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Pre-harvest measures against *Fusarium* spp. infection and related mycotoxins implemented by Dutch wheat farmers

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ABSTRACT

Fusarium spp. are one of the most widespread mycotoxin-producing fungi in small-grain cereals like wheat. Their rate of infection and production of mycotoxins is mainly influenced by weather and pre-harvest agronomic measures. Consequently, farmers' prevention and control of mycotoxins are imperative since it is difficult to remove mycotoxins further down the cereal supply chain. This study aimed to (i) identify which pre-harvest preventive and control measures Dutch wheat farmers currently apply against *Fusarium* spp. infection and mycotoxin contamination and to (ii) examine which farm and farmer characteristics explain the implementation of these measures. Field data on pre-harvest measures, like the selection of resistant varieties, fungicide use, and crop rotation, along with farm and farmer characteristics were collected from Dutch wheat farmers via an online questionnaire. Probit models were applied to examine farm and farmer characteristics that explain the implementation of pre-harvest measures. Results showed that most farmers applied six or more different measures against *Fusarium* spp. infection and mycotoxin contamination in wheat and that the use of pre-harvest measures is related to at least one other measure. However, results indicated that about 44% of farmers could become more effective if they implemented a benchmark approach consisting of a combination of fungicide use during flowering, selection of a *Fusarium* resistant wheat variety, and plowing or crop rotation. Five out of the ten evaluated farm and farmer characteristics significantly ($p < 0.05$) explained the implementation of at least one of the eight pre-harvest control measures. These five farm and farmer characteristics include wheat as main income crop, the use of a decision support system, the education level of the farmer, the farmer's knowledge about mycotoxins, and the farmer's level of risk aversion. Insight into relevant characteristics can be used by farmer cooperatives, processing industries and government agencies to improve the overall mycotoxin management of wheat farmers.

1. Introduction

Mycotoxins are fungal secondary metabolites that can cause adverse effects in humans and animals upon consumption. Mycotoxins occur in various crops like peanut (*Arachis hypogaea*), maize (*Zea mays*), and wheat (*Triticum* spp.), and have significant implications for food and feed safety, food security, and international trade (Dohlman, 2003; EFSA, 2011, 2017; Unnevehr and Roberts, 2002; Wilson et al., 2018; Zain, 2011). According to the European Commission (EC), an estimated 5–10% of crop losses worldwide are caused by mycotoxins (EC, 2015), leading to about a 2.4 billion Euro loss in Europe alone (Krska et al., 2016). Many studies have focused on pre-harvest preventive and control measures to reduce fungal infection and limit mycotoxin contamination in food and feed crops (Kabak et al., 2006; Parry et al., 1995; Van der Fels-Klerx et al., 2010; Wegulo et al., 2015). However, mycotoxin contamination still occurs, implying that the agricultural as well as food and feed industries remain vulnerable to fungi and subsequently mycotoxin contamination.

Among the many genera of fungi that can produce mycotoxins, *Fusarium* spp. are one of the most widespread in small-grain cereals like wheat. *Fusarium* spp. can affect crops if the seed is contaminated, or if it survives on debris in the soil and/or splashes onto the crop during wet conditions. Once present on the crop, *Fusarium* spp. can infect the plant and produce mycotoxins like deoxynivalenol (DON), zearalenone and fumonisins. *Fusarium* spp. infection in wheat leads to Fusarium Head Blight (FHB) which affects crop growth, physically alters kernels, and

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reduces the quality and safety of the grain (Parry et al., 1995). The rate of infection and production of mycotoxins in wheat by *Fusarium* spp. is mainly influenced by weather and pre-harvest agronomic measures (EC, 2006b).

Use of pre-harvest agronomic control measures by farmers is imperative to help prevent and control mycotoxins because it is difficult to remove mycotoxins further down the cereal supply chain (Kabak et al., 2006). Within the Dutch wheat production system, *Fusarium* spp., infection and mycotoxin contamination are regularly detected (Franz et al., 2009; Van der Fels-Klerx, 2014; Van der Fels-Klerx et al., 2012); hence, posing a continuous production risk with which farmers need to cope. For example, the percentage of tested wheat fields with DON concentrations above the maximum level of 1250 μg/kg for unprocessed cereals as set by Commission Regulation (2006)/1881/EC (EC, 2006c) is on average 11%, and ranged from 0% to 60% depending on the year (Franz et al., 2009). Although many studies have assessed the potential effectiveness of pre-harvest measures against *Fusarium* spp. infection and mycotoxin contamination, few, if any, have considered farmer's implementation. Since effective mycotoxin management along the supply chain depends on the implementation of these measures, it is important to be aware of the factors that can elucidate this implementation. Factors frequently identified as determinants for the implementation of crop management technologies are farm and farmer characteristics (Adesina and Chianu, 2002; Tey et al., 2017). Insight into relevant characteristics can be used by farmer cooperatives, processing industries and government agencies to design a targeted approach for farmers to (further) reduce *Fusarium* spp. infection and mycotoxin contamination.

This study aims to (i) identify which pre-harvest control measures Dutch wheat farmers currently apply against *Fusarium* spp. infection and mycotoxins and to (ii) examine which farm and farmer characteristics explain the implementation of these measures.

2. Materials and methods

Relevant pre-harvest measures for prevention and control of *Fusarium* spp. infection and mycotoxin contamination, as well as relevant farm and farmer characteristics relating to the implementation of management technologies, were selected by means of a literature study and expert consultation. Field data on pre-harvest measures and farm and farmer characteristics were subsequently collected from Dutch wheat farmers via an online questionnaire. Descriptive statistics were used to evaluate the implemented sets of measures. Probit models were applied in the context of the farmers' utility maximization framework to identify the farm and farmer characteristics that explain the implementation of pre-harvest measures. The utility maximization framework is based on the assumption that farmers choose measures that provide them with higher utility compared to the non-implemented ones (Adesina and Chianu, 2002).

2.1. Selection of pre-harvest measures

Several pre-harvest measures can be implemented to combat *Fusarium* spp. infection and mycotoxin contamination in wheat (EC, 2006b; Parry et al., 1995; Pirgozliev et al., 2003). From the literature study and expert consultation on potential pre-harvest measures, eight measures were selected for further investigation in this study: (1) decontamination of seeds; (2) crop rotation; (3) plowing after a grain harvest; (4) resistant cultivar lodging; (5) fungicide use during the entire wheat cultivation period; (6) fungicide use during wheat flowering; (7) resistant cultivar against *Fusarium* spp.; and (8) biological control. In addition, the combination of fungicide use during flowering, selection of a resistant variety and plowing or crop rotation were considered as the 'benchmark approach' in this study. The potential use of these measures is subsequently described in this section.

Fusarium spp. can grow systemically in the plant tissues from the seeds (Beccari et al., 2018), so decontaminated seeds are used to avoid initial fungal contamination by infected seeds (Inch and Gilbert, 2003). The use of decontaminated seeds was shown to increase the grain yield (May et al., 2010; Sooväli et al., 2017; Xue et al., 2017) and may reduce the likelihood of a *Fusarium* spp. infection, although studies with contradicting results have been reported (Beccari et al., 2018; Moretti et al., 2014).

Other pre-harvest measures, like crop rotation, plowing, or the selection of a variety that is resistant to lodging can be applied to combat mycotoxin contamination of crops. *Fusarium* spp. can survive on debris in the soil, and potentially contaminate and infect the next planted crop when that crop is susceptible to *Fusarium* spp., such as wheat, barley, or maize. To avoid this, a crop rotation plan in which two *Fusarium* susceptible crops (e.g., wheat, barley, or maize) that do not succeed each other should be applied (Edwards, 2004; Parry et al., 1995; Shah et al., 2018). Avoiding maize as pre-crop was shown to reduce the DON content by 67% compared to the DON content in wheat with maize as pre-crop (Beyer et al., 2006; Obst et al., 2000). Another measure to prevent *Fusarium* spp. survival is soil cultivation, like deep plowing after grain harvest, in which *Fusarium*-infected crop debris is destroyed or buried (Dill-Macky and Jones, 2000). Plowing (deep tillage) has been shown to reduce the DON content by 67% in wheat (Beyer et al., 2006; Blandino et al., 2012). Also, farmers can choose a wheat variety that is resistant to lodging. Lodging, the bending of the stalk or the entire plant, increases the moisture content of the plant and can increase *Fusarium* spp. infection and mycotoxin contamination if fungal spores are present in the soil. Lodged wheat was reported to have three times the mycotoxin (DON and nivalenol) concentration compared to crops that do not lodge (Nakajima et al., 2008).

Moreover, fungicide application, particularly during flowering, is an additional pre-harvest control measure that can be applied. Application of fungicides has been shown to reduce *Fusarium* spp. infection and mycotoxin production; however, the effect was dependent on the dose, type of fungicide, and application time (D'Angelo et al., 2014; Franz et al., 2009; Ioos et al., 2005; Paul et al., 2008; Yoshida et al., 2012). In wheat, the most effective fungicide application time was reported to be around the flowering stage (D'Angelo et al., 2014). This measure can decrease the DON content by around 50% compared to non-treated controls (Beyer et al., 2006; Blandino et al., 2012). Hence, fungicide application and fungicide use during flowering were included in the study for further analyses of pre-harvest measures.

Furthermore, the type of wheat variety may play a role in combating *Fusarium* spp. infection or mycotoxin contamination. There have been inherent differences reported in the susceptibility of wheat varieties to *Fusarium* spp. infection and mycotoxin accumulation, the selection of a resistant wheat variety is therefore a relevant pre-harvest measure that farmers can apply (Edwards, 2004; Kabak et al., 2006; Wegulo et al., 2015). The use of a *Fusarium* resistant cultivar was shown to decrease DON content by 61–76% compared to the use of a susceptible cultivar (Beyer et al., 2006; Blandino et al., 2012). Therefore, the selection of a *Fusarium* resistant wheat variety was also considered as a potential pre-harvest measure to analyze further.

Finally, biological control, like the use of microorganisms as antagonistic agents or non-chemical fungicides, potentially leads to an increase in grain weight and a decrease of FHB and mycotoxin contamination (see review of Shah et al. (2018)); however, they are not widely used commercially and are considered innovative methods.

The pre-harvest measures described above can be implemented individually or in combination. Combining measures to reduce the contamination of *Fusarium* spp. and severity of the infection is more effective than isolated approaches, especially when weather or environmental conditions are favorable for fungal infection (Blandino et al., 2017; Edwards, 2004; Kabak et al., 2006; McMullen et al., 2008, 2012; Wegulo et al., 2015). An effective approach in reducing FHB and mycotoxin production in grains by *Fusarium* spp. is one that combines measures that limit the survival of the fungus in debris, decreases the presence of the fungus on the plant, and reduces the severity of the infection. Blandino et al. (2012) compared the effect on FHB and DON contamination levels using a basic set of measures (direct sowing, selection of a susceptible variety, and no fungicide use) to the effect of using a combination of measures that included plowing, a *Fusarium* resistant variety and/or fungicide use during flowering. Compared to the basic set of measures, the combination of a *Fusarium* resistant variety and fungicide use during flowering reduced DON by 82%; plowing and fungicide use during flowering reduced DON by 87%; plowing and a *Fusarium* resistant variety reduced DON by 91%; and a combination of all three measures (plowing, using a *Fusarium* resistant variety and applying fungicide during flowering) reduced DON by 97%. These findings concur with McMullen et al. (2008), who showed that the use of a *Fusarium* resistant variety and crop rotation reduced FHB severity by 80%, and a combination of a *Fusarium* resistant variety, crop rotation and fungicide use during flowering reduced it by 92%. Therefore, the individual and combined effects of pre-harvest measures on farm and farmer characteristics were further analyzed during this study. Given the high level of effectiveness in reducing FHB and mycotoxins in grains caused by *Fusarium* spp., the combination of fungicide use during flowering, selection of a *Fusarium* resistant variety, and plowing or crop rotation (Blandino et al., 2012; McMullen et al., 2008) was referred to as the 'benchmark approach' in this study.

2.2. Selection of farm and farmer characteristics

Fourteen farm and farmer characteristics were assumed to be related to the implementation of pre-harvest measures. These were divided based on those pertaining to the farm (eight) and those to the farmer (six). The eight variables related to the characteristics of the farm were farm size, soil type, organic production, main crop, crop purpose, type of buyer, experience with past *Fusarium* spp. infections, and the use of a decision support system. The six variables related to characteristics of the farmer were age, gender, education, risk perception, risk aversion, and knowledge of mycotoxins.

2.2.1. Farm characteristics

Several studies have shown that **farm size** positively affects implementation decisions (Oude Lansink et al., 2003; Samson et al., 2016). For example, aflatoxin management practices in groundnut have been implemented more on large farms than on small farms (Kumar and Popat, 2010). Larger farms benefit from economies of scale as they can reduce their costs per hectare more easily. It was therefore expected that farmers who have a larger farm could take more measures or measures that require a larger scale. Another farm characteristic considered was **soil type**. Some soil types require different soil cultivation than others and not all soil types have been shown to be suitable for crop rotation (Bürger et al., 2012a; Morris et al., 2010). It was expected that farms with a certain soil type, e.g., heavy clay, would not apply crop rotation. In addition to the effect of soil type, **organic crops** have been reported to require different crop management practices than conventional crops (Mason and Spaner, 2006), because not all pre-harvest measures, like chemical fungicide use, are suitable for organic cultivation. It is therefore likely that on organic farms a different set of measures is taken, e.g., no use of chemical fungicides, as compared to conventional farms. Another characteristic considered besides farm size, soil type, and the organic crop is the **main crop** on the farm. At some farms, wheat might not be the main income crop; it is included in their crop rotation plan to control pests, diseases, and weeds, and for productive, economic and environmental reasons (Silva et al., 2017). For farmers who grow wheat as their main income crop, it is more important to deliver a product that is of good quality and safe to consume. Farmers with wheat as the main crop were therefore expected to take more or different measures than farmers for which wheat is not their main crop. Moreover, the **crop purpose** (i.e., for food, feed or seed) is a characteristic that was expected to determine the implementation of pre-harvest measures. Farmers grow wheat for food consumption, feed or seed production. Wheat used for food has stricter legal mycotoxin limits than wheat used for feed (EC, 2006a; c, 2013). It was therefore hypothesized that farmers growing wheat for food take more or different measures than farmers producing wheat for feed or seed purposes. In addition, the type of **buyer** was considered a characteristic to be related to the use of pre-harvest measures. Farms that sell their wheat to a collector or directly to a processing facility, probably take different measures because of contractual agreements. Furthermore, it was hypothesized that farmers who experienced severe *Fusarium* spp. infections in the **past** accumulated more knowledge on (non-)effective pre-harvest measures (Adesina and Chianu, 2002) and feel more pressure (Glanz et al., 2008) to take more or other measures than farmers who did not experience an infection. Finally, **decision** support **systems** were selected because they can be used to support the decision making progress on the measures to take against *Fusarium* spp. infection and mycotoxin contamination (Rossi et al., 2007, 2015; Silva et al., 2017). It has been shown that the use of a decision support system reduces external inputs (i.e., seeds, fungicides, and fertilizers) and costs, maintains or increases crop yield and quality, and keeps mycotoxin contamination below the legal limit (Rossi et al., 2015). It was therefore expected that when a farmer uses a decision support system, independent of other factors like education and knowledge, different sets of measures will be selected.

2.2.2. Farmer characteristics

Since the farmer makes the decision on which pre-harvest measures to implement, specific characteristics of the farmer, like age, gender, and education, were considered to be related to the implementation of pre-harvest measures. Studies have shown that the **age** of a farmer is negatively related to implementation of new measures (Bagheri et al., 2008; Comer et al., 1999; Oude Lansink et al., 2003) because older farmers are less open to change (Baur et al., 2016); however, studies are divided (Aramyan et al., 2007; Burton et al., 1999; Nave et al., 2013). Older farmers also have a shorter planning horizon, as they might exit farming in the near future (Samson et al., 2016), and implement measures that require less investment or labor (Adesina and Chianu, 2002) than younger farmers. Older farmers are more likely to have experience with *Fusarium* spp. infection and were expected to implement a different set of pre-harvest measures than younger farmers. In addition to age, **gender** has also been found to be a factor in farm adoption studies in the UK, where females were more likely to implement organic techniques (Burton et al., 1999) and in Nigeria, where men were more likely to adopt alley farming technology (Adesina and Chianu, 2002). In this study, one of the selected farmer characteristics was, therefore, gender, and it was expected that gender would affect the implementation of measures in the Netherlands as well. Another selected farmer characteristic was **education**. Farmers with a higher level of education are more likely to implement new technologies (Baur et al., 2016; Comer et al., 1999; Gebrezgabher et al., 2015) and are more open to change (Baur et al., 2016), although there are studies that show insignificant association between education and implementation rate (Burton et al., 1999; Nave et al., 2013). Furthermore, farmer characteristics like risk perception and risk aversion were selected in this study. **Risk perception** is defined as a combination of the expected severity of an infection and its probability of occurrence (Glanz et al., 2008). As demonstrated by Sok et al. (2016), livestock farmers who had a lower risk perception were less willing to vaccinate against a particular animal disease. Therefore, farmers with high risk perceptions were expected to implement more or different measures to reduce the probability of a *Fusarium* spp. infection. Also, farmers with a higher **risk aversion,** i.e., they take less risk than their peer farmers (Meuwissen et al., 2001), were more willing to vaccinate (Sok et al., 2016). Dutch wheat farmers with a higher risk aversion were therefore expected to take more measures. Moreover, farmers who know more about *Fusarium* spp. infection and mycotoxin contamination, i.e., have more **knowledge** on the subject, were expected to be able to make a better-informed decision (Breukers et al., 2012), and were expected to take different measures than farmers with less knowledge on this specific subject.

2.3. Survey

Data on the selected eight pre-harvest measures and fourteen farm and farmer characteristics were collected from Dutch wheat farmers by means of an online questionnaire. The specific questions and answer format related to these variables are presented in Table A.1 and A.2. The questions had been incorporated in a broader questionnaire on mycotoxin management that covered related research topics, like the perceived (cost-)effectiveness of pre-harvest measures by farmers. This online questionnaire was pre-tested by three Dutch farmers for consistency and clarity and adapted accordingly. The link to the online questionnaire was distributed via farmers' associations by email and newsletters to Dutch wheat farmers in 2017. In that year, according to the Dutch Central Agency for Statistics (CBS), around 7500 Dutch farms cultivated wheat on a total area of 120,000 ha (CBS, 2018). To enhance participation of farmers, they were incentivized by the chance of winning one of ten €25,- gift vouchers. Farmers could give their email address voluntarily for future contact, and all personal information was stored separately from the questionnaire output. The study protocol and consent procedure complied with the Netherlands Code of Conduct for Scientific Practice and were approved by the Social Sciences Ethics Committee of the Wageningen University (CoC number 09131098).

2.4. Data analysis

Descriptive statistics were used to explore the level of variation among questionnaire responses. Given insufficient variation among the responses for some characteristics (e.g., 98% of the farmers were male), four of the fourteen originally selected farm and farmer characteristics - soil type, organic production, buyer, and gender - were excluded from further analysis. The final data set included 103 questionnaires of which 75 respondents had completed the questionnaire. The remaining 28 questionnaires had some missing variables for farm and farmer characteristics. For example, 18 missed age and education, 10 missed farm size, 2 missed past infection, 3 missed the main crop, and 1 missed crop purpose. These missing data were captured by regression imputation (Hair, 2006). Data were collapsed, or dummies were created to reduce the number of variable states (Table 1). Data analysis was done in STATA (StataCorp, 2015).

Descriptive statistics were also used to calculate the percentage of farmers implementing a certain measure, the total number of pre-harvest measures farmers implemented, and the percentage of farmers that implemented the benchmark approach, i.e. application of fungicides use during flowering, use of a *Fusarium* resistant variety, and plowing or crop rotation.

2.5. Probit models

Univariate probit models were employed to evaluate the ten farm and farmer characteristics that explain the implementation of pre-harvest measures (Adesina and Chianu, 2002). The theoretical foundation of the univariate probit model assumes that farmers choose a measure if the implementation yields a higher utility than non-implementation. The implementation of a certain pre-harvest measure is a binary variable; farmers either implement a pre-harvest measure or not. The underlying utility (U) function ranks the preference of the farmer *i* and is assumed to be the function of farm and farmer characteristics 'X' (farm size, main crop, age, etc.) with coefficient 'β' and an error term 'ε' having a zero mean:

$$U_{i1}(X) = \beta_1 X_i + \in_{i1} \text{ for implementation of a pre} - \text{harvest measure}$$

$$U_{i0}(X) = \beta_0 X_i + \in_{i0} \text{ for non} - \text{implementation}$$

Farmers implement a certain pre-harvest measure only if $U_{i1} > U_{i0}$ (Judge et al., 1982). Thus, for farmer *i*, the probability of implementation is given by:

$$P(U_{i1} > U_{i0}) = P(\beta_1 X_i + \in_{i1} > \beta_0 X_i + \in_{i0}) = P(\in_{i0} - \in_{i1} < \beta_1 X_i - \beta_0 X_i) = P(\in_{i1} < \beta X_i) = \varphi(\beta X_i)$$

Where φ is the cumulative distribution function for the error term ε, which is assumed to be normally distributed in a probit model (Greene, 1993). Hence, for farmer *i*, the probability of implementing pre-harvest measure *m* is then given by (Judge et al., 1982):

$$\phi_m(\beta X_i) = \int_{-\infty}^{\beta X_i} \frac{1}{\sqrt{2\pi}} \exp\left(\frac{-t^2}{2}\right) dt$$

This function represents a univariate probit model in which the implementation of only one pre-harvest measure is considered. For each pre-harvest measure, one univariate probit model was run individually with the farm and farmer characteristics as independent variables (Table 1). Also, a univariate probit model was run to study the farm and farmer characteristics that are related to the implementation of the benchmark approach. In this analysis, the dependent variable was defined by the implementation of the benchmark approach consisting of fungicide use during flowering AND the use of a *Fusarium* resistant variety AND plowing AND/OR crop rotation.

Of all the univariate probit models (9 in total), marginal effects of the variables were calculated to indicate to what extent the (conditional) probability of the outcome variable (implemented pre-harvest measure) will change when the value of an independent variable (farm and farmer

Table 1
Uni- and bivariate probit model variables and their descriptive statistics.

Characteristic	Variable	Model parameter	Mean	St. dev.	Min	Max
Farm	Farm size	Numeric in ha	95.3	45.5	17.5	230
	Main crop	Dummy:1 if wheat is the main crop	0.15	0.36	0	1
	Wheat purpose	Dummy: 1 if wheat produced for human consumption	0.26	0.44	0	1
	Past infection	Dummy: 1 if a *Fusarium* spp. infection occurred in the past 5 years	0.67	0.47	0	1
	Use of a decision support system	Dummy: 1 if a decision support system is used	0.17	0.38	0	1
Farmer	Age	Dummy: 1 if age is over 55	0.40	0.49	0	1
	Education	Dummy: 1 if farmer followed higher education	0.54	0.50	0	1
	Risk aversion	Dummy: 1 if they take less risk than peers	0.47	0.50	0	1
	Risk perception[a]	Numeric: score 1-25	7.8	3.8	1	25
	Knowledge[b]	Numeric: score 0-5	3.0	1.3	0	5

[a] The scores to sub-questions on susceptibility and severity of an infection (Table A2) were multiplied to obtain a risk perception score (1–25).

[b] The knowledge score was calculated by the sum of the scores for 5 knowledge statements (Table A2): scored as 0 (don't know or answered incorrectly) or as 1 (answered correctly).

characteristic) is changed by one unit, while holding all other variables constant. All univariate probit models were tested for multicollinearity by their variance inflation factor. However, implementing a combination of measures, e.g., the benchmark approach, is shown to be more effective than the implementation of a single measure. Hence, it was expected *a priori* that the actual use of measures is mutually correlated, i.e., farmers decide on a package of measures rather than a single measure (Bürger et al., 2012a, 2012b; Loyce et al., 2008).[1] Therefore, to explore to what extent the implementation of a certain measure is interrelated with the selection of another measure, bivariate probit models were run for all combinations of measures (28 in total) taking into account the farm and farmer characteristics (Nkamleu and Adesina, 2000). The bivariate probit model is a joint model for two binary outcomes, based on the joint probability distribution of two normally distributed dependent variables. If the implementation of measures is correlated, ρ is significant. If ρ is insignificant, two separate univariate probit models will suffice (Greene, 1993; Nkamleu and Adesina, 2000).

3. Results and discussion

It is well known that certain pre-harvest measures can reduce *Fusarium* spp. infection and mycotoxin contamination (Kabak et al., 2006; Parry et al., 1995; Van der Fels-Klerx et al., 2010; Wegulo et al., 2015). However, to the best of our knowledge, no other study has investigated to what extent pre-harvest measures are actually implemented by farmers and which farm and farmer characteristics explain this implementation. Farmers' participation in this study was voluntary, and farmers who are *a priori* more involved in *Fusarium* and mycotoxin management might, therefore, be overrepresented among the respondents.

3.1. Implementation of pre-harvest measures by Dutch farmers

This study showed that most Dutch farmers already take multiple pre-harvest measures against *Fusarium* spp. infection and mycotoxin contamination (Fig. 1). Table 2 presents an overview of the implementation rate of the eight pre-harvest measures applied by Dutch wheat farmers, based on the survey results. The pre-harvest measure implemented by most farmers (92%) was the decontamination of seeds, whereas biological control was implemented by only 20% of the farmers. The implementation rate of the remaining pre-harvest measures ranged from 65% to 88% of the farmers.

Results indicated that farmers generally implemented a combination of measures (Fig. 1) and as hypothesized, the implementation of pre-harvest measures was mutually correlated (Table 3). Of the eight measures included in the questionnaire, thirty-eight different combinations of measures were used during the 2017 growing season, ranging from no measures (1% of the farmers) to the use of all eight measures (6% of the farmers). A combination of seven measures was most commonly applied (Fig. 1). The use of a *Fusarium* resistant wheat variety was correlated with the use of fungicides during the whole cultivation period, use of fungicides during flowering, or biological control (Table 3). Farmers who did not apply crop rotation were less likely to implement biological control but were more likely to use a lodging resistant wheat variety. The decision to plow after grain harvest and the use of contaminated seeds were positively correlated; however, not dependent on the decision to use any other measure.

[1] An application of a multivariate probit model would account for simultaneous choices (Mulwa et al., 2017; Oude Lansink et al., 2003; Ward et al., 2018), by estimating the parameters β and the variance covariance matrix of the multivariate normal distribution of the error terms (Cappellari and Jenkins, 2003; Greene, 1993; Judge et al., 1982). However, in this study, a multivariate approach was technically not feasible because of the relative limited size of the available data set related to the number of variables.

3.2. Farmer characteristics associated with the implementation of pre-harvest measures

Farm and farmer characteristics that were significantly related to the implementation of a certain pre-harvest measure were the use of wheat as the main crop, use of a decision support system, farmers' education level, mycotoxin knowledge, and risk aversion of the farmer. Although the selection of farm and farmer characteristics was made based on literature and expert consultation, not all characteristics that were expected to be related to the implementation of measures were statistically significant ($p < 0.05$), like farm size, wheat purpose, age and risk perception. Results showed that no farm and farmer characteristics were related to the use of a lodging resistant wheat variety or the use of decontaminated seeds, probably due to their high implementation rate: 88% and 92%, respectively (Table 2).

Having wheat as the main crop increased the probability to use fungicides during flowering by 36% and decreased the probability of applying crop rotation (no grain as pre-crop) by 34%. Although a rotation system without grain as a pre-crop is an effective pre-harvest measure against *Fusarium* spp. infection (Edwards, 2004; Parry et al., 1995; Shah et al., 2018), most of the farmers who do not have wheat as the main crop, had potatoes as the main crop, in which a rotation system with wheat is advised.

Results of the univariate probit models (Table 4) also showed that use of a decision support system increased the probability of the use of fungicides during flowering. Higher educated farmers were 17% more likely to use *Fusarium* resistant wheat varieties and 25% more likely to plow after a grain harvest compared to farmers with lower education levels. Increasing the specific mycotoxin knowledge levels by a point increased the probability of fungicide use by 10%.

Farm and farmer characteristics that were associated with the implementation of the benchmark approach (Table 4) were the wheat as primary crop, prior experience with *Fusarium* spp. infections, and education. Farmers with wheat as the main crop, farmers who experienced a severe *Fusarium* spp. infection in the past five years and farmers who followed higher education had, respectively, an 18%, 4% and 17% higher probability to implement the benchmark approach.

Overall, results showed that significant farm and farmer characteristics differed per pre-harvest measure (Table 4). This result concurs with the study by Knowler and Bradshaw (2007) on farmers' adoption of conservation agriculture, which found no universal variables that explain this adoption. This assumes that results of the current study are not easily compared with those of other studies, because relevant characteristics are context-specific and even differed within this study. However, this study provides valuable insights into relevant farm and farmer characteristics and how it influences the use of pre-harvest control measures, thereby aiding farmer cooperatives, processing industries, and government agencies in improving the overall mycotoxin management of wheat farmers.

3.3. Probit models

This paper employed univariate probit models to identify the farm and farmer characteristics that explain the implementation of pre-harvest measures. The results of the bivariate probit model in this study showed that the choice of some measures was indeed correlated, suggesting a multivariate probit model would have been an appropriate analysis (Cappellari and Jenkins, 2003; Greene, 1993; Judge et al., 1982; Mulwa et al., 2017; Oude Lansink et al., 2003; Ward et al., 2018). However, due to technical constraints (i.e., high variables to respondents rate), the multivariate probit model failed to converge. Several sets of three to four measures were selected based on the bivariate probit model results and tested in a multivariate probit model to check whether the univariate results differed from a potential complete multivariate model. The results (significance and direction of the marginal effects of the characteristics) did not differ greatly from those

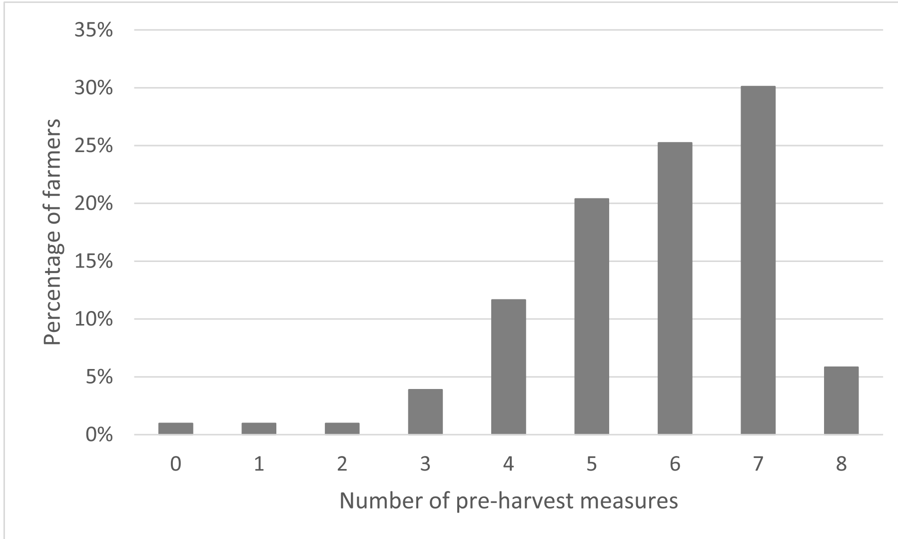

Fig. 1. Percentage of farmers per total number of pre-harvest measures taken per farmer.

Table 2
Implementation rate of pre-harvest measures against *Fusarium* spp. infection by Dutch wheat farmers.

Pre-harvest measure	Description	n	%
Decontamination of seeds	Use of decontaminated seeds	101	92
Crop rotation	Crop rotation: no grains as pre-crop	102	73
Plowing	Plowing after grain harvest	101	77
Resistant cultivar lodging	Lower the risk of lodging by selection of a wheat variety	101	88
Fungicide use	Fungicide use during the whole cultivation period	99	84
Fungicide use flowering	Fungicide use around flowering	100	65
Resistant cultivar *Fusarium*	Selection of *Fusarium* resistant wheat variety (resistance >7)	103	85
Biological control	Biological control	97	20

of the univariate model. Therefore, the models in this study were sufficient in providing insights into the important farm and farmer characteristics.

3.4. Benchmark approach

Although the use of more measures does not necessarily mean a more effective approach (Loyce et al., 2012), research has demonstrated that a combination of measures consisting of a targeted fungicide use during flowering, a *Fusarium* resistant cultivar, and soil cultivation or crop rotation is highly effective against *Fusarium* spp. infection and mycotoxin contamination (Blandino et al., 2012; McMullen et al., 2012). This study showed that this specific combination of measures or benchmark approach is implemented by 56% of the Dutch farmers (Fig. 2) indicating that about 44% of the farmers could become more effective in reducing mycotoxins in the field by implementing this benchmark approach.

However, there may be underlying factors for why these farmers did not implement the benchmark approach, like certain farm and farmer characteristics, environmental concerns, and perceived cost-effectiveness of the approach. Results showed that farmers were less likely to implement the benchmark approach if wheat was not their main crop, if they had a lower education level, or if they had not encountered a severe *Fusarium* spp. infection in the past five years (Table 4). Another factor might be the perceived effectiveness and cost-effectiveness of the pre-harvest measures in the benchmark approach. This benchmark approach is effective in reducing *Fusarium* spp. infection and can be cost-effective depending on the type of measure and external factors like price of wheat, premiums, and discounts (McMullen et al., 2012; Wilson et al., 2018). However, not all farmers of the non-benchmark group perceived the pre-harvest measures of the benchmark approach as effective and cost-effective. A third factor might be the farmers' environmental concerns of pesticide use; one of the benchmark approach pre-harvest measures is fungicide use during flowering, and 20% of the non-benchmark group did not use fungicides

Table 3
Correlation coefficients between different pre-harvest measures taking into account farm and farmer characteristics, i.e., ρ of bivariate probit models.

	Decontamination of seeds	Crop rotation	Plowing	Resistant cultivar lodging	Fungicide use	Fungicide use flowering	Resistant cultivar *Fusarium*	Biological control
Decontamination of seeds		0.25	0.76*	0.31	0.37	0.43	−0.37	0.11
Crop rotation	0.25		0.36	0.54	−0.11	−0.3	−0.27	−0.49*
Plowing	0.76*	0.36		0.62	0.42	0.3	0.28	0.37
Resistant cultivar lodging	0.31	0.54*	0.62		−0.12	−0.12	0.03	0.27
Fungicide use	0.37	−0.11	0.42	−0.12		0.68*	0.77*	0.14
Fungicide use flowering	0.43	−0.3	0.3	−0.12	0.68*		0.79*	0.17
Resistant cultivar *Fusarium*	−0.37	−0.27	0.28	0.03	0.77*	0.79*		0.99
Biological control	0.99*	0.27	0.14	0.17	0.37	−0.49*	0.11	

*$p < 0.05$.

Table 4
Marginal effects of farm and farmer characteristics on the use of pre-harvest measures as determined by univariate probit models.

	Decontamination of seeds	Crop rotation	Plowing	Resistant cultivar lodging	Fungicide use	Fungicide use flowering	Resistant cultivar *Fusarium*	Biological control	Benchmark approach
Total arable land	0.000	0.001	−0.002†	0.000	0.001	−0.001	0.001	0.000	0.001
Main crop	0.026	−0.340*	0.073	0.001	0.011	0.359*	0.019	0.025	0.182*
Wheat purpose	−0.115	0.041	−0.047	0.078	0.008	−0.147†	−0.050	−0.040	0.006
Past *Fusarium* spp. infections	0.052	−0.008	0.074	−0.078	0.054	−0.034	0.072	−0.016	0.044*
Use of a decision support program	−0.108	0.143	−0.158	−0.081	−0.050	0.306*	0.133	−0.033	0.092
Age	0.014	0.011	0.098	−0.037	−0.062	−0.011	−0.101	−0.160†	−0.087
Education	0.008	−0.079	0.250*	0.036	0.007	−0.034	0.174*	−0.005	0.173*
Mycotoxin knowledge	0.022	0.018	0.030	0.042	0.102*	−0.005	0.031	0.012	0.058
Risk perception	0.014	−0.008	−0.007	0.001	0.020†	0.019†	0.008	0.020†	−0.181
Risk aversion	0.007	0.040	0.139†	0.062	0.048	0.362*	0.110	0.125	0.124

*p < 0.05; †p < 0.10.

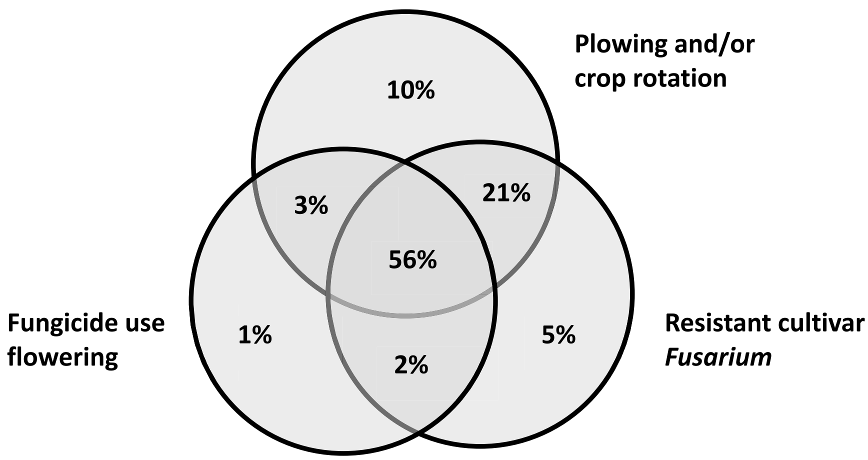

Fig. 2. Percentage of Dutch farmers (n = 103) who used (part of) the benchmark approach consisting of fungicide use during flowering, a *Fusarium* resistant variety, and plowing or crop rotation.

at all. French wheat farmers who were aware of the adverse effects of pesticides and wanted to reduce chemical inputs used fewer pesticides (Nave et al., 2013). Although 44% of the Dutch farmers could become more effective in reducing *Fusarium* spp. infection and mycotoxin contamination by implementing the benchmark approach, there are underlying factors that prevent farmers to implement the benchmark approach.

3.5. Fungicide use

The flexible use of fungicides during wheat flowering is effective in reducing *Fusarium* spp. infection (D'Angelo et al., 2014; Ioos et al., 2005; Paul et al., 2008; Yoshida et al., 2012) and is economically more attractive than fungicide use during the whole cultivation period. A reduction of pesticides, including fungicides, is better for the environment and can be cost-effective (EC, 2009; Jacquet et al., 2011; Nave et al., 2013). In this study, none of the respondents were organic farmers. Results showed that 15% of the farmers did not use fungicides at all, 79% of the farmers used fungicides during the whole cultivation period of which 53% also used fungicides during flowering. Moreover, 6% of the farmers used fungicides only during flowering and not during the rest of the cultivation period. Fungicide use during flowering was perceived as an effective measure for 81% of the farmers and a cost-effective measure for 60% of the farmers (data not shown). Farmers who are more likely to implement fungicide use during flowering had wheat as the main crop and were more risk-averse. In line with results from Nave et al. (2013), farm and farmer characteristics like farm size, age, and education were not related to the implementation of fungicides (Table 4). Fungicide use is an operational management decision, i.e., the choice for the application can be made during the growing season. The correct timing of fungicide application can be difficult to decide since weather conditions that are favorable for *Fusarium* spp. infection, e.g., humidity and rainfall, often coincide with unfavorable weather conditions for the application of fungicides (D'Angelo et al., 2014). A decision support system can assist with determining the optimal time for applying fungicides. Around 17% of the Dutch farmers used a decision support system to select measures against *Fusarium* spp. infection (Table 1) and those farmers who used a decision support system were more likely to use fungicides during flowering (Table 4). Stimulating farmers to use a decision support system might increase a targeted fungicide use (Nave et al., 2013), improve overall mycotoxin management and reduce overall input costs (McMullen et al., 2012; Rossi et al., 2007, 2015; Silva et al., 2017).

3.6. Biological control

Multiple studies have evaluated new biological measures, not to be confused with organic agriculture, against *Fusarium* spp. infections, as indicated by the recent review of Shah et al. (2018). Kabak et al. (2006) indicated that biological control measures could be an addition to chemical control. The current study showed that biological control measures were implemented by 5% of the farmers in the past, whereas 20% of the farmers implemented biological control in the 2017 growing season (Table 2). Out of all the farmers, 25% perceived biological control as an effective and cost-effective measure (data not shown). According to the expectations, results indicated that older farmers were less likely to implement biological control measures ($p < 0.10$) (Table 4). In the future, once effective and affordable biological measures are available, an improvement to the current mycotoxin management might be achieved by implementing additional biological control measures.

4. Conclusions

This study explored the implementation of pre-harvest measures against *Fusarium* spp. infection and mycotoxin contamination and related farm and farmer characteristics. Most Dutch wheat farmers used at least six mycotoxin pre-harvest measures and their use were mutually correlated. Although many farmers already implemented multiple measures, around half of the farmers could become more effective in reducing mycotoxins in the field by implementing the highly effective benchmark approach consisting of the combination of fungicide use during flowering, selection of a *Fusarium* resistant variety, and plowing or crop rotation. Furthermore, future improvements could be made by shifting from fungicide use during the whole cultivation period towards fungicide use during flowering only, and by including biological control. Farm and farmer characteristics that were positively associated with the implementation of individual pre-harvest measures were the use of wheat as the main crop, use of a decision support system, a higher level of education, a higher mycotoxin knowledge level, and a higher risk aversion. Specifically, farmers who do not have wheat as the main income crop should be reached to encourage fungicide use during flowering and to implement the benchmark approach to reduce *Fusarium* spp. infection. Knowing the effect of these characteristics on the use of pre-harvest measures can help, e.g., farmer cooperatives, processing industries, and government agencies to improve the overall mycotoxin management of Dutch wheat farmers. For example, this could be achieved through training and education to improve the knowledge levels of farmers and recommending the use of a decision support system which might increase better *Fusarium*- and mycotoxin management in wheat, thereby potentially reducing overall costs.

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Declarations of interest

None.

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Appendix A. Supplementary data

Table A1
Selected pre-harvest measures, and their related question and answer format in the questionnaire.

Variable	Question
	Do you expect to use this measure against *Fusarium* spp. infection in the coming year? (Yes/No)
Decontamination of seeds	Use of decontaminated seeds
Crop rotation	Crop rotation: no grains as pre-crop
Plowing	Plowing after grain harvest
Resistant cultivar lodging	Lower the risk of lodging by selection of a wheat variety
Fungicide use	Fungicide use during the whole cultivation period
Fungicide use flowering	Fungicide use around flowering
Resistant cultivar *Fusarium*	Selection of a *Fusarium* resistant wheat variety (resistance >7)
Biological control	Biological control

Table A2
Selected farm and farmer characteristics, and their related question and answer format in the questionnaire.

Variable	Question	Answer format
Farm size	What is the size of your arable land in hectares?	Size in ha
Soil type	What is the predominant soil type on which you normally grow wheat?	Multiple choice
Organic	Do you produce organic wheat?	Yes/no
Main crop	What is the most important crop at your arable farm?	Multiple choice
Selling	Do you sell your wheat via a collector/merchant, directly to a feed or food producer or to others?	Multiple choice
Wheat purpose	Do you grow wheat for human consumption, animal feed or seed production?	Multiple choice
Past infection	How often you think you have had a serious *Fusarium* spp. infection in wheat in the past 5 years?	6 point scale: <never to five times>
Decision support system	Do you use a decision support system to select appropriate measures against *Fusarium* spp. infection?	Yes/no
Gender	What is your gender?	Male/Female
Age	What is your age?	Ten-year age categories
Education	What is your highest level of education completed?	Eight educational categories
Risk aversion	Are you are willing to take more or less risk regarding *Fusarium* spp. infection and mycotoxin contamination compared to other farmers in your community?	5-point scale: <more to less risk>

(*continued on next page*)

Table A2 (*continued*)

Variable	Question	Answer format
Risk perception	1. Do you expect a serious *Fusarium* spp. infection in the coming five years 2. What consequences will this have?	5-point scale: <never to often> 5-point scale: <no consequences to significant consequences>
Knowledge	Indicate whether you agree or disagree with the following statements: 1. Harvest debris in the soil form a risk for *Fusarium* spp. infection 2. You can recognize a *Fusarium* spp. infection by black kernels *3. Fusarium* species can also be present in maize and barley *4. Fusarium* species produce mycotoxins like DON 5. Mycotoxins could be harmful for humans	Agree/Disagree/Don't know

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