DON Occurrence in Grains: A North American Perspective

ABSTRACT

In agricultural commodities, the occurrence of deoxynivalenol (DON) has been reported all over the world, with levels varying among grain types and years of production. The grain supply chain, including growers, buyers, and end users, have effectively managed DON with strategies to control this issue systematically. The safety of consumers is ensured through use of these management strategies. This is observed in this review of the North American systems. This article describes the occurrence and management of DON in North America, which is accomplished by 1) a review of the toxicological effects of DON; 2) a review of publically available data and introduction of new information regarding the occurrence of DON in wheat, maize, and barley in North America, including variability due to growing regions, grain varieties, and year of production; 3) an overview of industry practices to reduce DON contamination from field through milling when necessary; 4) a review of how all in the value chain, including growers, buyers, and end users, have effectively managed DON for more than 20 years; 5) a description of current maximum limits associated with DON; and 6) the economic impact of any potential changes in international regulations. This article focuses on wheat, maize, and barley grown in Canada and the USA, as these two countries are the major exporters of these grains in North America.

AUTHORS

Andrea Bianchini, The Food Processing Center, Food Science and Technology Department, University of Nebraska – Lincoln, NE, USA
Richard Horsley, Department of Plant Sciences, North Dakota State University, ND, USA
Maia M. Jack, CPGlobal, LLC, USA
Brent Kobielush, General Mills, MN, USA
Dojin Ryu, Bi-State School of Food Science, University of Idaho/Washington State University, ID, USA
Sheryl Tittlemier, Grain Research Laboratory, Canadian Grain Commission, Winnipeg, MB, Canada
William W. Wilson, Department of Agribusiness and Applied Economics, North Dakota State University, ND, USA
Hamed K. Abbas, USDA-ARS, NBCL, Stoneville, MS, USA
Susan Abel, Food & Consumer Products of Canada, Toronto, ON, Canada
Gordon Harrison, Canadian National Millers’ Association, Ottawa, ON, Canada
J. David Miller, Department of Chemistry, Carleton University, Ottawa, ON, Canada
W. Thomas Shier, Department of Medicinal Chemistry, University of Minnesota, MN, USA
Glen Weaver, Ardent Mills, Omaha, NE, USA

PUBLIC REVIEWERS

Dave Katzke, General Mills, MN, USA
Dirk E. Maier, Kansas State University, Grain Science & Industry, Manhattan, KS, USA
Jim Pestka, Food Science and Human Nutrition/Microbiology & Molecular Genetics, Michigan State University, East Lansing MI, USA

LIAISONS

Benjamin Boroughs, NAMA Liaison, Director of Regulatory and Technical Affairs
Anne R. Bridges, AACC Liaison, Director of Technical Resources

Introduction

Fungi associated with production and storage of grains in North America include the genera Fusarium, Penicillium, and Aspergillus. Mycotoxins are secondary metabolites of these filamentous fungi that can cause illness in humans and animals through absorption, ingestion, or inhalation. Since grains, in general, provide an ideal substratum (medium) for mold growth and mycotoxin production, close attention must be paid to their food and feed safety. Additionally, grains and grain-based products represent one of the major sources of carbohydrates for humans and livestock; therefore, their safety is of primary concern.

The prevalence of mycotoxins in grains is usually associated with the occurrence of the causal organisms and related causal factors, such as temperature and moisture, in both the field and in storage. Deoxynivalenol, also referred to as DON or vomitoxin, is one of a broad category of mycotoxins known as trichothecenes. DON is produced mainly by F. graminearum and F. culmorum, especially in grains. Production of DON by F. pseudograminearum has also been reported in warmer climates, although with less frequency than the major producers. F. graminearum is an important plant pathogen that causes Fusarium head blight (FHB) in wheat and barley and ear rot in maize. This leads to DON contamination of these crops during crop growth, prior to harvest. DON is found globally in these crops, as well as in rye, oats, and rice.

To minimize human exposure to DON via the consumption of contaminated grain-based foods, regulatory organizations have established advisory levels, guidelines, and regulations for various commodities and foods. In North America, the US-FDA has imposed a restriction of 1 mg/kg on processed grains. Health Canada has set regulations of 2 mg/kg in uncleaned soft wheat for use in nonstaple foods and 1 mg/kg in uncleaned soft wheat for use in baby foods; however, these regulations are currently under review.
Toxicity and Deoxynivalenol (DON)

DON was isolated from moldy barley by Japanese scientists in 1973 and recharacterized as "vomitoxin" by USDA researchers in the same year (8–12). Since then, toxicologists have sought to understand the acute and chronic effects that may be associated with the ingestion of DON.

The principal health risks of DON are associated with acute dietary exposure, which is caused by intake of large amounts of DON within a short time frame. Shortly after ingestion of heavily contaminated grains, DON causes vomiting and feed refusal in animals, especially swine, and causes gastroenteritis with vomiting in humans (13–15). To date there is no evidence of occurrence of adverse human health outcomes in North America associated with acute dietary intake of DON. The chronic effects of dietary intake of DON include weight gain suppression, anorexia, and altered nutritional efficiency (16). It has also been shown to adversely affect immune systems (17). With any toxicological risk assessment, it is important to understand the absorption, distribution, metabolism, and elimination of a given toxin or toxicant (18). Unlike other toxins, such as dioxin and other fat-soluble compounds, DON is water soluble, which allows it to be rapidly cleared in vivo. In rodents and swine, which are frequently used to study the adverse effects of DON (9), this toxin and its metabolites are absorbed and excreted quite rapidly (8). Specifically, studies have shown that 25% and 64% of radiolabeled, orally administered doses of DON and known metabolites in rats were detected within 96 hr in urine and feces, respectively (8,19). Subsequent analyses of the tissues in these rats showed that no radioactivity was retained in the tissues after 96 hr (8,19). Similarly, in pigs DON is rapidly excreted, with a plasma half-life of 3.9 hr and no significant retention in the tissues (8,19–23).

Acute exposure to DON is most notably characterized by emesis (8,9). A few outbreaks of grossly contaminated grain in Japan and Korea (1940s–1960s) (24), China (1984–1991) (25), and India (1988) (26) have been described, with the symptoms of the disease being typical of illnesses associated with DON exposure. However, current global regulations, better crop management techniques, improved resistance to FHB, and the advancement of milling practices have considerably reduced the number of acute incidences of DON-related illnesses. Additionally, animal studies have shown that DON most notably exerts its effects when exposure occurs in single or multiple bolus doses (9). The latter does not represent a likely scenario for the vast majority of the global population today who can readily access minimally contaminated sorted and cleaned grains that very rarely result in acute incidences.

In contrast, as previously mentioned, high chronic exposure has been shown to cause growth retardation, alter immune function, and interfere with reproduction and development (8,9). In 2001, the Joint Food and Agriculture Organization/World Health Organization (FAO/WHO) Expert Committee on Food Additives (JECFA) proposed a provisional maximum tolerable daily intake (PMTDI) for DON of 1 μg/kg body weight (bw) based on the growth effects associated with DON exposure (8,27,28). In the following decade, investigations into the mechanisms of the effect of DON on weight gain were pursued and understood (8,9,29–32). In 2010, JECFA extended the PMTDI to apply to both DON and its acetylated derivatives and concluded that mean estimates of national exposure to DON were below the PMTDI of 1 μg/kg bw (8,27,28). Likewise, recent national assessments determined that exposures to DON were below levels of concern. Based on these collective assessments, the current global limits on DON are not only protective from a chronic ingestion standpoint, but affirm that a level of 1 mg/kg on semiprocessed grains is safe, and levels proposed for unprocessed raw grain would have no benefit from a public health safety perspective, as described further below.

Although DON has been associated with a number of acute (8,9,13,25) and chronic (8,9) health events, the likelihood of such occasions remains relatively rare. In the USA, for instance, advisory levels for grain containing DON have been in place since 1982 (7). In fact, in 1993, an outbreak of DON in wheat led to the elimination of a previously held limit of 2 mg/kg on unprocessed raw wheat and wheat by-products. After this incident the US-FDA decided to rely on purchasing and cleaning practices to significantly reduce DON levels to the 1 mg/kg maximum for finished wheat products, including the following: flour, germ, and bran (7). Since then, the US-FDA continues to recognize an advisory limit of 1 mg/kg on finished food products containing wheat and wheat by-products. A level that remains protective for the USA population and USA export markets. The same is true for advisory levels on finished grain established by regulatory agencies elsewhere.

DON Occurrence in North America

The body of available research indicates that acceptably low DON levels in unprocessed grain products can be achieved in exports and shipments for domestic use in most crop years. These levels are achieved through the aggregation of grain stocks and blending that occurs along the supply chain, monitoring of DON levels in deliveries of grain shipments to processors, and a variety of grain sorting and cleaning technologies available to processors. The North American grain industry’s experience suggests that adoption of unduly

---

**Fig. 1.** Schematic of the North American grain-handling supply chain.
restrictive maximum limits for DON in unprocessed grains could actually hinder, rather than assist in, the management of DON levels in foods and feeds, while contributing to significantly higher costs to the entire supply chain.

**Wheat.** Due to its importance as a foodstuff and as an exported grain, the bulk of DON monitoring and surveillance data for grains pertains to wheat. DON is observed in wheat at various stages of the North American grain-handling chain, a general schematic of which is shown in Figure 1.

Wheat quality, including the occurrence of DON, is closely monitored throughout the North American grain-handling chain. For example, at the early to middle stages of the handling chain, DON is determined in soft and hard wheat delivered to USA wheat milling facilities by truck or railcar. In Figure 2, data from more than 42,100 samples representing wheat harvested throughout 12 consecutive seasons (2003–2014) from various production areas in the USA and shipped to USA milling facilities are summarized. Among the samples analyzed, 81.1% were below the limit of quantitation (LOQ) of the methods used (0.3–0.5 mg/kg).

To obtain each of the samples represented in Figure 2, the sampling process suggested by the USDA Grain Inspection, Packers and Stockyards Administration (GIPSA) for drawing a representative sample from a lot of grain was followed. Toxic levels were determined by enzyme-linked immunosorbent assay (ELISA). The method of choice (manufacturer and test type) varied from one milling facility to another; however, all of them used GIPSA-approved methods (e.g., Neogen 2/3, 5/5, Q+) with LOQ varying from 0.3 to 0.5 mg/kg. In this data set, reported values below the limit of detection (LOD) of the method used were assigned a numerical value of “zero” to calculate average values. For those reported values that were below the LOD but above the LOD, a numerical value of LOQ/2 was assigned to calculate average values. This data set was used to produce Figures 2, 3, 7, 13, and 14.

The annual average levels of DON found in USA wheat delivered to milling facilities were low and clustered around 0.5 mg/kg. However, as illustrated by the standard deviations in Figure 2, DON concentrations in individual samples in a given year do vary and can exceed 2 mg/kg. For example, in 2014 the average level of DON was 0.85 mg/kg, and the levels of DON measured in individual samples varied from LOD to 20.0 mg/kg. This variation can be seen more clearly in Figure 3, where DON levels at the processor level in soft and hard wheat harvested in the Midwestern and Northeastern regions of the USA from the 2003 to 2014 seasons are shown in more detail. Depending on the year and region, up to 14.3% of hard wheat samples showed levels of DON above 2 mg/kg, while up to 62% of soft wheat samples showed levels that high. Overall, during the period surveyed 1.7% of the hard wheat samples analyzed had levels of DON above 2 mg/kg, while more than 30% of the soft wheat samples had levels of DON that exceeded 2 mg/kg. These variations are discussed further later in this article.

The occurrence of DON in wheat taken at earlier stages in the handling chain has also been observed in Canadian wheat (Fig. 4) and durum (Fig. 5). DON was measured in 72% and 68% of wheat and durum samples, respectively, taken on farm and in 58% and 79% of wheat and durum samples, respectively, taken from primary elevator stocks before final blending of grain to meet quality specifications was performed. At later stages of the handling chain, <50% of wheat and durum samples contained quantifiable concentrations of DON. There were some instances of high concentrations of DON (i.e., >5 mg/kg) observed in individual Canadian samples, as with USA samples (Figs. 2 and 3). These instances occurred in samples taken from on farm, primary elevator stocks, or elevator loadings but not at later stages in the grain-handling chain. The average DON concentrations in exported Canadian wheat and durum were both <1 mg/kg.

The data incorporated into Figure 4 represents almost 13 million tonnes of wheat at the farm stage and more than 15 million tonnes exported at the end of the handling chain from 2009 through 2014, which encompasses years with higher and lower incidences of FHB (33). The data used to build Figure 4 included samples from primary elevator stock \( n = 3,281 \), elevator loading \( n = 572 \), and terminal stock \( n = 323 \) stages that were analyzed using ELISA or quantitative lateral flow test methods, with an LOD of 0.5 mg/kg. A small number of...
on-farm samples \( (n = 16) \) were analyzed using ELISA with an LOD of 0.25 mg/kg; the remaining samples \( (n = 29,254) \) were analyzed using ELISA with an LOD of 0.5 mg/kg. Shipments were analyzed using ELISA \( (n = 130; \text{LOD of 0.5 mg/kg}) \) and gas chromatography–mass spectrometry \( (n = 499; \text{LOQ of 0.05 mg/kg}) \) (34).

The data presented in Figure 5 represent durum analyzed in 2010 through 2014, mostly using ELISA or quantitative lateral flow test methods with an LOD of 0.5 mg/kg to evaluate samples at the farm \( (n = 2,297) \), primary elevator stock \( (n = 120) \), elevator loading \( (n = 554) \), terminal stock \( (n = 496) \), and shipment \( (n = 407) \) stages. Some on-farm samples \( (n = 53) \) were analyzed using an ELISA with an LOD of 0.25 mg/kg. In addition, some shipment samples \( (n = 68) \) were analyzed using gas chromatography–mass spectrometry \( \text{(LOQ of 0.05 mg/kg}) \) (34).

It is very difficult to directly compare the degree of DON occurrence in North American grains based on reports of DON in grains grown in other grain-producing regions, as different sampling schemes, sample preparation techniques, sample types, analytical methods, and production years all affect the concentrations of DON observed. Unfortunately, these details regarding samples, their provenance, and methods of analysis are often not provided in the scientific literature or are not provided in enough detail. However, in general, average reported concentrations for DON in wheat, maize, and barley grown in North America are similar to those reported for these grains grown in other regions.

A broad compilation of data on the global occurrence of DON in grains is provided in Figure 6 (35–67). In this figure the average values for reported DON concentrations in different commodities throughout the world are presented, as reported by more than 30 scientific papers published in the literature. These reports included samples from more than 30 countries in different regions of the world, such as Africa, the Americas, Asia, the Middle East, Australia, and Europe. The work in these reports analyzed samples mostly described as “field samples” or recently harvested grain, with a small percentage of the samples being described as “commercial samples.” The majority of the studies also indicated that the sampling followed an opportunistic approach, with very few being part of a comprehensive monitoring program for DON in grains. This may result in data
being presented that are not truly representative of the occurrence of DON in grain from a particular region or time period. Nonetheless, even though the method of analysis varied from study to study and included both rapid screening and comprehensive instrumental techniques such as ELISA and liquid chromatography–tandem mass spectrometry, with LODs varying from 0.01 to 180 µg/kg, the averages presented in Figure 6 illustrate that, among the commodities described, the levels of DON reported are similar. This applies for the different areas of the world, with the exception of some reports of high levels of DON in wheat in Africa. Wheat samples from Africa reported in this figure were collected in Morocco, Tunisia, and Kenya and reported in three independent studies (40,44,67). Overall, 856 wheat samples were collected in these three countries, and most of the contamination seemed to be associated with samples from Tunisia (average DON levels of 17.9 mg/kg). More information regarding the occurrence of DON in the Republic of South Africa is presented in Box 1. The differences among regions and grains are very typical of mycotoxin occurrence, as it varies based on the use of Good Agricultural Practices (GAPs), grain type and cultivar grown, toxigenicity of species and fungal strains associated with the crop, and weather (temperature and precipitation).

**Effects of Growing Seasons, Regions, and Years**

The presence of DON in wheat is governed by a number of factors that can vary among growing years and regions. These factors include environmental growing conditions such as temperature and precipitation, wheat type and cultivar grown, as well as the species and chemotype (subpopulation) of *F. graminearum* infecting the grain.

Figure 2 illustrates how DON can vary among growing years. Since wheat-growing regions are large in Canada and the USA, there can also be considerable variation in the presence of DON within growing regions. The annual average DON concentrations in wheat across all USA growing regions and classes delivered to milling facilities peaked at 0.85 mg/kg in 2014 and was at its lowest at 0.27 mg/kg in 2008. The effect of harvest year is further illustrated by Figure 3, where levels of DON in wheat, based on the data set provided by milling facilities in the USA, are reported for two growing regions (Midwest and Northeast) and two wheat classes (soft and hard) for different years (2003–2014). As noted by the bars in the chart, the Northeast is more prone to variation from year to year, regardless of the type of wheat grown, while the Midwest seems to show more variation for certain classes. Because mycotoxin production by molds is driven by intrinsic and extrinsic factors, the environmental conditions encountered by the grain in the field have a great impact on the mycotoxin levels detected in the grain. Among the intrinsic factors is mold species (or strains/chemotypes), while the extrinsic factors include temperature, water activity, nutrient availability, and chemical agents (68). As a result, it is not uncommon to observe DON levels in grain varying greatly from year to year. Higher levels of DON in wheat are usually associated with excessively wet periods close to the flowering stage, which is 6–8 weeks prior to harvest.

Another example of such variation in DON levels with harvesting year is illustrated by the data presented by Martínez.

**Box 1 – Deoxynivalenol Incidence in Africa**

In developing nations with many low- to middle-income and high-density populations, grains represent a primary food source. If not controlled properly, grains are predisposed to contamination by several fungi that can produce toxins: for instance, deoxynivalenol (DON). Figure 1 in this box shows overall DON levels in maize and wheat as reported in a survey conducted in the Republic of South Africa (RSA) by the Southern African Grain Laboratory (SAGL) from 2009 to 2014. Five harvesting seasons were evaluated, including 36 grain production regions (Fig. 2). Altogether these provinces account for an approximate production of 1.85 million tonnes/season for wheat and 9.5 million tonnes/season for maize. Every growing season, SAGL randomly selects wheat and maize samples for mycotoxin analysis that represent different growing regions as well as different classes and grades. For the period described here, mycotoxin analysis was performed using a validated multimycotoxin screening method (UPLC-MS/MS). The highest incidence of DON in maize was reported in a sample from the 2009–2010 growing season at 1.8 mg/kg; the highest incidence reported in wheat was in a sample from the 2012–2013 growing season at 0.4 mg/kg.

**Acknowledgments:** Information reported is courtesy of the Maize Trust and the Winter Cereal Trust (African industry organizations) via SAGL.
et al. (50). Data collected throughout two harvesting seasons (2012–2013 and 2013–2014) in the Pampas region of Argentina showed that in some years DON levels were higher than others, on average by 99.7%. Researchers have attributed the differences to weather-related events (Box 2).

Variation in DON content in Canadian wheat shipments also occurs from year to year (69). Variation in DON concentrations in durum and wheat among years appears to be related to the quality of the grain in the shipments, with higher DON concentrations seen in grain downgraded due to Fusarium damage. This work also reinforces the theory that annual variation in DON content occurs throughout the Americas.

These variations observed among years may be exacerbated or more difficult to predict due to climate change. A shift in environmental conditions could alter Fusarium populations. According to a re-

### Box 2 – Deoxynivalenol Incidence in Argentinian Wheat

The sporadic nature of Fusarium head blight and other diseases caused by Fusarium spp. affect different commodities throughout the world, and efforts have been made to reduce the presence of the causative agents. Such is the case for Argentina, where empirical forecasting models have been evaluated to estimate the spatial distribution of F. graminearum, a deoxynivalenol (DON) producing mold. These models predict the incidence of the disease based on environmental conditions such as maximum and minimum temperature, precipitation, and relative humidity. While validating the models in the Pampas region of Argentina, two harvesting periods were evaluated, including several wheat cultivars. The models were very accurate and correlated well with the mold incidence and levels of DON detected in the samples (Figs. 1–4). However, one interesting point to highlight from this study was a large decrease, on average (99.72%), in the levels of DON from 2012–2013 to 2013–2014, with no interventions applied by the researchers. Even though predictive models and other good agricultural practices have an impact on the quality of harvested grain, one cannot disregard many environmental factors unaccounted for that may impact DON levels. Research on the performance of the models was performed at the Agricultural Experimental Station Oliveros and the National Institute of Agricultural Technology in Argentina.

---

**Fig. 1.** DON incidence in the 2012–2013 harvest (Lat –32.55, Long –64.32).

**Fig. 2.** Spatial distribution obtained by the Agricultural Experimental Station model for Fusarium incidence in the 2012–2013 harvest.

**Fig. 3.** DON incidence in the 2013–2014 harvest (Lat –32.55, Long –64.32).

**Fig. 4.** Spatial distribution obtained by the Agricultural Experimental Station model for Fusarium incidence in the 2013–2014 harvest.
view prepared by Wu et al. (70), the *Fusarium* populations in North America have changed greatly in a period of 10 years. Historically, the 15-ADON chemotype of *F. graminearum* has been predominant in North America and 3-ADON in South America and Europe. However, the *Fusarium* populations in North America have been changing. For example in North Dakota, the 3-ADON chemotype comprised about 3% of *Fusarium* on wheat prior to 2002 and up to 44% of isolates collected in 2008. These population shifts may impact the levels of DON found in the grain at harvest, since greenhouse studies have shown that 3-ADON isolates produce higher levels of DON in FHB-susceptible and -resistant wheat varieties than do 15-ADON isolates (71). In addition, shifting environmental conditions could alter insect populations and impact fungal infection and mycotoxin production.

The effect of growing region, which is mostly associated with the climatic conditions of a region, is clearly illustrated in Figures 7 and 8. The map in Figure 7 is based on data gathered from milling facilities in the USA. In general, the samples were collected and analyzed using GIPSA-approved methods. The map in Figure 8 is based on samples collected from the Canadian Prairies from 2008 through 2013 as part of the Canadian Grain Commission’s Harvest Sample Program. The Canadian samples were analyzed using gas chromatography–mass spectrometry according to the method of Tittlemier et al. (69).

The maps in Figures 7 and 8 illustrate the variation in DON occurrence in wheat from different growing regions in North America. In the USA, soft wheat from the Midwestern, Northeastern, and Southern regions had higher levels of DON than hard wheat from the same regions (*P* < 0.05), with hard wheat representing 65% and soft wheat 19% of total USA wheat production during the period surveyed (2003–2014). Among soft wheat samples, the highest levels of DON were found in the Midwestern and Northeastern regions (*P* < 0.05), with levels, on average, 2–3 times higher in those regions than the levels observed in the Southern part of the country. When hard wheat samples were compared, the Northeastern region showed the highest levels, the Midwestern and Southern regions showed similar levels of DON, and the Western region showed the lowest levels of DON (*P* < 0.05). For this analysis, the means and standard deviations for each wheat class/region subset were calculated and compared pairwise using *t*-test statistics.

In western Canada, higher average DON concentrations have been observed in hard red spring (HRS) wheat grown in the eastern prairies of Manitoba (Fig. 8) compared with HRS wheat grown in western Saskatchewan and Alberta. These regional differences are driven by environmental factors such as temperature and precipitation that predominate around the time of anthesis (and thus affect *Fusarium* infection), as well as the geographical distribution of DON-producing *Fusarium* species. According to Cowger et al. (72) and Cowger and Arellano (73), DON levels, percentage of *Fusarium*-infected kernels, percentage of *Fusarium*-damaged kernels, and FHB symptoms at harvest-ripeness increased with an increasing number of wet days following anthesis. Canadian surveys have shown that the main
DON producer, *F. graminearum*, is present at higher levels in wheat from the eastern prairies, whereas other species such as *F. poae* and *F. avenaceum* are more important in the western prairies (74).

**Barley.** Limited information exists about levels of DON in North American barley. In one study, Schwarz et al. (75) collected barley samples at harvest throughout all barley-growing regions of North Dakota and Minnesota. The samples used in their survey were part of regional crop surveys and covered the period from 1993 until 2003. Samples were cleaned using a Carter Day Dockage Tester (Seedburo Equipment Co.), but no further processing or grading was done prior to DON analysis. The levels of DON observed in the samples are summarized in Table 1. The average DON levels detected in the samples varied from 0.5 to 10.3 mg/kg. In most of the surveyed years at least one-third of the samples had levels in excess of 3 mg/kg, with some years showing as much as 59% of the samples with those levels of contamination. Variation from year to year in DON levels and incidence is evident and illustrates once again the volatility of the natural occurrence of such toxins.

Data on the occurrence of DON in samples of Canadian barley are presented in Figure 9. These samples were analyzed in 2009 through 2014, mainly using ELISA or quantitative lateral flow test methods, with LOD of 0.5 mg/kg, to analyze samples at the farm level (*n* = 2,237), primary elevator stock (*n* = 118), and shipment (*n* = 14) stages. One on-farm sample was analyzed using ELISA with an LOD of 0.25 mg/kg. In addition, some shipment samples (*n* = 26) were analyzed using gas chromatography–mass spectrometry (LOQ of 0.05 mg/kg) (69). The mean DON concentration for on-farm samples was 0.7 mg/kg, which is within the range of means reported for comparable harvest samples presented in Table 1.

**Maize.** Data on the occurrence of DON in North American maize are presented in Table 2. The reports described in the table used different sampling strategies and methodologies to determine the level of contamination. For example, in the USA maize report on export data (76) a proportionate stratified sampling scheme was used to ensure samples taken for analysis were representative of USA yellow maize exports, the samples were prepared for analysis according to the GIPSA DON handbook, and an ELISA test kit (GIPSA approved) with an LOD of 0.3 mg/kg was used. The Canadian maize export data (69) were based on random sampling of shipment loads and gas chromatography–mass spectrometry analysis with an LOQ of 0.05 mg/kg. The Canadian field data (76–80) were obtained through random sampling of 10 consecutive ears at 2 locations per maize hybrid grown within a field. Another fundamental difference among the reports is the sampling stage. For example, the data relating to USA and Canadian exports are from samples taken at the end of the grain-handling chain (after the grain has been blended and cleaned), whereas the Ontario field samples were taken at the beginning of the handling chain. This lack of consistency with regard to the sampling point in the grain-handling chain, test methods used for DON analysis, and data reporting format preclude direct comparison of the results from the various studies. Nonetheless, the occurrence of DON in maize cannot be ignored, and the results summarized in Table 2 provide an indication of DON contamination observed over the past 4 years in maize samples from the beginning and end of the grain-handling chain. Based on this data, the majority of DON in USA- and Canadian-grown maize is present at concentrations lower than 2 mg/kg, with a small number of instances where DON concentrations exceeded 2 mg/kg. Additionally, as seen in the Ontario field data in Table 2, the proportion of these higher concentrations will vary from year to year.

**Table 1. Levels of deoxynivalenol (DON) in barley samples harvested in Minnesota and North Dakota (adapted, with permission of the American Society of Brewing Chemists, from Schwarz et al. [75])**

<table>
<thead>
<tr>
<th>CROP YEAR</th>
<th>NO. SAMPLES TESTED</th>
<th>MEAN</th>
<th>MIN</th>
<th>MAX</th>
<th>0.5-0.9</th>
<th>1.0-2.9</th>
<th>≥3.0</th>
<th>TOTAL</th>
<th>&lt;0.5 mg/kg</th>
<th>DON</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>243</td>
<td>0.5</td>
<td>&lt;0.5</td>
<td>5.6</td>
<td>21.4</td>
<td>12.8</td>
<td>1.2</td>
<td>117,893</td>
<td>76,169</td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td>224</td>
<td>0.7</td>
<td>&lt;0.5</td>
<td>12.8</td>
<td>16.1</td>
<td>12.1</td>
<td>6.4</td>
<td>57,752</td>
<td>38,415</td>
<td></td>
</tr>
<tr>
<td>2001</td>
<td>247</td>
<td>2.8</td>
<td>&lt;0.5</td>
<td>61.8</td>
<td>12.2</td>
<td>19.8</td>
<td>32.8</td>
<td>75,204</td>
<td>26,499</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>134</td>
<td>2.2</td>
<td>&lt;0.5</td>
<td>29.0</td>
<td>26.4</td>
<td>28.9</td>
<td>25.4</td>
<td>99,910</td>
<td>24,453</td>
<td></td>
</tr>
<tr>
<td>1999</td>
<td>153</td>
<td>1.1</td>
<td>&lt;0.5</td>
<td>10.6</td>
<td>28.1</td>
<td>24.8</td>
<td>7.9</td>
<td>57,525</td>
<td>22,559</td>
<td></td>
</tr>
<tr>
<td>1998</td>
<td>142</td>
<td>2.9</td>
<td>&lt;0.5</td>
<td>28.6</td>
<td>14.1</td>
<td>28.6</td>
<td>32.4</td>
<td>115,866</td>
<td>31,006</td>
<td></td>
</tr>
<tr>
<td>1997</td>
<td>156</td>
<td>5.5</td>
<td>&lt;0.5</td>
<td>44.1</td>
<td>7.7</td>
<td>16.0</td>
<td>47.4</td>
<td>113,732</td>
<td>32,807</td>
<td></td>
</tr>
<tr>
<td>1996</td>
<td>180</td>
<td>3.2</td>
<td>&lt;0.5</td>
<td>25.8</td>
<td>16.7</td>
<td>25.6</td>
<td>32.2</td>
<td>161,899</td>
<td>41,374</td>
<td></td>
</tr>
<tr>
<td>1995</td>
<td>132</td>
<td>6.4</td>
<td>&lt;0.5</td>
<td>34.6</td>
<td>7.6</td>
<td>18.9</td>
<td>59.1</td>
<td>118,399</td>
<td>17,042</td>
<td></td>
</tr>
<tr>
<td>1994</td>
<td>144</td>
<td>10.3</td>
<td>&lt;0.5</td>
<td>60.0</td>
<td>6.9</td>
<td>16.0</td>
<td>58.3</td>
<td>140,926</td>
<td>26,424</td>
<td></td>
</tr>
<tr>
<td>1993</td>
<td>147</td>
<td>3.7</td>
<td>&lt;0.5</td>
<td>17.2</td>
<td>5.4</td>
<td>21.1</td>
<td>53.1</td>
<td>132,832</td>
<td>27,100</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 9. Deoxynivalenol (DON) occurrence in Canadian barley along the grain-handling chain. LOQ = limit of quantitation; LOD = limit of detection.**

The North American grain supply chain, which includes growers, grain buyers, and
end users, has developed and refined management practices and tools to control FHB and DON with the benefit of three decades of modern experience in production, handling, and processing. These practices are effective in safeguarding the health of consumers.

Results from monitoring and surveillance activities indicate that acceptably low DON levels in unprocessed grain products can be achieved in exports and shipments for domestic use in most crop years following current advisory levels and guidelines for DON. These levels are achieved through the aggregation and blending of grain stocks that occurs along the supply chain, monitoring of DON levels in deliveries of grain shipments to processors, and a variety of grain sorting and cleaning technologies and methods that are available to processors.

All participants in the grain value chain in Canada and the USA (Fig. 1) effectively manage DON levels in wheat and other grains. Coordinated research across years and dozens of locations by scientists in both countries ensures that research occurs in all market classes of wheat and barley and for growers in all at-risk growing areas (81). The research also ensures that the recommendations made to growers are evidence-based. Growers (producers) use an integrated approach to reduce the likelihood of DON in wheat and barley that includes sowing resistant cultivars, use of fungicides, choice of previous crop, method of tillage, and disease forecasting (82–88). In maize, management of Gibberella ear rot with similar cultural practices has had a limited effect in reducing disease development and mycotoxin accumulation (89). However, maize hybrids do vary in their resistance to infection, and growers are encouraged to compare these differences when choosing a hybrid to plant (90).

Following the severe epidemic of FHB in wheat and barley in Canada and the USA in 1993, breeding for reduced DON became a higher priority (91). The use of disease screening nurseries and collaborative regional testing of advanced breeding lines and cultivars became routine and still continues today. Since the early 2000s, wheat and barley breeders have been successful in releasing cultivars with improved FHB resistance and reduced DON accumulation to replace susceptible cultivars (92–101). FHB severity and/or DON accumulation in the improved cultivars has been reduced by more than 50% compared with the susceptible checks (controls), and growers have been growing the new cultivars. For example, in the HRS wheat growing areas of Minnesota, North Dakota, and South Dakota in the USA, the frequency of FHB-susceptible HRS cultivars sown decreased from 76% in 1999 to 21% in 2011 (102). The sources of resistance in the improved cultivars includes exotic sources such as Sumai #3 from China and native resistance already present in existing breeding germplasm (103,104). The incorporation of quantitative trait loci (QTL) conferring FHB resistance by wheat breeding programs in Canada and the USA, including the QTL FHB1 from Sumai #3, has been enhanced through marker-assisted selection (105).

Appropriate crop rotation to reduce DON accumulation is a requirement that is well-understood by grain growers in high-risk areas (86). Additionally, combining improved cultivars with fungicides and optimal spray technology at flowering provides the best management practice for reducing the risk of DON in wheat and barley, as demonstrated by Wegulo et al. (84) (Fig. 10) and others (106–108).

Fungicides with proven effectiveness in reducing DON accumulation include tebuconazole (Folicur), prothioconazole (Proline), metconazole (Caramba), and a combination of prothioconazole and tebuconazole (Prosaro) (109). In a meta-analysis of more than 100 uniform fungicide trials conducted on wheat, Paul et al. (110) found metconazole reduced DON accumulation by 50% compared to the check (control), followed by tebuconazole (40%) and prothioconazole (32%) (Fig. 11).

Biological control agents are alternatives to synthetic fungicides. These agents may provide growers with an additional option for crop protection when the allowable window for applying synthetic fungicides has passed (111,112) or for organic production. Organisms that have been tested include the bacteria *Bacillus amyloliquefaciens*, *B. subtilis*, and *Lysobacter enzymogenes* and the yeasts *Cryptococcus nedaensis* and *C. flavescentis* (81). Taegro (113) is a strain of *B. subtilis* that is marketed as a biological control agent.

In uniform fungicide trials conducted by the U.S. Wheat and Barley Scab Initiative (USWBSI), none of the biological control agents by themselves has been as efficacious as synthetic fungicides in reducing DON (77). Growers, crop consultants, extension educators, and others in the value chain can access information on best management practices and resistant cultivars online at Scab Smart Management (114).

Important tools for alerting growers and others in the grain value chain of areas at risk for DON accumulation in-

### Table 2. Reported occurrences of deoxynivalenol (DON) in North American maize (69,76–80)

<table>
<thead>
<tr>
<th>SAMPLE TYPE</th>
<th>NUMBER OF SAMPLES ANALYZED</th>
<th>DISTRIBUTION OF DON (mg/kg)</th>
<th>DATA SOURCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize grown in USA and sampled at export 2013-2014</td>
<td>412</td>
<td>94.9% &lt;0.5, 5.1% 0.5 to 5.0</td>
<td>US Grains Council 2014 (76)</td>
</tr>
<tr>
<td>Maize grown in Canada and sampled at export 2010-2012</td>
<td>9</td>
<td>89% &lt;2, 11% ≥2 Median = 0.6</td>
<td>Tittemier, Gaba, and Chan 2013 (69)</td>
</tr>
<tr>
<td>Maize sampled directly from fields in southern Ontario, Canada 2014</td>
<td>202</td>
<td>60% &lt;0.5, 25% 0.5 to 1.9, 9% ≥2.0</td>
<td>Stewart and Tenuta 2014 (77)</td>
</tr>
<tr>
<td>Maize sampled directly from fields in southern Ontario, Canada 2013</td>
<td>197</td>
<td>84% &lt;0.5, 14% ≥0.6 to 1.9, 2% ≥2.0</td>
<td>Stewart and Tenuta 2013 (78)</td>
</tr>
<tr>
<td>Maize sampled directly from fields in southern Ontario, Canada 2012</td>
<td>171</td>
<td>86% &lt;0.5, 11% 0.6 to 1.9, 4% ≥2.0</td>
<td>Stewart and Tenuta 2012 (79)</td>
</tr>
<tr>
<td>Maize sampled directly from fields in southern Ontario, Canada 2011</td>
<td>99</td>
<td>76% &lt;2, 12% ≥2 to 4, 12% ≥4</td>
<td>Stewart and Tenuta 2011 (80)</td>
</tr>
</tbody>
</table>
clude web-based disease-forecasting tools that utilize hundreds of automated weather stations located across Canada and the USA (82,115–117). The system used in Ontario, Manitoba, and Saskatchewan in Canada, Weather Central (118), is based on research at the University of Guelph (82,115). A number of forecasting models are available in the USA; for example, the Fusarium Risk Assessment Tool (119), which was developed using USDA-ARS funds, and other forecasting models can be accessed through the USWBSI website (120). Both the Canadian and USA forecasting systems are widely used in the spring and summer in all regions as an indicator of FHB likelihood. Each of the forecasting websites differ slightly, but in general, users can go to the websites and enter information such as their location, the market class of wheat they are producing, the relative resistance of the cultivar they are growing, the date, and the number of hours out they want to forecast potential risk. Based on the information provided, the websites will return maps of the specified region indicating the potential risk of infection. The USWBSI also developed and maintains the FHB Alert System, which sends an e-mail or text message to subscribers in the USA to warn them that conditions in their region are favorable for FHB development. All of the forecasting tools and the FHB Alert System warn participants in the grain value chain about regions with potentially unacceptable levels of DON, growers of the need for timely applications of fungicides, and grain buyers to develop strategies before harvest to manage potential problems. This is the first phase of determining the potential risk of unacceptable DON levels by producers, procurers, and processors and has a large impact on the sampling plan and management of crop segregation. In years and regions with a high risk of DON, surveillance includes sampling of individual fields before harvest to ensure unacceptable grain is kept out of the food chain.

Large processors and end users have staff or consultants who monitor the expected condition of the crop to avoid sourcing grain from areas with FHB. The overall strategy in North America for managing grain contamination by F. graminearum and DON is illustrated in Figure 12.

The challenge of sourcing acceptable grain is impacted by the year-to-year variations in DON levels in different sourcing areas and even by how different cultivars within a market class respond to the disease. The North American grain-handling chain (Fig. 1) generally moves grain in bulk from individual farms to primary elevators, where grain from a number of individual farms is accepted for delivery and combined. Grain from primary elevators is then moved via rail and/or domestic shipping to terminal elevators, where it is combined with grain from other primary elevators. This results in a large volume of grain originating from a variety of locations that should meet the quality and safety specifications of end users. At each step in the value chain, processors test truck and/or railcar loads for DON levels to further segregate the grain or to reject a load and have it sent back to the supplier. Steps are taken by processors to ensure that DON concentrations are below US-FDA advisory levels or Health Canada guidelines.

Another challenge in procuring grain each crop year is that processors and other end users have limitations on the number and size of bins they have available for segregating incoming grain. Thus, it is critical that procurers determine the risk for unacceptable DON levels or other end-use quality traits in the origination.
areas for the different grains they wish to procure. After this is completed, the processor can create the blend that will meet the customers’ requirements. The ranking of components of the grain blend design is based on 1) food safety; 2) functional requirement; and 3) consideration of processing performance.

Another consideration is whether the processor is using grain from the export system or local origins. Elaborate systems are in place to assure consistency of grade, including minimizing DON levels in grains that are exported. Processors within Canada and the USA receive grain shipments originating from farms, primary elevators, and terminal elevators; thus, the domestic processor often has much more variation to deal with than a processor procuring grain through the export channel. Having a target for finished products is more appropriate to assure food safety compliance than targeting unprocessed raw grain with a fixed level when DON distributions are not known.

The relationships between FHB, FDK, and DON in grains are complex (121) but understood to result from both the plant response to the pathogen (122) and strain variation (123,124). Nonetheless, harvest surveys have demonstrated that DON in wheat can be managed by minimizing the amount of FDK present in grain and using FDK as a grading factor (69). Growers can reduce FDK in the harvested grain by adjusting airflow settings on their combines (125).

In addition to the blending that occurs along the Canadian and USA value chains, cleaning often occurs at larger primary and terminal elevators. Grain can be cleaned using a variety of techniques, such as optical sorting, sieving, and gravity tables. These handling steps can decrease the level of FDK and, thereby, DON levels in a volume of grain (126).

The ability to handle large volumes of grain of varying quality and meet desired specifications increases along the grain-handling chain. Figure 4 illustrates how higher concentrations (i.e., >2 mg/kg) of DON in wheat occurred at earlier stages in the grain-handling chain, such as on farm or at primary elevators, but not further along the grain-handling chain. The fraction of wheat samples containing DON at concentrations >2 mg/kg decreased from 19% on farm to 0.5% in shipments from terminal elevators when analyzed in nontargeted monitoring and surveillance programs (i.e., where the sampling scheme was not biased). A decrease in the occurrence of DON concentrations along the handling chain similar to that described for wheat was observed for Canadian durum and barley and is illustrated in Figures 5 and 9, respectively.

Processors at intermediate stages of the grain-handling chain can be more limited in their ability to manage DON in deliveries coming directly from farms or primary....

Fig. 12. Overall strategy for managing deoxynivalenol (DON) in grains.

Fig. 13. Levels of deoxynivalenol (DON) detected at the processor level in wheat samples from the Northeastern, Midwestern, Western, and Southern regions of the USA from 2003 through 2014 (n = 42,131). Samples include soft and hard wheat varieties. “Estimated Tonnes” lists the amount of wheat represented by the samples analyzed each year.

Fig. 14. Annual average deoxynivalenol (DON) concentrations in exported soft wheat sublots from the USA. Values in parentheses indicate the number of sublot samples analyzed each year.
of wheat leaving the USA as exports. Based on the data from the USA, as for Canada, in general as grain moves through the handling chain to export the average reported levels for DON are reduced, even more so for soft wheat than for hard wheat in the last 10 years.

Effect of Processing on DON Content in Wheat and Other Grains

Wheat Milling. Harvested grains are converted into flour and other fractions for human consumption or further manufacturing. Processing consists of cleaning (including sorting) and milling (Fig. 15). The sorting step removes any impurities, such as straw and dust, but can also be used to remove broken or mold-damaged grains. This selection or separation step is performed based on the physical parameters of the kernels, such as shape, size, specific gravity, relative density, and color.

Fusarium-infected grains become shriveled and lighter than healthy grains (126). Some studies observed that selection and separation based on gravity was effective in removing heavily infected grains with high concentrations of DON from healthy grains (126,130). Nevertheless, this management approach has two potential problems: 1) many Fusarium-infected grains, which may contain high levels of DON, can be physically indistinguishable from healthy grains and not removed by some sorting methods; and 2) FHB level is not always correlated with the concentration of DON in the grains when secondary Fusarium infection occurs (131).

Cleaning can also be used to remove infected grains. Nowicki et al. (132) reported that scouring was effective in reducing the level of DON by 22% because the toxin was unevenly distributed on the surface of grains; Fusarium was also removed from the surface of grains. According to Abbas et al. (133) the preparation cleaning step in the milling process reduced the concentration of DON by 6–19% in infected wheat grains, with cleaning efficiency depending on the initial condition of the grain and the extent of the contamination (Table 3). More recently, Lancova et al. (140) observed that the effective removal of screenings and the outer layers of bran from the surface of grains during cleaning steps reduced the concentration of DON by 48%.

The international wheat milling industry has carried out several DON reduction trials in wheat mills over the last 5 years. These normally have shown the need to both mechanically clean and to pass the wheat through an optical sorter.
to maximize reduction of DON levels. They showed typical reductions from 3 mg/kg in wheat to about 1 mg/kg at the output of the optical sorter placed after mechanical cleaning, although there was some variability depending on the incoming grain (personal communication). Mechanical cleaning normally consists of a combination of a classifier, gravity separation, and aspiration, sometimes also using a scourer.

The optical sorter, which is not standard in all mills, normally uses a light sort in the visible region and a light sort in the short-wave infrared (SWIR) region. The largest reduction (relative) is normally seen with the use of the SWIR region of the sorter. Typically the optical sorter will remove between 2 and 5% of the product stream to achieve these reductions. In smaller mills, some reduction can be achieved using only a visible light sort with a blue filter. In this case, reductions of 25% of the DON level or more have been achieved using a standard optical sorter as found in the cleaning section of a modern mill in Europe or the USA (personal communication). Optical sorting is a potential option for mills to use to manage high or variable DON levels in wheat and other grains; however, it is a significant investment for a mill.

During the milling process some grains are polished, removing most of the bran and germ and leaving the endosperm, followed by the reduction of the endosperm to a uniform particle size of flour. This process involves a sequence of breaking (stage 1), reducing (stage 2), and separating steps. In stage 1 the grains are passed through a set of rough or corrugated break rolls rotating at different speeds.

During the milling process (Fig. 15), separation involves passing the grain through 2–3 break rolls and 3–5 reduction rolls, each followed by sieving. This results in five fractions: white flour, wheat germ, wheat feed (red dog), wheat shorts, and wheat bran. According to several researchers, when milling wheat or maize mycotoxins tend to be concentrated in the germ and bran fractions (133,141–145). Similar to other mycotoxins, DON is a heat-stable compound (155) and may not be destroyed during most food processing operations, including milling (156). Therefore, the best way to reduce DON is to separate the highly contaminated kernels from the bulk during the preparation steps and subsequent sieving steps.

Research has shown that the white flour has approximately half the level of DON found in the cleaned wheat, while the bran can have levels two or more times greater than the initial whole wheat (133,150). According to the research of Tanaka et al. (150), the flour fraction of barley contained 3.2% of the DON, while the bran fraction contained 96.8% of the DON found in the whole grain. In the case of wheat, the bran contained 81.6% of the DON. Milling wheat and barley is effective in removing the DON contained in the outer layers of the kernels. It should also be noted that significant improvements have been made in modern mills to decrease DON in the flour fraction (Fig. 16).

There have been varying reports of reduction of DON levels using peeling or debranning of wheat. The assumption is that the mycotoxin is in the bran layer on the surface of the grain. Some trials have shown DON reductions of up to 50% after debranning, but it has also been suggested that reductions will be lower when the whole grain has been affected by fungal attack. DON may also be distributed throughout the milling fractions independent of wheat variety (131,133–136,140, 157,158).

Table 3. Effect of cleaning on removal of deoxynivalenol (DON) from grain (131,133–141)

<table>
<thead>
<tr>
<th>COUNTRY</th>
<th>COMMODITY</th>
<th>INITIAL DON CONCENTRATION (mg/kg)</th>
<th>REDUCTION AFTER CLEANING (%)</th>
<th>CLEANING</th>
<th>REFERENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>CANADA</td>
<td>Mixture of spring wheat varieties</td>
<td>1.4</td>
<td>0 - 14%</td>
<td>Carter Day dockage tester</td>
<td>Scott et al 1984 (134)</td>
</tr>
<tr>
<td>CANADA</td>
<td>Soft white winter wheat</td>
<td>0.8</td>
<td>23%</td>
<td>Carter Day dockage tester</td>
<td>Young et al 1984 (135)</td>
</tr>
<tr>
<td>USA</td>
<td>Hard red winter wheat</td>
<td>7.9 - 9.6</td>
<td>6 - 19%</td>
<td>Carter Day dockage tester</td>
<td>Abbas et al 1985 (133)</td>
</tr>
<tr>
<td>USA</td>
<td>Soft wheat</td>
<td>0.03 - 2.9</td>
<td>16%</td>
<td>Combination of screening and air flow</td>
<td>Seitz and Bechtel 1985 (131)</td>
</tr>
<tr>
<td>USA</td>
<td>Hard red winter wheat</td>
<td>0.6 - 5.1</td>
<td>34 - 45%</td>
<td>Normal (the cleaning house), Double (twice in the cleaning house), High aspiration (the air suction using the normal cleaning flow), Washer (Smico wheat washer after the normal cleaning flow)</td>
<td>Seitz 1980 (136)</td>
</tr>
<tr>
<td>CANADA</td>
<td>Durum wheat</td>
<td>1.8 - 6.9</td>
<td>45 - 74%</td>
<td>Hand picking</td>
<td>Dexter et al 1996 (137)</td>
</tr>
<tr>
<td>ITALY</td>
<td>Durum wheat</td>
<td>0.4 - 13.1</td>
<td>1 - 31%</td>
<td>Rational Komser service Mod. M220V after (equipped with an aspiration system and two sieves)</td>
<td>Visconti et al 2004 (138)</td>
</tr>
<tr>
<td>USA</td>
<td>Soft red winter wheat</td>
<td>0.6 - 20</td>
<td>average 51%</td>
<td>Carter Day dockage tester</td>
<td>Delviche et al 2005 (139)</td>
</tr>
<tr>
<td>CZECH REPUBLIC</td>
<td>Wheat</td>
<td>0.09 - 3.0</td>
<td>45 - 59%</td>
<td>Sieving, scouring and polishing (the laboratory aspirator of dust particles Labofix Brabender)</td>
<td>Lancova et al 2008 (140)</td>
</tr>
<tr>
<td>UNITED KINGDOM</td>
<td>Wheat</td>
<td>0.01 - 0.32</td>
<td>- 8° - 78% (average 46%)</td>
<td>Separator/classifier (sieving), with aspiration</td>
<td>Soudamore and Patel 2008 (141)</td>
</tr>
</tbody>
</table>

* Represents an increase
Dry Milling of Maize (Corn). With wheat, the milling process does not reduce the total amount of DON but rather converts the wheat into fractions, segregating the DON in lower value fractions while the high-value fraction, white flour, is relatively low in the toxin. Maize goes through a different milling process (159). After cleaning, maize kernels are soaked twice in water, then passed through a degerminator and dried again. The degermed maize is then sifted and either placed on gravity tables for production of germ and coarse grits or rolled to make flour or fine grits. During the milling process, the DON segregated heavily into the bran, screenings, germ, and germ meal fractions, leaving the grits and flour fractions with 5–10% of the DON level contained in the bran (160). Most products for human consumption are prepared from flour and grits. Therefore, it is possible to reduce DON in human foods during the milling process. Similar to wheat milling, these results suggest the milling process does not remove DON but redistributes it. This explains the consistent tendency for DON to segregate into milling fractions used for animal feed and out of fractions used for human foods; thus, it makes much more sense to regulate milled products than unprocessed raw grain.

Oat Milling. When oats are milled, they undergo a dehulling process to remove the husk from the grain before kilning (heat treatment to inactivate lipase). Most of the DON in oats is concentrated in the hull, so dehulling oats results in a reduction in the level of DON compared to the initial grain. This is evidenced by the oat flakes produced by the milling process, which contain 5–10% of the DON present in the oats before milling (161).

Risk Management Measures for DON

Maximum levels (MLs), which are the maximum concentrations of a specific substance recommended to be legally permitted in a specific commodity, provide dietary guidance for consumers. MLs are not necessary for all contaminants in all foods. Establishing an ML for a given contaminant in a certain food would be necessary only if and when the contaminant may be found in amounts that result in significant adverse public health impacts. In this case, the ML would afford adequate assurances of safety. The main criterion is that the contaminant is a significant contributor to total dietary exposure for consumers. Therefore, determination of MLs for DON across multiple grains must satisfy the “significant contributor to total dietary exposure for consumers” criterion and provide health benefits. Setting levels for DON in an unprocessed raw commodity that is not typically consumed in that form and that contributes minimally to dietary exposure from the finished food product (after processing) may not significantly change health outcomes. Determination of MLs for DON across multiple grains must afford adequate health protections in bad climatic years, provide additional health benefits at a reasonably achievable level, and be practically achievable so that trade disruptions do not occur.

Emesis is the critical effect in DON acute food toxicity. The acute reference dose (ARfD) of 8 µg/kg bw/day of DON for DON across multiple grains must satisfy the “significant contributor to total dietary exposure for consumers” criterion and provide health benefits. Setting levels for DON in an unprocessed raw commodity that is not typically consumed in that form and that contributes minimally to dietary exposure from the finished food product (after processing) may not significantly change health outcomes. Determination of MLs for DON across multiple grains must afford adequate health protections in bad climatic years, provide additional health benefits at a reasonably achievable level, and be practically achievable so that trade disruptions do not occur.

Table 4. Effect of milling on removal and distribution of deoxynivalenol (DON) from grain (126, 131–138,140,146–154)

<table>
<thead>
<tr>
<th>COUNTRY</th>
<th>COMMODITY</th>
<th>INITIAL DON CONCENTRATION (mg/kg)</th>
<th>DON REDUCTION (%)</th>
<th>MILL TESTED*</th>
<th>REFERENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>CANADA</td>
<td>Hard red spring wheat</td>
<td>4.6</td>
<td>11%</td>
<td>a</td>
<td>Scott et al 1983 (146)</td>
</tr>
<tr>
<td>CANADA</td>
<td>Mixture of spring wheat varieties</td>
<td>1.2</td>
<td>1.1%</td>
<td>b</td>
<td>Scott et al 1984 (134)</td>
</tr>
<tr>
<td>CANADA</td>
<td>Soft white winter wheat</td>
<td>0.4 - 0.6</td>
<td>19 - 33%</td>
<td>b</td>
<td>Young et al 1984 (135)</td>
</tr>
<tr>
<td>CANADA</td>
<td>Hard red winter wheat</td>
<td>1.0 - 8.7</td>
<td>15 - 24%</td>
<td>b</td>
<td>Young et al 1984 (135)</td>
</tr>
<tr>
<td>USA</td>
<td>Hard red winter wheat</td>
<td>6.4 - 8.6</td>
<td>31 - 85%</td>
<td>b</td>
<td>Abbas et al 1985 (133)</td>
</tr>
<tr>
<td>USA</td>
<td>Soft wheat</td>
<td>0.03 - 3.4</td>
<td>10%</td>
<td>c</td>
<td>Seitz et al 1985 (131)</td>
</tr>
<tr>
<td>USA</td>
<td>Hard red winter wheat</td>
<td>0.6 - 5.1</td>
<td>56%</td>
<td>a, c, d</td>
<td>Seitz et al 1986 (136)</td>
</tr>
<tr>
<td>JAPAN</td>
<td>Wheat</td>
<td>0.2</td>
<td>26 - 53%</td>
<td>c</td>
<td>Tanaka et al 1986 (147)</td>
</tr>
<tr>
<td>KOREA</td>
<td>Wheat</td>
<td>0.3</td>
<td>24 - 39%</td>
<td>b</td>
<td>Lee et al 1987 (148)</td>
</tr>
<tr>
<td>CANADA</td>
<td>Western red winter wheat</td>
<td>10.7 -11.1</td>
<td>59 - 60%</td>
<td>b</td>
<td>Nowicki et al 1988 (132)</td>
</tr>
<tr>
<td>USA</td>
<td>Eastern white winter wheat</td>
<td>0.5 - 10.0</td>
<td>16 - 82%</td>
<td>a</td>
<td>Tkachuk et al 1991 (126)</td>
</tr>
<tr>
<td>USA</td>
<td>Hard red winter wheat</td>
<td>2.6</td>
<td>46%</td>
<td>b</td>
<td>Trigo-Stockill et al 1996 (149)</td>
</tr>
<tr>
<td>CANADA</td>
<td>Red spring wheat</td>
<td>1.1 - 9.0</td>
<td>30 - 67%</td>
<td>a</td>
<td>Dexter et al 1996 (137)</td>
</tr>
<tr>
<td>JAPAN</td>
<td>Wheat</td>
<td>0.2 - 0.4</td>
<td>0 - 93%</td>
<td>c</td>
<td>Tanaka et al 1999 (150)</td>
</tr>
<tr>
<td>ITALY</td>
<td>Durum wheat</td>
<td>0.3 - 9.7</td>
<td>24 - 76%</td>
<td>b</td>
<td>Visconti et al 2004 (138)</td>
</tr>
<tr>
<td>CZECN REPUBLIC</td>
<td>Wheat</td>
<td>0.04 - 1.4</td>
<td>39 - 72%</td>
<td>b</td>
<td>Lancova et al 2008 (140)</td>
</tr>
<tr>
<td>CZECN REPUBLIC</td>
<td>Soft winter wheat</td>
<td>0.082 - 1.7</td>
<td>25 - 59%</td>
<td>b</td>
<td>Kostlaneka et al 2011 (151)</td>
</tr>
<tr>
<td>UNITED KINGDOM</td>
<td>Wheat</td>
<td>0.09 - 0.3</td>
<td>30%</td>
<td>b</td>
<td>Edwards et al 2011 (152)</td>
</tr>
<tr>
<td>JAPAN</td>
<td>Soft wheat</td>
<td>0.9 - 5.3</td>
<td>36 - 43%</td>
<td>b</td>
<td>Thammawong et al 2011 (153)</td>
</tr>
<tr>
<td>JAPAN</td>
<td>Soft wheat</td>
<td>0.9 - 1.9</td>
<td>64 - 65%</td>
<td>b</td>
<td>Zheng et al 2014 (154)</td>
</tr>
</tbody>
</table>

* a: Allis-Chalmers laboratory mill; b: Bühler experimental mill; ci: Miag multitam mill; d: Weber hammer mill.

Fig. 16. Deoxynivalenol (DON) distribution (%) in milled wheat fractions (total DON amount in cleaned grains = 100%). (Derived from data presented in Tables 3 and 4.)
used in international standards was established by the 72nd JECFA in 2010 (162). This ARfD is used in the derivation of proposed MLs that would adequately protect health (163). JECFA reported that “dietary exposures to DON up to 50 µg/kg bw/day are not likely to induce emesis” (162). This suggests that JECFA has established an ARfD that affords at least a five-fold margin of safety.

The 2006 WHO Global Environment Monitoring System/Food Contamination Monitoring and Assessment Programme (GEMS/Food) identified food consumption patterns for 13 regional clusters (164). The regions likely to contribute most to DON exposure from different grains for the global population are represented by clusters B and E (Table 5). Using this information, the proposed MLs for unprocessed raw wheat, maize, and barley were calculated. Based on the predicted consumption of unprocessed raw grains, the calculated MLs that would adequately protect health based on worst-case scenario assumptions were 43, 4, and 11 mg/kg for wheat, maize, and barley, respectively (details provided in Tables 5 and 7). The unprocessed raw grain consumption assumptions removed contributions from primarily flour.

The WHO GEMS/Food cluster diets were updated in 2012 (165). The 2012 update employed a new approach to assess diets and consumption patterns, reorganizing the regional dietary consumption patterns into 17 clusters (Table 6). MLs for consumption of unprocessed raw wheat, maize, and barley that adequately protect health can be recalculated using the new GEMS database information. These are based on worst-case scenario assumptions (removing contributions primarily from flour). Based on the predicted consumption of unprocessed raw grains, calculated MLs were 21, 19, and 9 mg/kg for wheat, maize, and barley, respectively (details provided in Tables 6 and 7).

In summary, understanding the differences in consumption patterns across regional clusters of different unprocessed raw grains intended for sale and for direct human consumption is necessary to determine appropriate MLs for these grains. It is assumed that these grains will not undergo further processing. Additionally, contributions from different grains (durum wheat, soft wheat, maize, and barley), whether unprocessed raw, semi-processed, or processed, to the overall consumption of grain-based products should be tallied. This would allow for an accurate assessment of appropriate MLs for various grains at each stage of the harvesting and milling continuum. Furthermore, MLs proposed should correspond to the point at which the grains are analyzed and sampled for DON. This would ensure consistency of the reporting basis between MLs and the occurrence data. The point of sampling and analysis varies from country to country. For example, in the United Kingdom the sampling is a mixture of point-of-sale data and harvest data. To compare data and provide consensus on appropriate MLs, the international community must first attain consensus on stages of the harvesting and milling continuum at which sampling and analysis should be done.

### Table 5. Grain consumption rates (g/day) derived from the 2006 WHO Global Environment Monitoring System (GEMS) cluster diets

<table>
<thead>
<tr>
<th>GEMS CODE</th>
<th>CEREALES</th>
<th>CLUSTER B*</th>
<th>CLUSTER E**</th>
</tr>
</thead>
<tbody>
<tr>
<td>GC 654 WHEAT</td>
<td>TOTAL WHEAT</td>
<td>396.3</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>Wheat germ</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>Wheat bulgar wholmeal</td>
<td>10.2</td>
<td>10.2</td>
</tr>
<tr>
<td></td>
<td>Wheat flour</td>
<td>296.3</td>
<td>296.3</td>
</tr>
<tr>
<td>GC 645 MAIZE</td>
<td>TOTAL MAIZE</td>
<td>148.4</td>
<td>15.4</td>
</tr>
<tr>
<td></td>
<td>Maize flour</td>
<td>15.4</td>
<td>15.4</td>
</tr>
<tr>
<td></td>
<td>Germ maize</td>
<td>8.9</td>
<td>8.9</td>
</tr>
<tr>
<td>GC 640 BARLEY</td>
<td>TOTAL BARLEY</td>
<td>48.6</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>Pot barley</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>Barley, pearled</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Barley flour and grits</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

* Cluster B regions include Cyprus, Greece, Israel, Italy, Lebanon, Portugal, Spain, Turkey, United Arab Emirates.
** Cluster E regions include Austria, Belgium, Croatia, Czech Republic, Denmark, France, Germany, Hungary, Ireland, Luxembourg, Malta, Netherlands, Poland, Slovakia, Slovenia, Switzerland, United Kingdom, Northern Ireland.
FAO/Stat assigned conversion factors for the various subcategories to calculate total consumption.

### Table 6. Grain consumption rates (g/day) derived from the 2012 WHO Global Environment Monitoring System (GEMS) cluster diets

<table>
<thead>
<tr>
<th>GEMS CODE</th>
<th>CEREALES</th>
<th>CLUSTER G7*</th>
<th>CLUSTER G8**</th>
<th>CLUSTER G10***</th>
</tr>
</thead>
<tbody>
<tr>
<td>GC 654 WHEAT</td>
<td>TOTAL WHEAT</td>
<td>253.07</td>
<td>182.62</td>
<td>15.17</td>
</tr>
<tr>
<td></td>
<td>Wheat flour</td>
<td>182.62</td>
<td>182.62</td>
<td>15.17</td>
</tr>
<tr>
<td>GC 645 MAIZE</td>
<td>TOTAL MAIZE</td>
<td>39.99</td>
<td>39.99</td>
<td>3.33</td>
</tr>
<tr>
<td>GC 640 BARLEY</td>
<td>TOTAL BARLEY</td>
<td>53.45</td>
<td>2.48</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>Barley, pearled (include pot)</td>
<td>2.48</td>
<td>2.48</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>Barley flour and grits</td>
<td>0.33</td>
<td>0.33</td>
<td>0.33</td>
</tr>
</tbody>
</table>

* Cluster G7 regions include Australia, Bermuda, Finland, France, Iceland, Luxembourg, Norway, Switzerland, United Kingdom, and Uruguay.
** Cluster G8 regions include Austria, Germany, Poland, and Spain.
*** Cluster G10 regions include Belarus, Bulgaria, Canada, Croatia, Cyprus, Estonia, Italy, Japan, Latvia, Malta, New Zealand, Republic of Korea, Russian Federation, and United States of America. FAO/Stat assigned conversion factors for the various subcategories to calculate total consumption.

### Table 7. Comparison between corrected maximum levels (MLs) from 2006 WHO Global Environment Monitoring System/Food Contamination Monitoring and Assessment Programme (GEMS/Food) consumption data, 2012 WHO GEMS/Food consumption data, and proposed MLs in the Codex Committee on Contaminants in Foods (CX/CF) 12/6/9 (166)

<table>
<thead>
<tr>
<th>RAW GRAIN (HIGHEST EXPOSURE CLUSTER DIET FROM GEMS/FOOD 2006)</th>
<th>CORRECTED PROPOSED ML BASED ON PREDICTED RAW GRAIN CONSUMPTION FROM 2006 GEMS/FOOD DATA (mg/kg)</th>
<th>CORRECTED PROPOSED ML BASED ON PREDICTED RAW GRAIN CONSUMPTION FROM 2012 GEMS/FOOD DATA (mg/kg)</th>
<th>PROPOSED ML BASED ON TOTAL GRAIN CONSUMPTION AS REFLECTED IN CX/CF 12/6/9 (mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WHEAT</td>
<td>43.2</td>
<td>20.9</td>
<td>1.1</td>
</tr>
<tr>
<td>MAIZE</td>
<td>3.7</td>
<td>19.2</td>
<td>3.2</td>
</tr>
<tr>
<td>BARLEY</td>
<td>10.6</td>
<td>9.0</td>
<td>9.9</td>
</tr>
</tbody>
</table>

Method for Estimating Intake of Unprocessed Raw Grains

Total grain consumption is not an appropriate substitute for unprocessed raw grain consumption when used to establish an ML for DON in unprocessed raw grains intended for direct human consumption. This assumption can result in an overestimation of the actual unprocessed raw...
grains consumed and would generate an unrealistically low ML that would not provide additional public health benefits.

To eliminate the inherent uncertainties associated with the GEMS/Food data relative to the amount of unprocessed raw grains actually consumed globally, it may be prudent to seek actual unprocessed raw grain (specifically durum wheat, soft wheat, maize, and barley) consumption data from impacted nations to serve as the basis for the proposed ML. Risk management decisions should be based on the most appropriate data when specifying proposed mitigation measures for DON contamination of unprocessed raw grains intended for direct human consumption.

It is an internationally accepted principle that MLs for DON in unprocessed raw grain should be set at levels that are as low as reasonably achievable (167) and that MLs should be adequately protective of health, yet also practically achievable so trade disruptions do not occur or are minimized to the extent possible.

Aggregate Impact of DON on North American Food Grains

The long-term prospective impacts of imposing limits or further regulations regarding DON would affect growers, millers, food processors, traders, handlers, and ultimately consumers. Currently the USA domestic industry conforms to advisory limits. Other countries have limits on unprocessed raw and/or processed grains. Proposals have been made that would change these limits to be more restrictive, particularly for unprocessed raw grains. If adopted, this would impact the entire value chain, which could result in escalated costs, reduced exports, expanded use of wheat as feed within North America, increased testing and segregation costs, and growers inevitably further switching away from wheat and other affected grains in regions that are vulnerable to or at higher risk for excessive DON levels.

The presence of DON has major implications for the entire supply chain of affected grains, including both for domestic processors of grain-based products and for exporters and importers. The presence of FHB in North America and the resultant incidence of DON raise costs and risks for growers, inducing them to use more costly management practices and/or shift to other crops. In addition, it raises the cost of developing new cultivars, since all lines of germplasm must be screened for Fusarium resistance regardless of other traits being pursued. The presence of DON also reduces the quantity of vulnerable crops produced, raises production costs, and increases premiums for wheat and other grains at risk for DON contamination. This leads to higher overall costs and risks and more complicated logistics for domestic processors and importers, and, finally, it raises the costs of breeding. All of these effects would be exacerbated by proposals to measure and limit DON on unprocessed raw materials instead of products.

Earlier studies by Johnson et al. (168) and Nganje et al. (169–171) have estimated the value of economic losses due to DON to the USA industry. Johnson et al. (168) estimated production and price effects for HRS wheat, durum, and soft red winter (SRW) wheat from 1993 to 1997. They estimated relationships for yield as a function of rainfall, temperature, and trend. To proportion losses due to FHB and determine yields without FHB, they utilized the difference between the forecasted yields and actual yields, together with expert opinion. Acreage adjustments were included to compensate for higher acreage abandonment in FHB outbreaks. Price effects were evaluated as the production shortfall impact on market prices and the effect of crop quality premiums and discounts. The economic impact of production losses ranged from 3.6 million tonnes in 1993 to a low of 1.7 million tonnes in 1996. Price effects due to production shortfalls resulted in higher prices than would have occurred without FHB outbreaks. Combining the two effects reduced the total impact of FHB. The largest production effect occurred in 1993; however, when considering both price and production effects, the largest losses occurred for all classes in 1995, due mostly to the large negative price effects on SRW wheat. For HRS wheat, the year with the largest loss was 1994 at $245 million.

Nganje et al. (169) updated the results from Johnson et al. (168) to cover the years 1998–2000 and expanded the analysis to include malting barley. Nganje et al. (169, 170) used generated losses attributable to FHB to estimate direct and secondary yield losses that were then utilized within an input–output model of the economy to project direct and secondary economic impacts on the larger economy. Direct economic losses in the USA were estimated at $870 million from 1998 to 2000.

More recent estimates of outbreaks have tended to focus on yield losses and the extent of coverage of FHB outbreaks. Cowger and Sutton (172) estimated the impacts of the 2003 SRW wheat outbreak. They interviewed researchers, extension specialists, extension agents, millers, and growers in the southeastern USA for opinions on the 2003 infestations. Lilleboe (173,174) summarized the effects of FHB in 2010 and 2011 across states and crops for the USA. McMullen et al. (81) summarized past studies on the economic estimates of FHB outbreaks and the degree and location of FHB outbreaks by class of wheat since 1991.

Grower Risks and Responses to the Incidence of FHB

One of the fundamental impacts of FHB on growers is that it increases risks, raises costs, and ultimately increases the propensity for growers to switch to other crops with less risk and/or an increase in the risk premiums for growing these crops.

FHB Risks

There are two notable risks related to FHB for growers. One is the incidence of FHB during production, which reduces yields and damages kernels, potentially to the point of being unmerchantable. Some crops are more susceptible to Fusarium infection and DON production due to factors such as variety, growing regions, and weather variations from year to year. Soft wheat varieties, especially soft white winter (SWW) wheat, when grown in temperate regions like eastern and midwestern areas of the USA and eastern Canada are vulnerable to DON production. This is a result of the higher frequent rainfall coupled with warm temperatures that are typical for these areas, in addition to the emerging growth of other crops (i.e., maize) in these regions. This corroborates discussions presented in previous sections concerning regional vulnerability to DON production throughout North America and elsewhere. While published data for maize are more limited for North America, the presence of DON has been demonstrated. Variability in occurrence of FHB also is seen from year to year. For example, in 1996 the SWW wheat crop in Ontario and the eastern USA was dramatically affected by FHB, cutting yields by a third, with much of the crop unusable for human consumption. HRS wheat and durum crops were severely impacted in 1993, followed by several other years, including 1998–2010 and 2014 (81).

The other critical risk related to FHB is price discounts, or more specifically, postharvest price discounts. These discounts
are encountered in numerous forms. The most common current forms are simply rejecting the product, reclassifying it to a lower grade/class, or applying price discounts. The former two have obvious, although random, price adjustments. Table 8 shows discounts that were applied in 2014 for *Fusarium*-damaged kernels (FDK or scab) for a representative country elevator in North Dakota for HRS wheat. At the time these discounts were applied, wheat prices were $6/bu ($220/tonne). As an example, a discount of $1 is about 17% of the price of the crop or a loss of $40/acre ($99/ha), which is sufficient to shift plantings to other crops.

Currently, it is common to either test a sample of the grain analytically at internal labs, send it to a grain inspection service for a certified test, or require growers to provide a certificate of a test result prior to unloading the grain. Similar procedures are used at export elevators. The presence of FDK results in financial losses to growers due to the penalties or reclassifications of wheat lots, as shown in Table 8. If the levels exceed grading standards or contractual obligations, excessive FDK levels can rise to the point of a total crop loss for a grower.

### Farm Management Practices and Costs

As described earlier, growers now have a number of farm management practices that can be adopted with the goal of mitigating some of the risks of DON. These include, but are not limited to, crop choices, choices among improved varieties regarding DON resistance, agronomic practices including crop rotation, application of fungicides, etc. Farm management practices to control DON were analyzed recently by McGee et al. (175) and are presented in Figure 12. As discussed earlier, fungicides are particularly important and, in response to the 1996 crop failure, were registered in Canada for mitigating FHB in soft wheat starting in 1999. In addition, varying forecasting tools now exist. DONcast is one modeling tool that has been available to growers in Ontario since 2000; other similar models are available in Canada (118) and the USA production regions (119,176,177).

To understand the quantitative impacts of these on farm management decisions, Wilson and Dahl (178) quantified the riskiness of alternative grains in North Dakota. These include not only price risks but also risks related to yield, quality rejection, and post-harvest quality discounts. These results illustrate the riskiness of HRS and durum wheat relative to competing crops.

### Switching to Competing Less Risky Crops

DON has resulted in growers shifting production to less risky crops/crop rotations. Changes in cropping patterns have been influenced by many factors, includ-

---

**Table 8. Example of wheat discounts for *Fusarium*-damaged wheat kernels (FDK) at a representative primary elevator in North Dakota**

<table>
<thead>
<tr>
<th>%FDK PRESENT (PINK KERNELS)</th>
<th>FINANCIAL PENALTY (CENTS PER BUSHEL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 – 2.0%</td>
<td>0</td>
</tr>
<tr>
<td>2.1 – 2.5%</td>
<td>-20</td>
</tr>
<tr>
<td>2.6 – 3.0%</td>
<td>-40</td>
</tr>
<tr>
<td>3.1 – 3.5%</td>
<td>-60</td>
</tr>
<tr>
<td>3.6 – 4.0%</td>
<td>-80</td>
</tr>
<tr>
<td>4.1 – 4.5%</td>
<td>-100</td>
</tr>
<tr>
<td>4.6 – 5.0%</td>
<td>-120</td>
</tr>
<tr>
<td>Over 5%</td>
<td>Please call before delivery</td>
</tr>
</tbody>
</table>

Any grain that is sample grade is subject to rejection. Call for pricing.

<table>
<thead>
<tr>
<th>Country</th>
<th>DON LIMIT (mg/kg)</th>
<th>DON LIMIT (mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOLIVIA</td>
<td>2</td>
<td>JAPAN*</td>
</tr>
<tr>
<td>CANADA*</td>
<td>2.0 (&quot;under review&quot;)</td>
<td>JAMAICA</td>
</tr>
<tr>
<td>BRAZIL</td>
<td>2</td>
<td>JORDAN</td>
</tr>
<tr>
<td>CHILE</td>
<td>2</td>
<td>MALAYSIA</td>
</tr>
<tr>
<td>CHINA*</td>
<td>1</td>
<td>MEXICO</td>
</tr>
<tr>
<td>COLOMBIA*</td>
<td>1.25; 2 in contracts</td>
<td>NICARAGUA</td>
</tr>
<tr>
<td>COSTA RICA</td>
<td>2</td>
<td>NIGERIA</td>
</tr>
<tr>
<td>DOMINICAN REPUBLIC</td>
<td>2</td>
<td>PAKISTAN</td>
</tr>
<tr>
<td>ECUADOR</td>
<td>2</td>
<td>PANAMA</td>
</tr>
<tr>
<td>EGYPT*</td>
<td>1.25; 2 in some contracts</td>
<td>PERU</td>
</tr>
<tr>
<td>EL SALVADOR</td>
<td>2</td>
<td>PHILIPPINES</td>
</tr>
<tr>
<td>EUROPEAN UNION*</td>
<td>1.25 common wheat; 1.75 durum</td>
<td>RUSSIA*</td>
</tr>
<tr>
<td>GUATEMALA</td>
<td>2</td>
<td>SINGAPORE</td>
</tr>
<tr>
<td>HAITI</td>
<td>2</td>
<td>SOUTH KOREA*</td>
</tr>
<tr>
<td>HONDURAS</td>
<td>2</td>
<td>TAIWAN</td>
</tr>
<tr>
<td>INDONESIA</td>
<td>2</td>
<td>THAILAND</td>
</tr>
<tr>
<td>INDIA*</td>
<td>1</td>
<td>TRINIDAD-TOBAGO</td>
</tr>
<tr>
<td>IRAQ</td>
<td>2</td>
<td>VIETNAM</td>
</tr>
<tr>
<td>ISRAEL*</td>
<td>1</td>
<td>VENEZUELA</td>
</tr>
</tbody>
</table>

* Government regulation

The supply chain for these grains was described earlier. It is important to note that the supply chain has adapted to the incidence of DON and efficiently and effectively manages its impact. However, these adaptations have a cost, do not eliminate DON completely, and have the effect of reducing the product stream.

As grain moves along the supply chain (Fig. 1), its quality is improved by the application of several management strategies, including segregation, blending, and cleaning (183–185). These strategies allow not only for the improvement of the quality of the grain, but also its safety by managing the presence of DON. This management, including the monitoring of grain for DON along the handling chain, requires resources for proper sampling, analytical testing, and interpretation of test results. These activities add time, as well as cost, to the handling of grain.

At the mill level (or point of first processing), the incidence of DON is also managed. The most effective way (Fig. 15) is to remove Fusarium-damaged kernels from the unprocessed raw grain during the initial sorting and cleaning steps prior to milling. Cleaning and scouring of wheat prior to milling reduces DON content, and the milling industry also uses optical sorters that can effectively reduce DON content.

Further processors of grains such as mills and food manufacturers specify thresholds for DON as a primary means of ensuring finished goods as consumed will meet the <1 mg/kg advisory level set by the US-FDA. DON level mitigation can be achieved through careful selection of lots of grain; blending, cleaning, and sorting; removal of the husk, hull, and bran layers; and dilution with other ingredients in a processed food. DON levels are not reduced through washing or cooking.

Processors such as bakers or breakfast cereal manufacturers have few tools available to reduce DON levels. This is particularly problematic for products that contain whole grain and whose primary component is a grain such as soft wheat. Whole grain crackers and cereals are examples of products for which ingredient dilution and bran removal are not available options. For these processors, the primary tool available is the inclusion of DON limits in contractual agreements. For primarily whole grain products to be sold in Canada or the USA, contracts limit DON to <1 mg/kg. For products destined for Europe, contracts will often set the thresholds for DON at 0.5 mg/kg. To illustrate, a list of countries and their contract limits on DON in wheat is provided in Table 9. It is clear from this list, that importers can effectively limit their DON content.
content through maximum specifications. It is worth mentioning, however, that some grain suppliers are reluctant to contract based on DON levels given that analytical tests add cost and delivery delays. Some handlers have been slow to adopt quantitative DON testing.

Some further processors of grains, especially small- and medium-sized enterprises, that have less leverage at the grower level maintain that a ML set on grains could enhance market pressures for growers to expand the use of tools such as fungicides. Others argue that sufficient safeguards are already in place, which is evidenced by targeted surveys of foods at the retail level that show a very high compliance level for achieving DON levels of <1 mg/kg in the finished food. Both parties agree, however, that setting any limit for DON on unprocessed raw grain would be highly problematic for North America given the vastly different agronomic practices from those in Europe, such as farm size, transport, and storage, in addition to differences in climate and farm support payments.

Prospective Impacts of Establishing International MLs for DON in Unprocessed Raw Grain on Supply Chain and Marketing Practices

Currently, MLs in the USA are applied on semiprocessed grains. However, some countries would like MLs to be applied to unprocessed raw grains, which could detect affected grain prior to entering the primary elevators. The latter would be more costly and restrictive.

There are different points in the supply chain (Fig. 1) at which MLs could be applied, including at the farm, at the point of entry into the marketing system (i.e., the primary elevator), at terminals, at the points of first processing, or on finished products. Due to the density of transactions and costs of executing such a program, it would seem most practical that these regulations or standards would be evaluated at mills. This is a point with fewer locations and would likely be the most cost-effective. For these reasons, the direct impacts of establishing MLs on DON would be on domestic mills, while there would be indirect impacts on growers and exports and imports (discussed below).

In response to this proposed regulation, domestic mills would seek to purchase wheat with greater assurance of conformance to the MLs and/or add preprocessing functions to assure meeting MLs for DON. This could include a number of strategies: sourcing wheat from production regions that typically experience lower incidence of Fusarium and lower DON levels (where possible); imposing stricter limits on wheat and/or larger discounts for excessive DON; requiring more extensive cleaning prior to shipment from the elevator; and segregation, testing, and cleaning at the mill to assure ML conformance.

Ultimately, this would add costs to both purchasing and processing. These added costs would vary through time and geographically. In-mill costs of cleaning, scouring, added storage, etc. would also vary through time but, nevertheless, would be a real added cost to the milling sector. Since such MLs currently are not applied to unprocessed raw grains, major processors have not yet quantified the costs associated with such proposed regulations. To do so would require detailed simulation modeling of these functions and risks. Ultimately, these costs would vary by location and be determined by logistics and the mill’s capability for segregation and cleaning.

As previously discussed, growers currently seek to control DON through crop rotation strategies, adoption of improved cultivars, and use of fungicides and optimal spray technology at flowering. Tighter MLs on DON would have the following impacts: more intensive management, including variety selection and fungicide use, all of which will add costs; larger discounts for excessive DON; and greater risk for wheat and other crops grown with excessive DON, leading to a shift to other crops with less risk or greater returns. These impacts would vary geographically and through time. It is important to note that as the risk associated with wheat production increases and concurrently competing crops become more viable and profitable there would be a move away from production of wheat and other affected crops in the USA, Canada, and elsewhere. This likely would reduce supplies and increase prices to all consumers.

Importers of grains, at least from North America, also have tools available for controlling DON content. In concept these are similar to those of domestic mills and include primarily contract limits for DON content. Additionally, these can include targeting locations, ports, and suppliers that have the ability to reduce DON content in years when it is problematic. This is most commonly accomplished by targeting origins and cleaning at the country and export elevator (183,184) prior to shipment, ultimately to meet specifications set by importers. It is clear from these strategies, that importers can effectively limit their DON content through contract limits. Of course, tighter controls would accrue greater costs due to testing and potential rejections. Meeting these specifications could impact the available supply of wheat.

Finally, importers would also be impacted indirectly. If stricter MLs are imposed, the strategy of domestic mills in grain-exporting countries would change and could reduce (slightly) the available supply of DON-compliant wheat to the export market. For this reason, there would be a minor component of crops with unacceptable (even if precautionary) DON levels that would be channeled elsewhere in the market system. This would include the export market or markets for nonfood uses. For importers, this could increase the risks of receiving shipments containing DON at unacceptable concentrations and, as a result, would require more scrutiny of contract limits and price differentials. The response would be to increase the intensity of cleaning and targeting of origins for grain prior to exporting, which also would affect costs.

Final Remarks

In agricultural commodities, the occurrence of DON has been reported all over the world, with levels varying among grain types and years of production. The grain supply chain, including growers, buyers, and end users, has effectively managed DON with strategies to control this issue systematically. The safety of consumers is ensured with use of these management strategies.

Based on the information reviewed and introduced in this report, the occurrence of DON in North America does not appear to be different than that reported around the world. Sporadically, levels of DON in grains (wheat, maize, and barley) can be much higher than usual in certain years due to more severe Fusarium infection. Cool and wet conditions during specific developmental stages of grains (e.g., wheat flowering) promote Fusarium infection, although wet conditions at harvest can lead to secondary Fusarium infection and DON production as well. Other factors influencing the levels of
DON in agricultural crops include the growing region and its climate, in addition to wheat class. As discussed in the report, management of FHB and consequently DON in grains is a complex problem with numerous component methods available. Each method, such as crop rotation, tillage, cultivar resistance, fungicides, biological control agents, and optimized spray technologies, provides some benefit, but using multiple approaches is the most efficient way for growers to manage this problem.

As far as the levels of DON found at different stages of the grain-handling chain, the data presented suggest that as grain moves along the chain, its quality is improved by the application of management strategies such as blending, cleaning, and selecting. These strategies allow not only for the improvement of the quality of the grain, but also for the safeguarding of its safety, by managing the presence of DON. Indeed, numerous studies with the major grains, including wheat, maize, and oats, have shown that DON in whole grains is mainly redistributed during processing into the bran and germ fractions rather than the endosperm. The flour fraction (from the endosperm) destined for human consumption typically contains DON levels that are 10–20 times lower than those observed in the bran or germ fractions, which are mostly used for animal feed. The technology or equipment used in the mill affects the recovery and segregation of DON in each fraction. Therefore, it would be plausible to adopt different standards or regulatory limits for different milled fractions of grains instead of applying a single level for the whole grain. That is, if action levels are to be endorsed, they should be endorsed for 1) flour and other milling fractions intended for direct human consumption; and 2) bran, germ, and other fractions intended for feeding to various animal populations.

MLs should be adequately protective of health yet also practically achievable so that trade disruptions do not occur. Since unprocessed raw grains are not typically consumed in that form and contribute minimally to dietary exposure from the finished food product (after processing), setting MLs for unprocessed raw grain would not significantly change health outcomes.

In the grain supply chain, current practices for managing risks of excessive DON content in grain include 1) targeting locations with less incidence of DON; 2) including contract limits and discounts for excessive DON; 3) segregating wheat in storage; 4) selectively testing and/or cleaning to assure contract performance; and 5) where appropriate, use of cleaning and/or scouring to remove kernels with excessive DON content. Through these processes, North American domestic mills effectively and efficiently control the incidence of excessive DON in their products. Any additional restrictions would increase costs and risks to mills not only in North America but also globally.

More restrictive interventions on DON content would have numerous impacts. It is important to note that there would be increased costs and risks related to executing any further restrictions. A more strict management, including the monitoring of grain along the handling chain for DON, would require resources for proper sampling and analytical testing, lead to an increase in risks to growers, and cause changes at the processor level that also would impact grain to be exported. All of these effects would add costs to the grain-handling chain. Additionally, improvements in management of DON at the farm, elevator, and processor levels have shown that any regulatory limits would more efficiently safeguard public health if applied to the finished product rather than to unprocessed raw grains.

Acknowledgments
Juan Carlos Batista (SENASA, Argentina); Benedict Deeholts (Buhler Sortex Limited, UK); Wiana Louw (SAGL, Southern African Grain Laboratory NPC, South Africa); Rodrigo Mendoza (University of Nebraska – Lincoln, NE, USA); Donald Mennel (Mennel Milling Company, Fostoria, OH, USA); National Grain and Feed Association (Washington, DC, USA); Terry Nelsen (AACCI Statistician, USA); North American Export Grain Association (Washington, DC, USA); North American Millers Association; Lauren Robin (FDA/CFSAN, USA); Luis Eduardo Sabillon (University of Nebraska – Lincoln, NE, USA); Paul Schwarz (North Dakota State University, ND, USA); U.S. Grains Council (Washington, DC, USA); U.S. Wheat Associates (Arlington, VA, USA); Felicia Wu (Michigan State University, MI, USA). Data were provided by Viteera Inc., Pioneer Grain Company Operations, and Richardson International Corporate Quality Assurance and Food Safety.

References


Larsen, J. C., Hunt, J., Perrin, I., and Ruckenbauer, P. Workshop on tricho-


71. Puri, K. D., and Zhong, S. The 3ADON population of Fusarium graminearum found in North Dakota is more aggressive and produces a higher level of DON than the prevalent 15ADON population in spring wheat. Phytopathology 100:1007, 2010.


118. Weather INnovations. Weather Central. Published online at www.weathercentral.ca. Weather INnovations, Chatham, ON, Canada, 2014.


164. WHO Global Environment Monitoring System (GEMS). GEMS 2006 Cluster Diets Database (www.who.int/foodsafety/chem/ClusterDietsAug06.xls); WHO Country Assignments to the 13 Proposed GEMS/Food Consumption Cluster Diets


