Fusarium graminearum

(Fusarium Head Blight)

T. Kelly Turkington[1], Andrew Petran[2], Tania Yonow[3,4], and Darren J. Kriticos[3,4]

[1] Lacombe Research Centre and Beaverlodge Research Farm, Agriculture and Agri-Food Canada, Lacombe, Alberta, Canada
[2] Department of Horticultural Sciences, University of Minnesota, St. Paul, MN, USA
[3] HarvestChoice, InSTePP, University of Minnesota, St. Paul, MN, USA
[4] CSIRO, Biosecurity and Agriculture Flagships, Canberra, Australia

Background Information

Common Names:
Fusarium head blight; FHB, head blight of maize

Scientific Name:
Fusarium graminearum (anamorph = asexual stage),
Gibberella zeae (teleomorph = sexual stage)

Synonyms:
Botryosphaeria saubinetii, Dichomera saubinetii, Dothidea zeae, Fusarium roseum, Gibbera saubinetii, Gibberella roseum, Gibberella saubinetii, Sphaeria saubinetii, Sphaeria zeae

Taxonomy:
Kingdom: Animalia; Phylum: Ascomycota;
Class: Sordariomycetes; Order: Hypocreales;
Family: Nectriaceae

Crop Hosts:
Wheat (*Triticum* spp. L.), barley (*Hordeum vulgare* L.), oat (*Avena sativa*), maize (*Zea mays*), triticale (x *Triticosecale*)

Figure 1. Typical signs of *Fusarium graminearum* on wheat. Photograph from USDA ARS, http://www.ars.usda.gov/Main/docs.htm?docid=9756.

Introduction

Fusarium graminearum Schwabe [teleomorph *Gibberella zeae* (Schweinitz) Petch], is of world-wide importance on small grain cereals and corn, occurring under a wide range of soil and environmental conditions (CAB International 2003; Gilchrist and Dubin 2002; Parry et al. 1995; Stack 2003). Since the early 1990s, fusarium head blight (FHB) caused primarily by *F. graminearum* has become one of the most significant cereal diseases faced by producers in central Canada and the prairie region, and the midwestern United States (e.g., Gilbert and Tekauz 2000; McMullen et al. 1997b; Tekauz et al. 2000). *Fusarium graminearum* was identified by CIMMYT to be a major limiting factor to wheat production in many parts of the world (Stack 1999). The fungus can produce several mycotoxins, including deoxynivalenol (DON) and zearalenone. In non-ruminants, feed contaminated with DON can reduce growth rates, while zearalenone can cause reproductive problems (Charmley et al. 1996; D'Mello et al. 1999). Barley (*Hordeum vulgare* L. emend. Bowden) infected with *F. graminearum* and contaminated with mycotoxins can also cause quality problems for the malting and brewing industries (Schwarz 2003). *Fusarium graminearum* has also been linked to human illnesses (Goswami and Kistler 2004).

Fusarium graminearum is a genetically diverse species, with eleven distinct lineages currently known as the FG complex (Qu et al. 2008). There is little gene flow within these lineages, and all are well suited to infect their hosts in warm and wet climates (O'Donnell et al. 2000; Hope et al. 2005). According to Qu et al. (2008) one lineage in China can begin infection below 15 °C, and all lineages can overwinter on crop debris in any climate wheat is grown. This leaves high risk of continual infection, especially with rotations of less than two years between host crops.

Environmental conditions, especially temperature and moisture, are the key factors influencing the distribution and severity of fusarium head blight caused by *F. graminearum* (Shaner 2003; Stack 1999; Sutton 1982; Xu 2003). Moisture appears to be the most important environmental factor influencing the severity of infection caused by *F. graminearum* in small grain cereals, given

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that fusarium head blight development can occur at temperatures that range from approximately 9 °C to 30 °C (Anon. 2011; de Wolf et al. 2003; McMullen et al. 1997a; Shaner 2003; Stack 1999).

Known Distribution

Fusarium graminearum has been reported wherever wheat is grown (Sutton 1982; CAB International 2003; Goswami and Kistler 2004), and infection has reached epidemic proportions in the United States over the last decade (O'Donnell et al. 2000). In South America, *F. graminearum* persists in southern Brazil and northern Argentina, while in Africa it plagues eastern South Africa and countries along the south coast of the Mediterranean (Wang et al. 2011). *Fusarium graminearum* persists within all of central Europe and southwestern Russia, and infects wheat fields grown along the eastern coast of China, and further inland where irrigation is used (Hope 2005; Qu et. al, 2008). In North America, increased levels of *Fusarium* head blight and percentage seed infection with *F. graminearum* have been associated with wheat under irrigation compared with dryland production (Clear and Patrick 2010; Strausbaugh and Maloy 1986; Turkington et al. 2005).

Description and Biology

Airborne ascospores produced by *G. zeae*, the sexual stage of *F. graminearum*, fall on flowering spikelets of wheat, germinate and enter the plant through natural openings, such as degrading anther tissue or stomates (Bushnell et al. 2003; Trail 2009). The fungus then grows, spreading through the xylem and pith of the wheat. As colonization continues, tissue becomes bleached and necrosis occurs (Figure 1).

Following infection, the fungus expresses genes for mycotoxin production, including DON, which causes shriveled, undersized grains known as tombstones (Trail 2009).

Fusarium graminearum has both sexual and asexual lifecycles (Figure 2) (Mathre 1997; Parry et al. 1995). Sexual reproduction takes about two weeks, and since *F. graminearum* is homothallic, it does not need two parents. Meiosis produces ascospores, which are forcibly discharged into the air through flask-shaped perithecia. Asexual conidia are produced during especially wet periods, and are moved via rain-splash dispersal. Conidia also overwinter on crop residues.

Host Crops and Other Plants

Fusarium graminearum affects many cereal crops. The main host crops are wheat (*Triticum* spp.), and barley (*Hordeum* spp.); however, rye (*Secale cereale*) and triticale (*X Triticosecale*) can also be affected (Parry et al. 1995). *Fusarium graminearum* causes head blight or 'scab' on rice (*Oryza* spp.), oats (*Avena* spp.) and Gibberella stalk and ear rot disease on maize (*Zea* spp.), and can also infect other plant species without causing

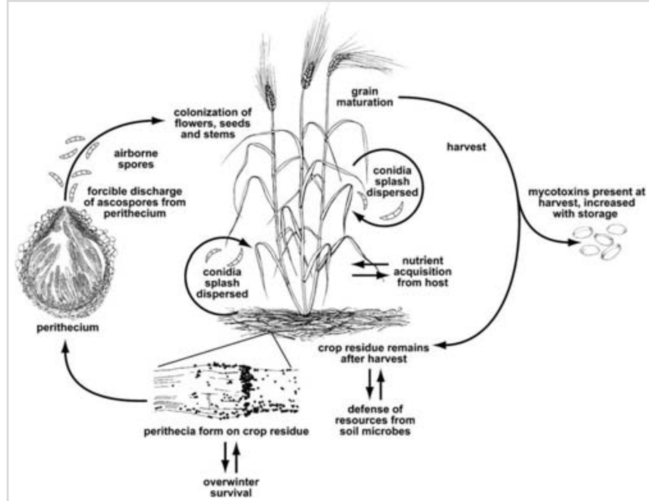

Figure 2. *Fusarium graminearum* life cycle (Trail 2009).

disease symptoms. Other host genera include *Agropyron*, *Agrostis*, *Bromus*, *Calamagrostis*, *Cenchrus*, *Cortaderia*, *Cucumis*, *Echinochloa*, *Glycine*, *Hierochloe*, *Lolium*, *Lycopersicon*, *Medicago*, *Phleum*, *Poa*, *Schizachyrium*, *Secale*, *Setaria*, *Sorghum*, *Spartina*, and *Trifolium* (Farr et al. 1989; Goswami and Kistler 2004).

Potential Distribution

CLIMEX (Sutherst et al. 2007) was used to infer potential distribution and abundance of *F. graminearum* based on knowledge regarding prevailing conditions where the species exists. CLIMEX calculates an Ecoclimatic Index (EI) that describes the suitability of locations for growth and survival. The EI is defined by variables that reflect conditions during the growing season (Growth Index) combined with variables that describe the effect of stress (Stress Index).

Temperature parameters were initially based on published information related to FHB biology (Anderson 1948; Anon. 2011; Clear and Patrick 2010; Doohan et al. 2003; McMullen et al. 1997; Parry et al. 1995; Shaner 2003; Sutton 1982; Xu 2003). Adjustments were made to reflect the known distribution and severity of FHB in the eastern prairies of Canada, especially Manitoba, and Prince Edward Island on the east coast of Canada (Clear and Patrick 2010; Gilbert and Tekauz 2000; Martin and Johnston 1997; Martin and MacLeod 1991; Tekauz et al. 2000).

Moist conditions resulting from high relative humidity, dew, rainfall or irrigation during flowering are critical for head infection (Mathre 1997; Wiese 1987). Much research indicates that high levels of moisture are associated with infections (e.g., Anderson 1948; McMullen et al. 1997a; De Wolf et al. 2003). Overall, adequate periods of either high humidity or surface wetness over successive days are required for FHB epidemics to occur. Soil moisture parameters were fitted iteratively to distribution data on FHB at Manitoba and Prince Edward Island where FHB is an established problem. As suggested pre-

Table 1. CLIMEX Parameter Values for *Fusarium graminearum*

Parameter	Description	Value
Moisture		
SM0	lower soil moisture threshold	0.2
SM1	lower optimum soil moisture	0.45
SM2	upper optimum soil moisture	1.5
SM3	upper soil moisture threshold	2.5
Temperature		
DV0	lower threshold	9 °C
DV1	lower optimum temperature	20 °C
DV2	upper optimum temperature	25 °C
DV3	upper threshold	35 °C
Heat Stress		
TTHS	heat stress temperature threshold	35 °C
THHS	temperature threshold stress accumulation rate	0.005 week^{-1}
Dry Stress		
SMDS	soil moisture dry stress threshold	0.2
HDS	stress accumulation rate	-0.01 week^{-1}
Wet Stress		
SMWS	soil moisture wet stress threshold	2.5
HWS	stress accumulation rate	0.01 week^{-1}
Threshold Annual Heat Sum		
PDD	number of degree-days above DV0 needed to complete one generation	300 °C days
Irrigation Scenario		
	2.5 mm day^{-1} as top-up throughout the year	

viously by Yonow et al. (2004) for *Pyrenophora semeniperda* (Brittlebank and Adam) Shoemaker, the lower soil moisture parameter (SM0) was set to 0.2.

Cold Stress was not used in the model, as *F. graminearum* overwinters in the coldest grain-growing areas. Wet Stress parameters have minimal impact worldwide, although some Wet Stress does accumulate in small areas of Colombia, Sierra Leone, and in parts of Asia. Heat Stress precludes persistence across the globe where temperatures regularly exceed 35 °C. There are areas of limiting Dry Stress on all continents. A PDD value of 300 was set to limit the distribution in Norway, whilst retaining as suitable the areas shown in Lanseth and Elen (1997) and Koziak et al. (2004). The PDD value has minimal impact in the southern hemisphere, only precluding *F. graminearum* from persisting in the coldest areas of the Andes and in Tierra del Fuego. Its impact is greatest in the northern hemisphere, where most of the Arctic Circle and some surrounding areas are made unsuitable.

To verify the model (Table 1) for temperate northern climates, results were compared with independent data for the observed distribution of FHB for northern European countries (Baumgardt et al. 2008; Börjesson 2010; Bottalico 1998; Bottalico and Perrone 2002; CAB International 2003; Elen et al. 1997; Fredlund et al. 2008; Gagkaeva et al. 2004; Henriksen 1999; Hofgaard et al. 2010; Kosiak et al. 1997, 2003, 2004; Langseth and Elen 1996; 1997; Waalwijk et al. 2003; Yli-Mattila et al. 2002, 2008, 2010). The EI values are consistent with the known northern European occurrences of this disease and the projected range is also consistent with distribution data available elsewhere (Fernandes et al. 2004) (Figure 3).

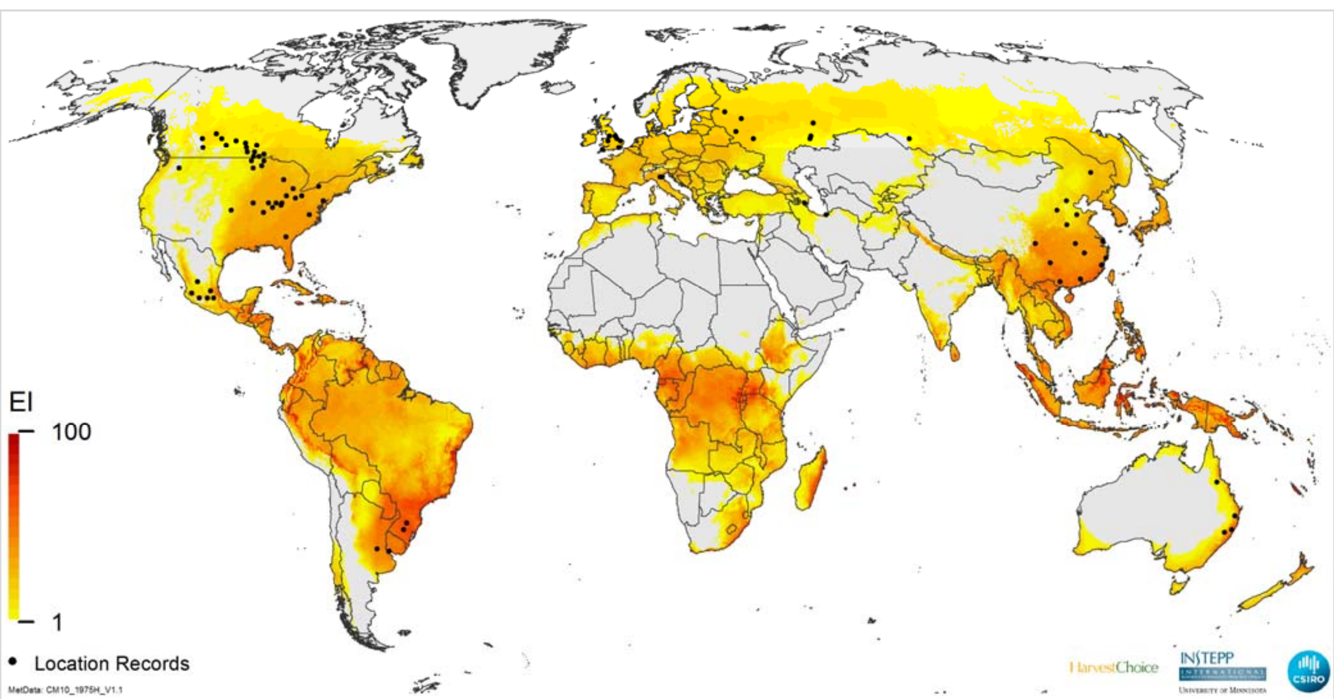

Figure 3. Modelled global climate suitability for *Fusarium graminearum* under dryland production. Location records taken from the Global Biodiversity Information Facility (GBIF).

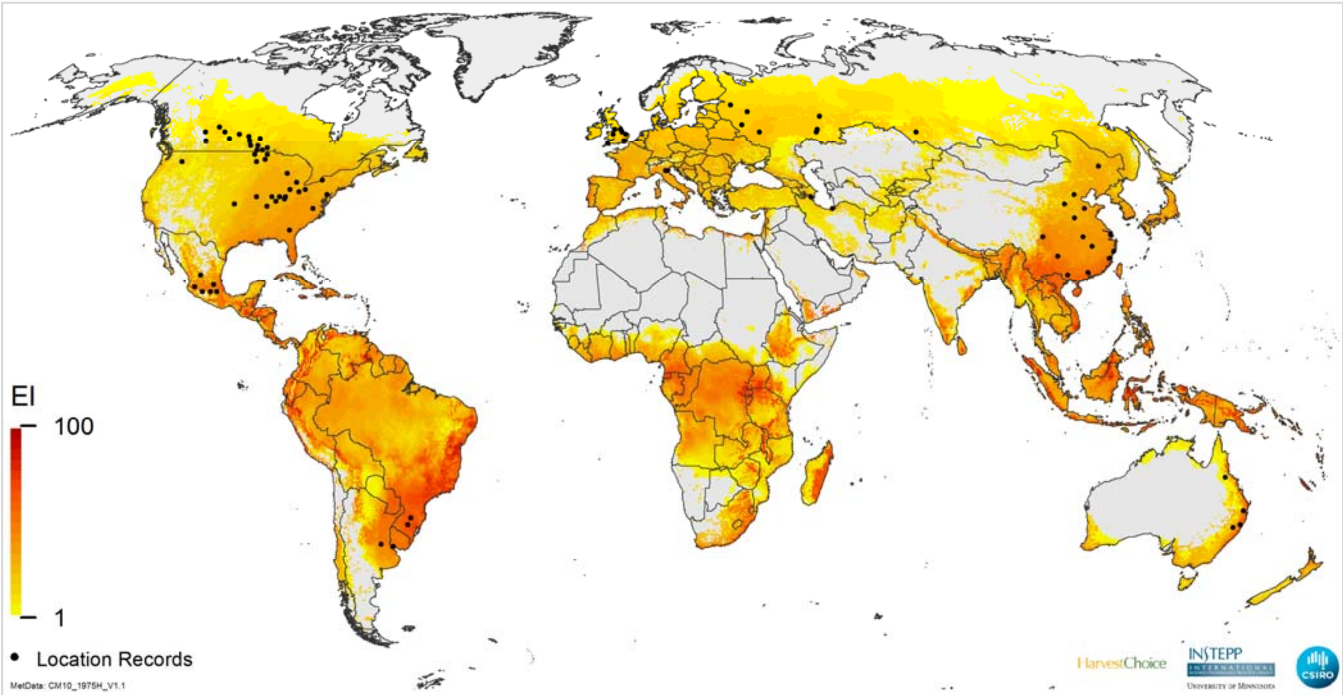

Figure 4. Modelled global climate suitability for *Fusarium graminearum* as a composite of natural rainfall and irrigation based on the irrigation areas identified in Siebert et al. (2005). Location records taken from GBIF.

An irrigation scenario of 2.5 mm day-1 applied as top-up increases both the potential range of *F. graminearum* as well as the suitability of areas already within the modelled range (Figure 4).

Potential Impact in Africa

The projected potential distribution in Africa (Figure 5) matches the known distribution of *F. graminearum*, and indicates areas at climatic risk.

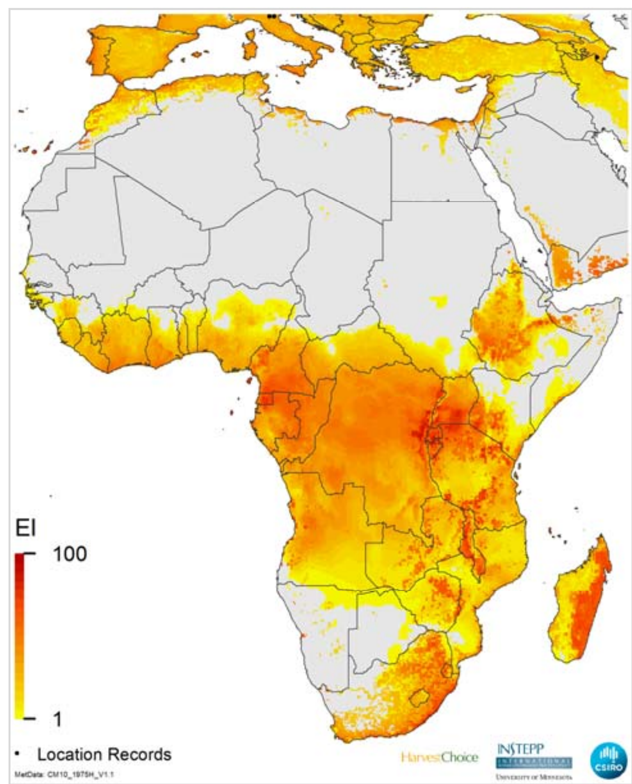

Figure 5. Modelled climate suitability of Africa for *Fusarium graminearum* as a composite of natural rainfall and irrigation based on the irrigation areas identified in Siebert et al. (2005). Location records taken from GBIF.

References

Anderson, A.L. (1948). The development of *Gibberella zeae* head -blight of wheat. *Phytopathology* 38: 599–611.

Anonymous. (2011). The *Fusarium* Head Blight Prediction Center [online]. Penn State University, Ohio State University, Purdue University, North Dakota State University, and South Dakota State University. http://www.wheatscab.psu.edu/ [accessed 28 March 2014].

Baumgardt, M., Grudzinska-Sterno, M., Djurle, A., Yuen, J., and Stenlid, J. (2008). Mycotoxin producing *Fusarium* species in oats during the growing season. *Cereal Research Communications* 36, Suppl. B: 473–475.

Börjesson, T. (2010). Survey of *Fusarium*-species and toxins in Swedish wheat 2005-2009. *Fusarium* – Mycotoxins, Taxonomy, Pathogenicity and Host Resistance. Proceedings of the 11th European *Fusarium* Seminar, Radzikow, Poland, 20–23 September 2010. pp 151–152.

Bottalico, A. (1998). *Fusarium* diseases of cereals: species complex and related mycotoxin profiles, in Europe. *Journal of Plant Pathology* 80: 85–103.

Bottalico, A. and Perrone, G. (2002). Toxigenic *Fusarium* species and mycotoxins associated with head blight in small-grain cereals in Europe. *European Journal of Plant Pathology* 108: 611–624.

Bushnell, W.R., Hazen, B.E., and Pritsch C. (2003). Histology and physiology of *Fusarium* head blight. In: Leonard, K.J. and Bushnell, W.R. (eds.), *Fusarium* Head Blight of Wheat and Barley. APS Press, St. Paul, MN. pp 44–83.

CAB International. (2003). *Gibberella zeae* (Schwein.) CPC Datasheet [online]. Crop protection compendium. Wallingford, Oxford, United Kingdom: CABI Publishing, CAB International. http://www.cabi.org/cpc/ [accessed 28 March 2014].

Charmley, L.L., Trenholm, H.L., and Prelusky, D.B. (1996). Mycotoxins. Their origin, impact and importance: insights into common ways to control and eliminate. *Feed Compounder* 16: 14–17.

Clear, R.M. and Patrick, S.K. (2010). *Fusarium* head blight in western Canada [online]. Grain Research Laboratory, Canadian Grain Commission. 25 January 2010. http://www.grainscanada.gc.ca/str-rst/fusarium/fhbwc-foc-eng.htm [accessed 28 March 2014].

D'Mello, J.P.F., Placinta, C.M., and Macdonald, A.M.C. (1999). *Fusarium* mycotoxins: a review of global implications for animal health, welfare and productivity. *Animal Feed Science and Technology* 80: 183–205.

De Wolf, E.D., Madden, L.V., and Lipps, P.E. (2003). Risk assessment models for wheat *Fusarium* head blight epidemics based on within-season weather data. *Phytopathology* 93: 428–435.

Doohan, F.M., Brennan, J., and Cooke, B.M. (2003). Influence of climatic factors on *Fusarium* species pathogenic to cereals. *European Journal of Plant Pathology* 109: 755-768.

Elen, O., Langseth, W., Liu, W., Haug, G., Skinnes, H., Gullord, M., and Sundheim, L. (1997). The content of deoxynivalenol and occurrence of *Fusarium* spp. in cereals from field trials in Norway. *Cereal Research Communications* 25: 585–586.

Farr, D.F., Bills, G.F., Chamuris, G.P., and Rossman, A.Y. (1989). Fungi on plants and plant products in the United States. APS Press, St. Paul, MN.

Fernandes, J.M., Cunha, G., Del Ponte, E., Pavan, W., Pires, J., Baethgen, W., Gimenez, A., Magrin, G., and Travasso, M. (2004). Modelling *Fusarium* head blight in wheat under climate change using linked process-based models. Proceedings of the 2nd International Symposium on *Fusarium* Head Blight, incorporating the 8th European *Fusarium* Seminar, 11–15 December 2004, Orlando, pp 441–443.

Fredlund, E., Gidlund, A., Olsen, M., Börjesson, T., Spliid, N.H., and Simonsson, M. (2008). Method evaluation of *Fusarium* DNA extraction from mycelia and wheat for down-stream real-time PCR quantification and correlation to mycotoxin levels. *Journal of Microbiological Methods* 73: 33-40.

Gagkaeva, T. Yu and Yli-Mattila, T. (2004). Genetic diversity of *Fusarium graminearum* in Europe and Asia. *European Journal of Plant Pathology* 110: 551–562.

Gilbert, J. and Tekauz, A. (2000). Review: Recent developments in research on *Fusarium* head blight of wheat in Canada. *Canadian Journal of Plant Pathology* 22: 1–8.

Gilchrist, L. and Dubin, H.J. (2002). *Fusarium* head blight. In: Curtis, B.C., Rajaram, S., Gómez Macpherson, H. (eds.), FAO Plant Production and Protection Series No. 30, Bread Wheat Improvement and Production. Food and Agriculture Organization of the United Nations, Rome. http://www.fao.org/docrep/006/y4011e/y4011e0j.htm#bm19 [accessed 28 March 2014].

Goswami, R.S. and Kistler, H.C. (2004). Heading for disaster: *Fusarium graminearum* on cereal crops. *Molecular Plant Pathology* 5: 515–525.

Henriksen, B. (1999). Factors affecting *Fusarium* infection and mycotoxin content in cereal grains. Doctor Scientiarum Theses. Agricultural University of Norway, Ås.

Hofgaard, I., Brodal, G., Elen, O., Aamot, H.U., Jestoy, M., and Klemsdal, S. (2010). Occurrence of *Fusarium* spp. and mycotoxins in Norwegian oats and spring wheat sampled in a six-year period from 2004–2009. *Fusarium* – Mycotoxins, Taxonomy, Pathogenicity and Host Resistance (pp 171–172). Proceedings of the 11th European *Fusarium* Seminar, Radzikow, Poland, 20–23 September 2010.

Hope, R., Aldred, D., and Magan, N. (2005). Comparison of environmental profiles for growth and deoxynivalenol production by *Fusarium culmorum* and *F. graminearum* on wheat grain. *Letters in Applied Microbiology* 40: 295–300.

Kosiak, B., Torp, M., and Thrane, U. (1997). The occurrence of *Fusarium* spp. in Norwegian grain – A survey. *Cereal Research Communications* 25: 595–596.

Kosiak, B., Torp, M., Skjerve, E., and Thrane, U. (2003). The prevalence and distribution of *Fusarium* species in Norwegian grain – a survey. *Acta Agriculturae Scandinavica Section B-Soil and Plant Science.* 53: 168–176.

Kosiak, B., Torp, M., Skjerve, E., and Andersen, B. (2004). *Alternaria* and *Fusarium* in Norwegian grains of reduced quality—a matched pair sample study. *International Journal of Food Microbiology* 93: 51– 62.

Langseth, W. and Elen, O. (1996). Differences between barley, oats and wheat in the occurrence of deoxynivalenol and other trichothecenes in Norwegian grain. *Journal of Phytopathology* 144: 113–118.

Langseth, W. and Elen, O. (1997). The occurrence of deoxynivalenol in Norwegian cereals: differences between years and districts, 1988–1996. *Acta Agriculturae Scandinavica Section B-Soil and Plant Science* 47: 176–184.

Martin, R.A. and Johnston, H.W. (1997). Diseases of cereal crops in the Atlantic provinces, 1996. *Canadian Plant Disease Survey* 77: 59–60.

Martin, R.A. and MacLeod, J.A. (1991). Influences of production inputs on incidence of infection by *Fusarium* species on cereal seed. *Plant Disease* 75: 784–788.

Mathre, D.E. (1997). Compendium of Barley Diseases. 2nd Edition. APS Press, St. Paul, MN. 90 pp.

McMullen, M., Enz, P.J., Lukach, J., and Stover, R. (1997a). Environmental conditions associated with *Fusarium* head blight epidemics of wheat and barley in the northern Great Plains, USA. In: Dill-Macky, R. and Jones, R.K. (eds.), National *Fusarium* head blight forum, Sheraton Inn Midway, November 10-12, 1997, St. Paul, MN. pp 46–47.

McMullen, M., Jones, R., and Gallenberg, D. (1997b). Scab of wheat and barley: a re-emerging disease of devastating impact. *Plant Disease* 81: 1340–1348.

O'Donnell K., Kistler H.C., Tacke B.K., and Casper H.H. (2000). Gene genealogies reveal global phylogeographic structure and reproductive isolation among lineages of *Fusarium graminearum*, the fungus causing wheat scab. *Proceedings of the National Academy of Sciences* 97(14): 7905-7910.

Parry, D.W., Jenkinson, P., and McLeod, L. (1995). *Fusarium* ear blight (scab) in small grain cereals – a review. *Plant Pathology* 44: 207–238.

Qu, B., Li, H.P., Zhang, J.B., Xu, Y.B., Huang, T., Wu, A.B., Zhao, C.S., Carter, J., Nicholson, P., and Liao, Y.C., (2008). Geographic distribution and genetic diversity of *Fusarium graminearum* and *F. asiaticum* on wheat spikes throughout China. *Plant Pathology* 57: 15-24.

Schwarz, P.B. (2003). Impact of *Fusarium* head blight on malting and brewing quality of barley. In: Leonard, K.J. and Bushnell, W.R. (eds.), *Fusarium* head blight of wheat and barley. APS Press, St. Paul, MN. pp 395–419.

Shaner, G. (2003). Epidemiology of *Fusarium* head blight of small grain cereals in North American. In: Leonard, K.J. and Bushnell, W.R. (eds.), *Fusarium* head blight of wheat and barley. APS Press, St. Paul, MN. pp 84–119.

Siebert, S., Döll, P., Hoogeveen, J., Faures, J.-M., Frenken, K., and Feick, S. (2005). Development and validation of the global map of irrigation areas. *Hydrology and Earth System Sciences* 9: 535–547.

Stack, R.W. (1999). Return of an old problem: *Fusarium* head blight of small grains. American Phytopathological Society, APSnet Features, 1999. http://www.apsnet.org/publications/apsnetfeatures/Pages/HeadBlight.aspx [22 June 2000; accessed 28 March 2014].

Stack, R.W. (2003). History of *Fusarium* head blight with emphasis on North America. In: Leonard, K.J., Bushnell, W.R. (eds.), *Fusarium* head blight of wheat and barley. APS Press, St. Paul, MN. pp 1–34.

Strausbaugh, C.A. and Maloy, O.C. (1986). *Fusarium* of irrigated wheat in central Washington. *Plant Disease* 70: 1104–1106.

Sutherst, R.W., Maywald, G.F., and Kriticos, D.J. (2007). CLIMEX Version 3: User's Guide. www.Hearne.com.au: Hearne Scientific Software Pty Ltd.

Sutton, J.C. (1982). Epidemiology of wheat head blight and maize ear rot caused by *Fusarium graminearum*. *Canadian Journal of Plant Pathology* 4: 195–209.

Tekauz, A., McCallum, B., and Gilbert, J. (2000). Review: *Fusarium* head blight of barley in western Canada. *Canadian Journal of Plant Pathology* 22: 9–16.

Trail, F. (2009). For blighted waves of grain: *Fusarium graminearum* in the postgenomics era. *Plant Physiology* 149: 103-110.

Turkington, T.K., Clear, R.M., and Patrick, SK. (2005). Characteristics of wheat fields positive for *Fusarium graminearum* in Alberta, in 2002 and 2003. *Canadian Journal of Plant Pathology* 27: 479 [abstr.].

Waalwijk, C., Kastelein, P., de Vries, I., Kerényi, Z., van der Lee, T., Hasselink, T., Köhl, J., and Kema, G. (2003). Major changes in *Fusarium* spp. in wheat in the Netherlands. *European Journal of Plant Pathology* 109: 743–754.

Wang, J.H., Ndoye, M., Zhang, J.B., Li, H.P., and Liao, Y.C. (2011). Population structure and genetic diversity of the *Fusarium graminearum* species complex. *Toxins* 3: 1020-1037.

Wiese, M.V. (1987). Compendium of Wheat Diseases. 2nd Ed. APS Press, St. Paul, Minn. 112 pp.

Xu, X. (2003). Effects of environmental conditions on the development of *Fusarium* ear blight. *European Journal of Plant Pathology* 109: 683–689.

Yli-Mattila, T., Paavanen-Huhtala, S., Parikka, P., Konstantinova, P., Gagkaeva, T., Eskola, M., Jestoi, M., and Rizzo, A. (2002). Occurrence of *Fusarium* fungi and their toxins in Finnish cereals in 1998 and 2000. *Journal of Applied Genetics* 43A: 207–214.

Yli-Mattila, T., Paavanen-Huhtala, S., Jestoi, M., Parikka, P., Hietaniemi, V., Gagkaeva, T., Sarlin, T., Haikara, A., Laaksonen, S., and Rizzo, A. (2008). Real-time PCR detection and quantification of *Fusarium poae*, *F. graminearum*, *F. sporotrichioides* and *F. langsethiae* in cereal grains in Finland and Russia. *Archives of Phytopathology and Plant Protection* 41: 243–260.

Yli-Mattila, T., Rämö, S., Tanner, R., Loiveke, H., and Hietaniemi, V. (2010). *Fusarium* DNA levels as compared to mycotoxin levels in Finnish and Estonia grain samples. *Fusarium* – Mycotoxins, Taxonomy, Pathogenicity and Host Resistance (pp 223–224). Proceedings of the 11th European *Fusarium* Seminar, Radzikow, Poland, 20–23 September 2010.

Yonow, T., Kriticos, D.J., and Medd, R.W. (2004). The potential geographic range of *Pyrenophora semeniperda*. *Phytopathology* 94: 805–812.

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Revision History

Figure 4 was a duplicate of Figure 3 in the original September 2014 publication. The revised March 2016 version contains the correct figure.