which grain can be contaminated by several  
88 genera of mycotoxin-producing fungi (Brodal et al. 2016), especially by different species of  
89 *Fusarium* causing head blight. This plant disease results from a complex of species belonging  
90 to the *Fusarium* genus (Parry et al. 1995). *Fusarium* head blight (FHB) leads to important  
91 economic consequences worldwide, important yield losses and reduction in quality production  
92 leading to the destruction of contaminated grain lots, as well as potential contamination by a  
93 range of harmful mycotoxins to human and animal health (Reddy et al. 2010). These  
94 mycotoxins, amongst others deoxynivalenol and zearalenone, are produced by several  
95 *Fusarium* species, especially *Fusarium graminearum* (Reddy et al. 2010; Dean et al. 2012).  
96 The mycotoxins are subject to government regulation in the EU, i.e., defined limits in cereals  
97 for human consumption (Commission Regulation (EC) No 1881/2006).

98 Speculation has arisen about the potential higher contamination level of mycotoxins produced  
99 by *Fusarium* species in organic compared to conventional production model, and a set of studies  
100 have investigated this issue. However, in the current state of knowledge, organic farming seems  
101 usually able to maintain a low level of contamination by mycotoxins, comparable or lower than  
102 in conventional farming (Brodal et al. 2016). The hypothesis that several agricultural practices  
103 would be less favourable for the development of *Fusarium* species causing FHB in organic  
104 farming has been proposed. In fact, a low level of nitrogen supply and a crop sequence including  
105 fewer cereals reduce the severity of FHB and the level of mycotoxins (Dill-Macky and Jones  
106 2000; Lemmens et al. 2004; Heier et al. 2005; Bernhoft et al. 2012).

107 While many studies have focused on the level of mycotoxins in organic and conventional  
108 farming (see e.g., Edwards 2009; Bernhoft et al. 2012; Brodal et al. 2016), only few have  
109 considered the incidence of different fungal genera in/on the grain of bread wheat. These latter  
110 studies have shown a low incidence of *Fusarium* species on organically produced grain, while  
111 the fungal community was dominated by other fungal genera (Lazzaro et al. 2015; Lenc 2015).  
112 However, these studies mainly relate to few years and a limited number of varieties, furthermore  
113 not identifying the main explanatory factors of the *Fusarium* incidence in the different  
114 production models.

115 In this study, we monitored, each year over a 13-year period in several sites in France and for  
116 a set of bread wheat genotypes, the incidence of four fungal genera on grain of bread wheats  
117 from both conventional and organic farming conditions.

118 More specifically, we addressed the following questions:

119 (1) What was the incidence of the four genera of fungi on the grain of bread wheat over the  
120 period and between sites in both conventional and organic farming systems?

121 (2) To what extent do year, site, genotype and their interactions explain differences in incidence  
122 of the genus *Fusarium* as well as other fungal genera in/on the grain of bread wheat in both  
123 conventional and organic farming systems?

124

125

126 **Material and methods**

127

128 Sample collection

129

130 Wheat samples were collected immediately after harvest from experimental field trials from  
131 2007 to 2019 in three areas in France (Brittany, Ile-de-France and Poitou-Charentes) in both  
132 conventional and organic farming systems. In our study, conventional farming systems  
133 corresponded to low-input systems with no fungicide and growth regulator used, a lower sowing  
134 rate and a reduction of nitrogen application (based on N balance sheet minus 60 kgN/ha) but  
135 with herbicides used to suppress weeds (see Le Campion et al. 2014 for details).

136 For each site in low-input farming, when available, a site in organic farming located near the  
137 conventional farming site was chosen to limit variation due to large-scale environmental  
138 variables such as meteorological conditions (see Online Resource 1 for coordinates). However,  
139 no organic farming site was repeatedly available near the low-input site in Poitou-Charentes,  
140 so only two sites were monitored in organic farming conditions while three sites were monitored  
141 in low-input farming conditions. In each site and each year, four repetitions were carried out  
142 for each wheat genotype in plots of 8.5m<sup>2</sup> using a randomised block design.

143 Samples were made in conditions of natural contamination on a substantial list of genotypes  
144 representative of the winter bread wheat varieties sown in low-input and organic farming over  
145 the period considered, including susceptible to tolerant wheat genotypes to FHB. *Fusarium*  
146 *graminearum* was the main species of *Fusarium* in France during the period studied. Given the  
147 duration of the period studied, the genotypes monitored have been replaced over the years,  
148 representing 34 wheat genotypes under low-input conditions and 14 wheat genotypes under  
149 organic conditions, for a total of 289 wheat samples collected under low-input and 155 wheat  
150 samples collected under organic conditions. Only wheat genotypes monitored for at least two  
151 years were retained in this study. The kernels were harvested at maturity with 14% of moisture  
152 (0.5-1kg per sample), and sub-samples of 100 kernels were chosen randomly and stored in paper  
153 bags at room temperature with 13-15% humidity until analysed for about 6 months. Visible  
154 FHB contamination on spikes was not observed in the field during any of the years concerned  
155 in this study.

156

157 Morphological characterization of fungal colonies

158

159 To determine the incidence of the different fungal genera, one hundred kernels were randomly  
160 chosen from each sub-sample, surface disinfected with 1% NaClO solution for 2 min, rinsed 4  
161 times with running water, and dried for 12h under laminar flow hood. The use of running water  
162 cannot exclude a contamination introducing fungal spores and/or bacteria on the grains. Ten  
163 kernels were evenly placed into 10 separate Petri dishes (Ø 55 mm) containing potato dextrose  
164 agar, and incubated for 5 days at room temperature under conventional lighting without day-  
165 night cycle. Each colony was identified on cultural and morphological criteria to genus level  
166 among four genera, i.e. *Alternaria*, *Epicoccum*, *Fusarium* and *Microdochium* based on  
167 pigmentation of aerial mycelium and growth rate of mycelium, especially following the  
168 descriptions proposed by Pitt and Hocking (1997). The incidence was considered as the  
169 proportion of kernels infected by fungi of these four genera. During this long-term monitoring,  
170 we used the same morphological characterization of fungal colonies. However, we point out  
171 that the results of this study are relative to the method used. In particular, it is possible that some  
172 fungal species can be overgrown by colonies of other fungal species growing more rapidly,  
173 even if the incubation time was intended to limit this type of bias.

174

175 Incidence of different fungal genera on wheat grains in low-input and organic farming  
176 conditions

177

178 The average incidence of each genus, or the absence of aerial mycelium development, is  
179 graphically represented per year and site, considering all bread wheat genotypes combined. This  
180 graphical representation constitutes a synthesis of the useful data for low-input and organic  
181 farming, i.e., 13 years  $\times$  3 sites  $\times$  5-16 genotypes per year for low-input farming conditions and  
182 13 years  $\times$  2 sites  $\times$  5-8 genotypes per year in organic farming conditions. This graphical  
183 representation has not been subjected to statistical analysis due to the unbalanced design of the  
184 data, i.e., the lack of data in certain years on certain sites. The statistical analyses described  
185 hereafter were conducted on a suitable sub-dataset.

186

187 Sources of variability of the incidence of fungi on wheat grain per genus in low-input and  
188 organic farming conditions

189

190 For each fungal genus and farming condition separately, we assessed the effects of year, site,  
191 genotype and their interactions on the incidence of fungi on wheat grains using linear models.  
192 First, some data were removed before applying statistical analyses, i.e., the genotypes tested in  
193 a single or two sites for low-input and a single site for organic farming conditions. The datasets  
194 focused on 7 years  $\times$  3 sites  $\times$  26 genotypes in low-input and 11 years  $\times$  2 sites  $\times$  13 genotypes  
195 in organic farming conditions (see Online Resource 2 for the list of genotypes).

196 Second, we implemented a full additive linear model including year, site, genotype and all  
197 second-order interactions, and we compared this full model with all other simpler additive  
198 models, including only a subset of the environmental variables. The comparison was based on  
199 the second-order Akaike information criterion (AIC<sub>c</sub>; Sugiura 1978), and considering all the  
200 explanatory variables as factors. We checked for homogeneity of variances (Bartlett test, visual  
201 inspection), normality of the residuals (Shapiro test, visual inspection) and influential points  
202 (Cook's distance). Sum to zero contrasts were applied prior to fitting models. We applied a  
203 transformation (log<sub>10</sub>+1, Box-Cox+1, Box and Cox 1964) or not on the response variable due  
204 to asymmetry in the data distribution depending on the fungal genus. Assumptions were met  
205 after transformation or not for the genera *Fusarium*, *Epicoccum* and *Alternaria*.

206 Third, the best model was retained, that corresponds to the most parsimonious model with the  
207 lowest AIC<sub>c</sub> (AIC<sub>best</sub>). The best model was compared with the intercept-only model using AIC<sub>c</sub>  
208 values, i.e.,  $\Delta AIC_c = AIC_0 - AIC_{best}$  in order to ensure the relevance of the best model (a value  
209 lower than 2 indicating that the best model was equivalent to the intercept-only model, Burnham  
210 and Anderson 2004). The goodness of fit of the models was estimated using an adjusted R<sup>2</sup>  
211 (R<sup>2</sup><sub>adj</sub>). We performed a type III ANOVA on the best model.

212 Concerning the genus *Microdochium*, no transformation was relevant to validate the  
213 assumptions. This result is due to the very strong asymmetry in the data distribution due to the  
214 absence of *Microdochium* observed in most cases (70% in low-input conditions, 52% in organic  
215 conditions), making the application of a linear model unsuitable. We have chosen not to present  
216 the results for the genus *Microdochium* in this study. First, this asymmetry requires the use of  
217 another type of model that would not be directly comparable with the results of the linear  
218 models (e.g. quasi-binomial generalized linear model). Then, there was non-independence of  
219 the four fungal genera in our study, the development of the aerial mycelium of a given fungal  
220 genus excluding the development of another genus (except in very rare exceptions), so showing  
221 the results of the four genera would lead to overinterpreting the data.

222 Statistical analyses were performed using R 4.0.1 (R Development Core Team 2022), its  
223 packages 'ggplot2' for graphical presentation, 'forecast' for Box-Cox transformation,  
224 'AICcmodavg' for model selection based on AIC<sub>c</sub> and 'car' for type III ANOVA.

225 **Results**

226  
 227 Incidence of different fungal genera on wheat grain in low-input and organic farming conditions  
 228

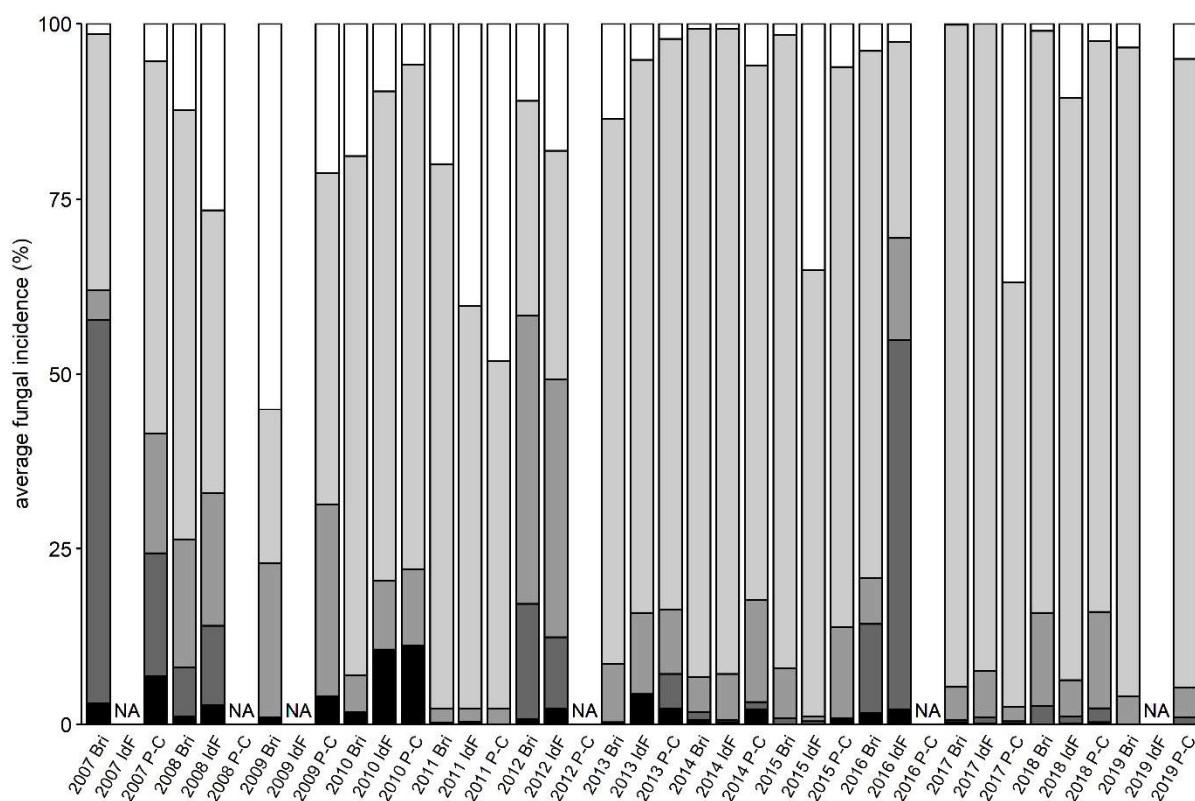
229 Data is based on 289 wheat samples collected under low-input and 155 wheat samples collected  
 230 under organic farming conditions. Several main trends can be drawn from these long-term time  
 231 monitoring. As stated above, it should be noted that the results are relative to the method used  
 232 to characterize the fungal colonies.

233 First, the incidence of the genus *Fusarium* in bread wheat grains was generally low to nil, with  
 234 a few rare exceptions (Fig. 1, Fig. 2). Indeed, the incidence of *Fusarium* was higher than 10%  
 235 only in 2008 in organic conditions and in 2010 in low-input conditions, while lower than or  
 236 equal to 1% in 61% of ‘year × site’ combinations in organic conditions and 64% of ‘year × site’  
 237 combinations in low-input conditions.

238 Second, the absence of aerial mycelium on bread wheat grain was not the most frequently  
 239 observed case. Indeed, we observed a single combination with more than 50% of grains without  
 240 fungal development in low-input conditions and no combination in organic farming conditions  
 241 (Fig. 1, Fig. 2). On average, 89% of wheat grains were characterized by a fungal development  
 242 in both low-input and organic conditions, with significant variability between ‘year × site’  
 243 combinations.

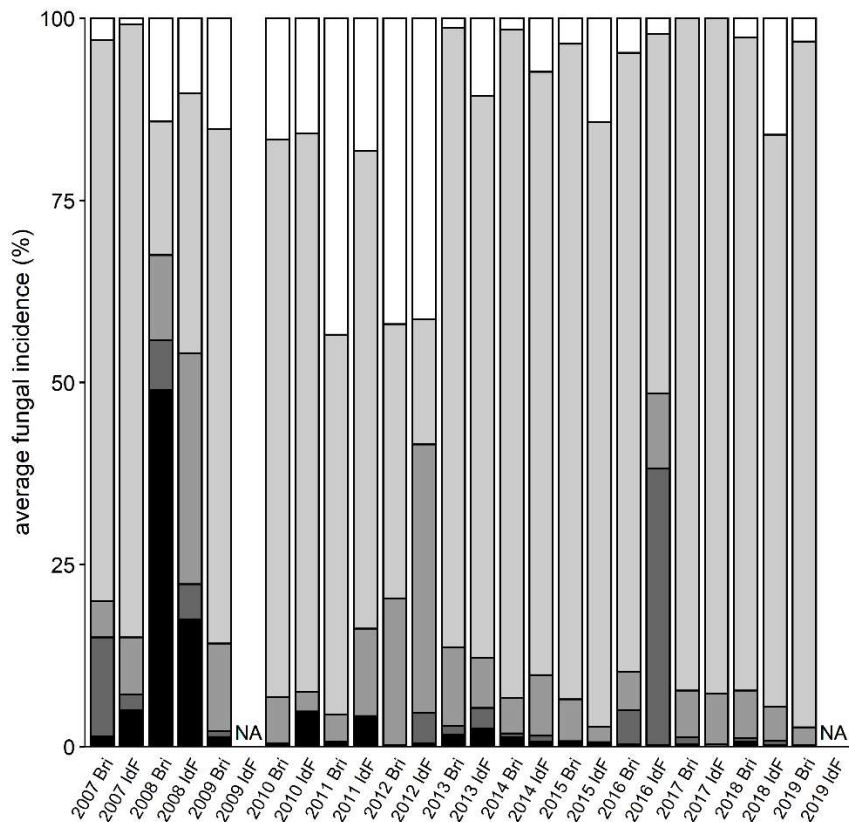
244 Third, in the vast majority of combinations considered, the genus *Alternaria* was dominant on  
 245 wheat grains, i.e., in 89% of combinations in low-input conditions and 92% of combinations in  
 246 organic conditions. The other genera showed a high incidence only in certain years and in  
 247 certain sites. For instance, the genus *Microdochium* showed substantial development in Ile-de-  
 248 France in 2016, while the genus *Epicoccum* was characterized by a higher incidence in 2012  
 249 (Fig. 1, Fig. 2).

250



251

252 **Fig. 1** Average incidence of the four different fungal genera on bread wheat grain in low-input farming between  
 253 2007 and 2019 at three sites are represented by the following shades of gray from bottom to top: *Fusarium* in  
 254 black, *Microdochium* in dark gray, *Epicoccum* in gray, *Alternaria* in light gray, and absence of aerial mycelium  
 255 observed in white. All bread wheat genotypes per year and site have been used to compute the average incidence,  
 256 i.e., between 5 and 16 genotypes depending on the year considered. NA indicates an absence of data monitored  
 257 concerning the particular ‘year × site’ combination. Bri = Brittany, IdF = Ile-de-France, P-C = Poitou-Charentes  
 258



259 **Fig. 2** Average incidence of the four different fungal genera on bread wheat grain in organic farming between  
 260 2007 and 2019 at two sites are represented by the following shades of gray from bottom to top: *Fusarium* in black,  
 261 *Microdochium* in dark gray, *Epicoccum* in gray, *Alternaria* in light gray, and absence of aerial mycelium  
 262 observed in white. All bread wheat genotypes per year and site have been used to compute the average incidence, i.e.,  
 263 between 5 and 8 genotypes depending on the year considered. NA indicates an absence of data monitored  
 264 concerning the particular ‘year × site’ combination. Bri = Brittany, IdF = Ile-de-France  
 265  
 266

267 Sources of variability of the incidence of fungi on wheat grain per genus in low-input and  
 268 organic farming conditions  
 269

270 Considering the relevant sub-datasets and after confirmation that the prerequisites were met, a  
 271 best model was identified for each case studied. This best model was always much more  
 272 relevant than the intercept-only model, confirming that at least some explanatory variables are  
 273 significantly explanatory for each case (Table 1). Moreover,  $R^2_{adj}$  was between 0.62 and 0.92,  
 274 highlighting medium to high accuracies, depending on the model (Table 1). The statistical  
 275 analyses carried out underlined that, for all the models tested, regardless of the fungal genus  
 276 and the farming conditions, the year and the ‘year × site’ interaction had a large effect on the  
 277 incidence of fungi on wheat grain. In contrast, the site effect was often non-significant or weakly  
 278 significant, especially under organic conditions, and a low genotype effect was observed only  
 279 for *Alternaria* in organic conditions (Table 1). It should be noted that a bias of the statistical  
 280 analysis was related to the replacement of genotypes studied over time. Indeed, the long-term



281 monitoring did not always characterize the same genotypes, this effect being then partially  
 282 confused with the year effect, potentially explaining why the year effect is usually the only one  
 283 significant in the analysis.

284  
 285

286 **Table 1** Results of the best additive linear models indicating the effect of year, site, genotype and year × site  
 287 second-order interaction on the incidence of the genera *Fusarium*, *Epicoccum* and *Alternaria* in both low-input  
 288 and organic farming conditions considered separately. Box-Cox+1 and log<sub>10</sub>+1 refer to the Box-Cox  
 289 transformation (transformation parameter λ = -1) and the base 10 logarithm after adding a constant (+1) to the raw  
 290 values, respectively. AIC<sub>0</sub> - AIC<sub>best</sub> corresponds to the difference of AIC<sub>c</sub> between the best model and the intercept-  
 291 only model. The goodness of fit of the models was estimated using an adjusted R<sup>2</sup> (R<sup>2</sup><sub>adj</sub>). P-value estimation is  
 292 based on F-test, \*P < 0.05, \*\*\*P < 0.001, n.s., not significant. / indicates that the explanatory variable was not  
 293 included in the best model. Degrees of freedom (df) vary between models applied on datasets in low-input and  
 294 organic farming conditions

Farming conditions	Fungal genus	Transformation	AIC <sub>0</sub> - AIC <sub>best</sub>	R <sup>2</sup> <sub>adj</sub>	F-test (P-value)				
					Intercept	Year	Site	Genotype	Year × Site
						df = 6	df = 2		df = 12
Low-input	<i>Fusarium</i>	Box-Cox+1	140.03	0.66	216.46***	22.67***	22.15***	/	4.39***
	<i>Epicoccum</i>	log <sub>10</sub> +1	129.40	0.64	371.00***	16.68***	8.30***	/	8.92***
	<i>Alternaria</i>	none	120.74	0.62	854.01***	15.62***	0.80n.s.	/	6.63***
						df = 10	df = 1	df = 12	df = 10
Organic	<i>Fusarium</i>	log <sub>10</sub> +1	167.79	0.77	48.06***	18.78***	6.65*	/	5.71***
	<i>Epicoccum</i>	log <sub>10</sub> +1	101.37	0.62	95.68***	19.03***	1.74n.s.	/	6.36***
	<i>Alternaria</i>	none	279.47	0.92	519.28***	66.46***	2.54n.s.	2.94**	14.66***

## 295 Discussion

296

297 This long-term study focusing on the incidence of four fungal genera on bread wheat grain over  
 298 a 13-year period in several sites on hundred samples collected in both conventional low-input  
 299 and organic farming conditions led to conclude two general trends.

300 First, the incidence of the genus *Fusarium* in bread wheat grains was generally low to nil, both  
 301 in low-input and organic farming conditions, as observed in previous studies (Lazzaro et al.  
 302 2015; Lenc 2015). In the vast majority of situations studied, the genus *Alternaria* was dominant  
 303 on wheat grain, while the other genera studied were generally few or not observed, except in  
 304 atypical years, sometimes only in one site. In our case, these particular results could be  
 305 explained by meteorological conditions favourable to the development of fungal genera  
 306 associated with maize as preceding crop (van der Velde et al. 2020), as also observed in other  
 307 studies during part of the period considered here (Giraud et al. 2010; Chandelier et al. 2011). It  
 308 should be noted that in 2008 in low-input conditions in Brittany, i.e., 1km away from the organic  
 309 trial characterized by a incidence near 50% of the genus *Fusarium*, considering a similar sowing  
 310 period but faba bean as preceding crop, the incidence of *Fusarium* was under 5%.

311 Second, the main explanatory factors of the incidence of fungi on wheat grain, independently  
 312 of the genus and the farming conditions, were the year and the ‘year × site’ interaction, while  
 313 the site and the genotype were less explanatory. These results appear consistent with the trends  
 314 observed on the graphical representations, suggesting the dominant influence of the  
 315 environmental conditions of the year and the site on the relative development of the fungal

316 genera on wheat grains. If certain conditions are known to favour the genus *Fusarium*, their  
317 combination have been rarely observed during our study period, except in 2008 in Brittany.  
318 Indeed, in organic farming but also in low-input conditions, both the low level of nitrogen  
319 supply and a crop sequence including fewer cereals with maize rarely as the preceding crop,  
320 reduce the risk of FHB development (Dill-Macky and Jones 2000; Lemmens et al. 2004; Heier  
321 et al. 2005; Osborne and Stein 2007; Bernhoft et al. 2012). Moreover, the main conducive  
322 weather conditions to FHB development are known, i.e., usually warm and moist conditions  
323 near and during the flowering period of winter wheat (Osborne and Stein 2007). However, the  
324 best predictors and window frames identified are partially different among studies (Kriss et al.  
325 2010; Bernhoft et al. 2012; Landschoot et al. 2012; Shah et al. 2013). In the absence of these  
326 conditions, the genus *Alternaria* predominated very frequently in our conditions.

327  
328

## 329 **Conclusions**

330

331 Even though it should be noted that the results of this study are relative to the particular method  
332 used to characterize the fungal colonies, these results confirm the low to nil incidence of the  
333 genus *Fusarium* in most years in organic farming, just as in low-input farming conditions. These  
334 results are in accordance with previously published studies highlighting the low contamination  
335 level of mycotoxins, comparable or lower in organic than in conventional farming (Brodal et  
336 al. 2016). Moreover, from a breeder's point of view, this low incidence of FHB largely  
337 dependent on environmental conditions and agronomic choices (Osborne and Stein 2007),  
338 makes phenotypic selection of more resistant genotypes in fields both more complex and less  
339 effective than for other diseases in northwestern Europe. Indeed, resistance testing appears to  
340 be more efficient under uniform and intermediate to high disease pressure, as usually achieved  
341 using artificial inoculation, and marker-assisted selection is widely put forward for FHB  
342 resistance (Buerstmayr et al. 2020). However, some additional morphological characteristics  
343 may also be considered in a breeding scheme, with taller plants characterized by anther  
344 extrusion being frequently more resistant to FHB (Buerstmayr et al. 2020). The results of the  
345 survey support that organic and low-input production of bread wheat does not represent a  
346 significant risk for the development of FHB in France. To go further in the characterization of  
347 *Fusarium graminearum* for future studies aimed at improving resistance to FHB, we strongly  
348 recommend the use of other methods (Horevaj et al. 2011; Kumar et al. 2015).

349  
350

## 351 **References**

- 352 Bernhoft A, Torp M, Clasen PE, Løes AK, Kristoffersen AB (2012) Influence of agronomic  
353 and climatic factors on *Fusarium* infestation and mycotoxin contamination of cereals in  
354 Norway. *Food Addit. Contam. Part A* 29(7):1129-1140.
- 355 Bourguet D, Guillemaud T (2016) The hidden and external costs of pesticide use. *Sustain.*  
356 *Agric. Rev.* 35-120.
- 357 Box GE, Cox DR (1964) An analysis of transformations. *J. Royal Stat. Soc. Ser. B (Methodol.)*  
358 26(2):211-243.
- 359 Brodal G, Hofgaard IS, Eriksen GS, Bernhoft A, Sundheim L (2016) Mycotoxins in organically  
360 versus conventionally produced cereal grains and some other crops in temperate regions.  
361 *World Mycotoxin J.* 9(5):755-770.
- 362 Buerstmayr M, Steiner B, Buerstmayr H (2020) Breeding for *Fusarium* head blight resistance  
363 in wheat - Progress and challenges. *Plant Breed.* 139(3):429-454.
- 364 Burnham KP, Anderson DR (2004) Multimodel inference: understanding AIC and BIC in  
365 model selection. *Sociol. Methods Res.* 33(2):261-304.

366 Chandelier A, Nimal C, André F, Planchon V, Oger R (2011) *Fusarium* species and DON  
367 contamination associated with head blight in winter wheat over a 7-year period (2003–  
368 2009) in Belgium. *Eur. J. Plant Pathol.* 130(3):403-414.

369 Dean R, Van Kan JA, Pretorius ZA, Hammond-Kosack KE, Di Pietro, A., Spanu PD, Rudd JJ,  
370 Dickman M, Kahmann R, Ellis J, Foster GD (2012) The Top 10 fungal pathogens in  
371 molecular plant pathology. *Mol. Plant Pathol.* 13(4):414-430.

372 Dill-Macky R, Jones RK (2000) The effect of previous crop residues and tillage on *Fusarium*  
373 head blight of wheat. *Plant Dis.* 84(1):71-76.

374 Edwards SG (2009) *Fusarium* mycotoxin content of UK organic and conventional wheat. *Food*  
375 *Addit. Contam.* 26(4):496-506.

376 Garcia JM, Teixeira P (2017) Organic versus conventional food: A comparison regarding food  
377 safety. *Food Rev. Int.* 33(4):424-446.

378 Giraud F, Pasquali M, Jarroudi ME, Vrancken C, Brochot C, Cocco E, Hoffmann L, Delfosse  
379 P, Bohn T (2010) *Fusarium* head blight and associated mycotoxin occurrence on winter  
380 wheat in Luxembourg in 2007/2008. *Food Addit. Contam.* 27(6):825-835.

381 Heier T, Jain SK, Kogel KH, Pons-Kühnemann J (2005) Influence of N-fertilization and  
382 fungicide strategies on *Fusarium* head blight severity and mycotoxin content in winter  
383 wheat. *J. of Phytopathol.* 153(9):551-557.

384 Horevaj P, Milus EA, Bluhm BH (2011) A real-time qPCR assay to quantify *Fusarium*  
385 *graminearum* biomass in wheat kernels. *J. Appl. Microbiol.*,111(2):396-406.

386 Kriss AB, Paul PA, Madden LV (2010) Relationship between yearly fluctuations in *Fusarium*  
387 head blight intensity and environmental variables: a window-pane analysis.  
388 *Phytopathol.* 100(8):784-797.

389 Kumar A, Karre S, Dhokane D, Kage U, Hukkeri S, Kushalappa AC (2015). Real-time  
390 quantitative PCR based method for the quantification of fungal biomass to discriminate  
391 quantitative resistance in barley and wheat genotypes to *Fusarium* head blight. *J. of*  
392 *Cereal Sci.* 64:16-22.

393 Lairon D (2010) Nutritional quality and safety of organic food. A review. *Agronomy Sustain.*  
394 *Dev.* 30(1):33-41.

395 Landschoot S, Waegeman W, Audenaert K, Vandepitte J, Baetens JM, De Baets B, Haesaert G  
396 (2012) An empirical analysis of explanatory variables affecting *Fusarium* head blight  
397 infection and deoxynivalenol content in wheat. *J. of Plant Pathol.* 94(1):135-147.

398 Lazzaro I, Moretti A, Giorni P, Brera C, Battilani P (2015) Organic vs conventional farming:  
399 Differences in infection by mycotoxin-producing fungi on maize and wheat in Northern  
400 and Central Italy. *Crop Prot.* 72:22-30.

401 Le Campion A, Oury F-X, Morlais JY, Walczak P, Bataillon P, Gardet O, Gilles S, Pichard A,  
402 Rolland B (2014) Is low-input management system a good selection environment to  
403 screen winter wheat genotypes adapted to organic farming?. *Euphytica* 199(1):41-56.

404 Lemmens M, Haim K, Lew H, Ruckebauer P (2004) The effect of nitrogen fertilization on  
405 *Fusarium* head blight development and deoxynivalenol contamination in wheat. *J. of*  
406 *Phytopathol.* 152(1):1-8.

407 Lenc L (2015) *Fusarium* head blight (FHB) and *Fusarium* populations in grain of winter wheat  
408 grown in different cultivation systems. *J. of Plant Prot. Res.* 55(1):94-109.

409 Loyce C, Meynard JM, Bouchard C, Rolland B, Lonnet P, Bataillon P, Bernicot M-H, Bonnefoy  
410 M, Charrier X, Debote B, Demarquet T, Duperrier B, Félix I, Heddadj D, Leblanc O,  
411 Leleu M, Mangin P, Méausoone M, Doussinault G (2012) Growing winter wheat  
412 cultivars under different management intensities in France: A multicriteria assessment  
413 based on economic, energetic and environmental indicators. *Field Crops Res.* 125:167-  
414 178.

415 Magkos F, Arvaniti F, Zampelas A (2006) Organic food: buying more safety or just peace of  
416 mind? A critical review of the literature. *Critical Rev. Food Sci. Nutr.* 46(1):23-56.  
417 Osborne LE, Stein JM (2007) Epidemiology of *Fusarium* head blight on small-grain cereals.  
418 *Int. J. Food Microbiol.* 119(1-2):103-108.  
419 Parry DW, Jenkinson P, McLeod L (1995). *Fusarium* ear blight (scab) in small grain cereals—  
420 a review. *Plant Pathol.* 44(2), 207-238.  
421 Pitt JI, Hocking AD (1997) *Fungi and food spoilage*, 2nd edn. Cambridge University Press,  
422 England  
423 R Development Core Team (2022) *R: A Language and Environment for Statistical Computing.*  
424 R Foundation for Statistical Computing, Vienna, Austria.  
425 Reddy KRN, Salleh B, Saad B, Abbas HK, Abel CA, Shier WT (2010) An overview of  
426 mycotoxin contamination in foods and its implications for human health. *Toxin Rev.*  
427 29(1):3-26.  
428 Shah DA, Molineros JE, Paul PA, Willyerd KT, Madden LV, De Wolf ED (2013) Predicting  
429 *Fusarium* head blight epidemics with weather-driven pre-and post-anthesis logistic  
430 regression models. *Phytopathol.* 103(9):906-919.  
431 van der Velde M, Lecerf R, d'Andrimont R, Ben-Ari T (2020) Assessing the France 2016  
432 extreme wheat production loss - Evaluating our operational capacity to predict complex  
433 compound events. In: Sillmann J, Sippel S, Russo, S (eds) *Climate Extremes and Their*  
434 *Implications for Impact and Risk Assessment*, Elsevier, pp 139-158  
435 van der Werf HM (1996) Assessing the impact of pesticides on the environment. *Agric.*  
436 *Ecosyst. Environ.* 60(2-3):81-96.  
437 Sugiura N (1978) Further analysts of the data by akaike's information criterion and the finite  
438 corrections: Further analysts of the data by akaike's. *Commun. Stat.-Theory Methods*,  
439 7(1):13-26.