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Research Review 102

Updating UK management guidelines for ergot (a review)

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1. Abstract

Claviceps purpurea is a fungus that infects various plant species, including domesticated grasses and cereals, such as such as rye, triticale, barley, wheat and oats. The pathogen infects the ovaries and causes the production of sclerotia in place of healthy grain. These sclerotia contain toxic alkaloids that can make the grain unsafe for consumption by humans or livestock. This review investigates potential management strategies for controlling or reducing the level of ergot in cereals in the UK. The findings of the review can be used to update ergot management guidelines.

A new life cycle diagram of ergot has been developed to clearly show the developmental stages of ergot. Four key stages were identified that offered the opportunity for control or management of ergot: reduction of primary inoculum, establishment of a less susceptible crop, reduction of secondary inoculum, and harvest and storage management of infected grain. Current regulations in Great Britain for grain and grain products for human consumption are based on weight of ergot sclerotia alone. However, many customers base their specifications on EU regulatory limits, which include maximum alkaloid concentrations. These EU alkaloid limits are challenging, as grain can be below the maximum sclerotia threshold while containing alkaloid levels that are above threshold.

Four main areas for controlling ergot are reviewed: practical agronomy measures, methods for limiting contamination at harvest, sorting and removal of ergot from the grain and breeding for ergot avoidance or resistance in cereals. It is clear from the review that there is no single factor that can control ergot on its own, and effective management relies on implementing a range of factors in an integrated approach.

Crop rotation, cereal species, sowing clean seed, grass-weed control, ploughing, and varietal choice were identified as key agronomic factors for managing ergot. Establishing a uniform crop, avoiding late tillering, controlling grass weeds in non-host crops, seed treatments, sowing margins with late flowering or low infectivity species and keeping accurate records of infestations were identified as agronomic factors that could have a moderate effect on ergot levels. Cultivator and combine hygiene and monitoring soil copper, boron and pH levels were identified as agronomic factors that would have a lower impact but could still have a useful effect as part of an integrated approach. Scouting fields before harvest and monitoring for grain contamination as it enters the store could have a moderate impact, whilst minimising the handling of infected grain before sieving/sorting could help reduce alkaloid levels. At harvest, combining infected areas separately and keeping the grain separate was seen as a key method of reducing ergot contamination.

Areas were identified where knowledge is lacking and further research is required. These include the effects of minimum tillage on sclerotia burial and subsequent germination, effects of current seed treatments on ergot germination, efficacy of modern fungicides applied to the ear, efficacy of modern spray technology to deliver fungicides to the required area of the ear, efficacy of biological products on ear protection and suppression of sclerotia germination, potential for assessing varietal susceptibility to ergot (possibly based on flowering period/openness of flowering/propensity of late tillering), breeding for ergot resistance, the effects of copper/boron deficiency on susceptibility to ergot in the UK and the development of an ergot forecasting model to help inform farmers and industry of the likely risk of ergot development in the current season.

2. Introduction

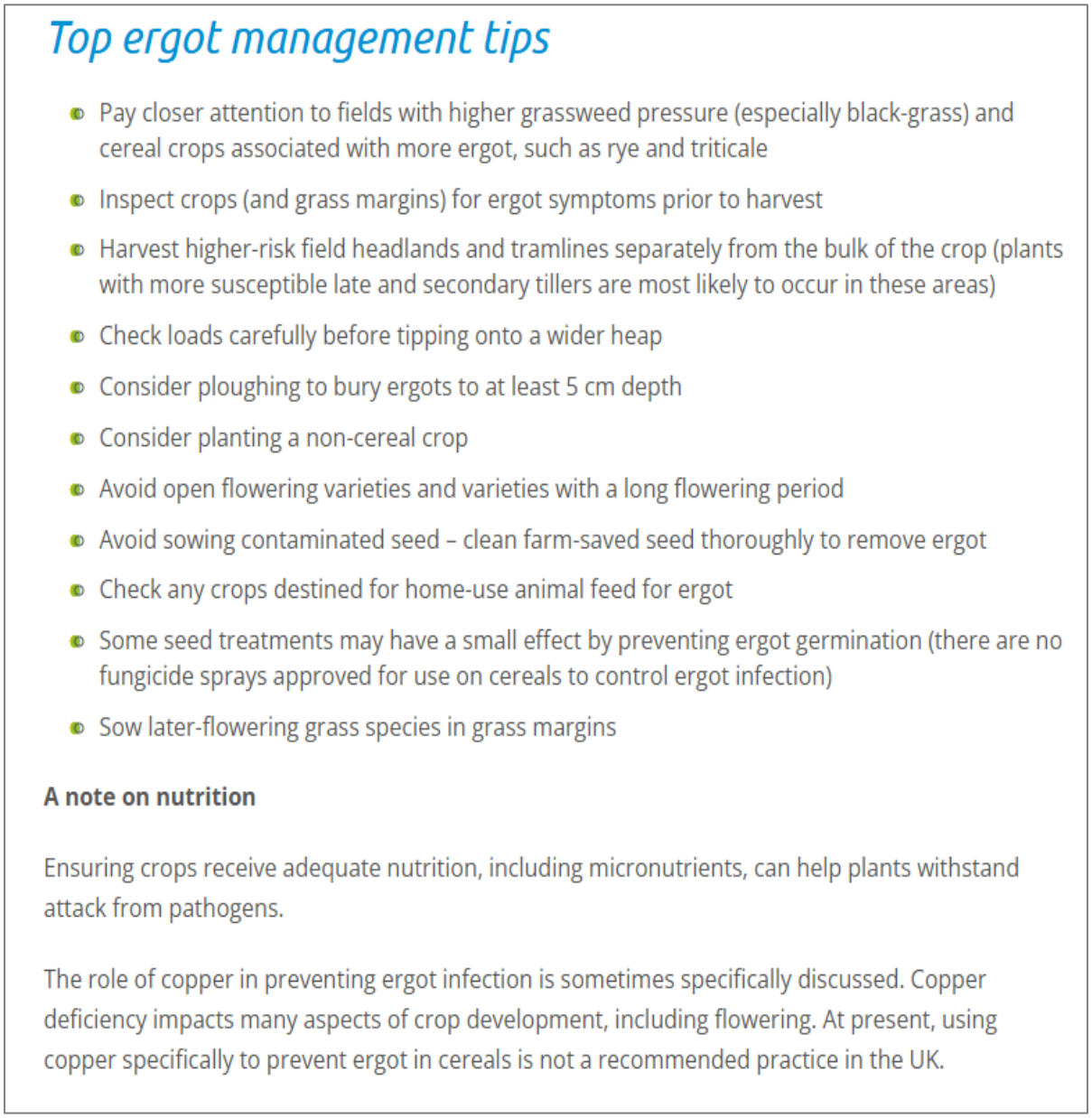
Ergot is the surviving form of the fungus *Claviceps purpurea,* which has a wide host range and can infect several grass hosts, including wheat, barley, oats, rye and triticale (Alderman, 2006). It is of such importance because if ergot is consumed by humans or livestock, it can cause health problems including seizures, psychosis, stomach pain, nausea/vomiting, reduced milk production and reduced circulation.

Historically, *C. purpurea* has been associated with its grass hosts for thousands of years. The greatest impact of the fungus on humans has been in association with rye, which is its most susceptible cereal host. Rye was grown extensively in the Middle Ages, with the first large-scale epidemic from ergot being reported in the Rhine Valley in 857 A.D. The susceptibility of the host plant is often influenced by pollination type and pollen availability, with rye and triticale being most susceptible (Menzies and Turkington, 2015). Infection from *Claviceps purpurea* is considered to be a biotrophic relationship which keeps the host plant alive as the disease progresses. The disease cycle begins with ergot sclerotia in the soil which overwinter and germinate in the spring, after a period of vernalization. These germinating sclerotia produce stroma with asci-containing perithecia which release ascospores. There ascospores land on open flowers of a cereal crop or grassweed, penetrate the stigma hairs and then hyphae grow down into the ovary. The greatest threat from ergot is not a reduction in yield or reduction in grain quality, but the contamination of the grain with ergot sclerotia which contain the toxic alkaloids.

The occurrence of ergot in cereals and grasses has often been sporadic, as it is favoured by cool, damp conditions during flowering. This promotes germination of sclerotia and ascospore release while also inhibiting pollination and extending the period of host susceptibility when the florets are open. When a conducive environment aligns with heading of grasses or small grains, the probability of ergot and grain contamination with toxic alkaloids increases. Interest in ergot is stimulated after years where there is a widespread outbreak in cereal crops, whilst it becomes of less interest in subsequent years if the disease is less present. The occurrence of ergot in recent years has been steadily increasing in the UK. This is thought to be due in part to modern farming practices which favour the development of ergot, such as direct drilling, the establishment of grass margins and beetle banks, short rotations and the increasing challenges of grassweed control due to herbicide resistance. The incidence of ergot in 2024 was particularly high due to a perfect storm of environmental factors. This included difficult conditions for crop establishment which resulted in uneven and inconsistent crops with a long flowering period, difficult ground conditions for applying autumn and spring herbicides, and cool, damp conditions around flowering which were favourable for infection and prolonged the flowering period.

There has only been a limited amount of research to investigate the distribution of ergot in the UK. Whilst localized differences in weather conditions during ergot sclerotia germination and flowering of the crop play an important role in determining the level of ergot pressure, factors such as nature and aggressiveness of grass weed problems, soil type and micronutrient status, cultivation method, rotation and crop type and species will all play a site-specific role. A UK wide survey demonstrated the widespread prevalence of ergot amongst grasses and established that open flowering and male-sterile cereals were at risk from ergot infection over a wide area of the country (Wood and Coley-Smith, 1980).

It is well established that prevention of ergot is the best management strategy, as once ergot is observed in the field, control options then rely on using harvest and post-harvest strategies to limit the level of contamination of the grain. The current ergot management top tips on the AHDB website for controlling ergot are as shown below:



Top ergot management tips

- Pay closer attention to fields with higher grassweed pressure (especially black-grass) and cereal crops associated with more ergot, such as rye and triticale
- Inspect crops (and grass margins) for ergot symptoms prior to harvest
- Harvest higher-risk field headlands and tramlines separately from the bulk of the crop (plants with more susceptible late and secondary tillers are most likely to occur in these areas)
- Check loads carefully before tipping onto a wider heap
- Consider ploughing to bury ergots to at least 5 cm depth
- Consider planting a non-cereal crop
- Avoid open flowering varieties and varieties with a long flowering period
- Avoid sowing contaminated seed – clean farm-saved seed thoroughly to remove ergot
- Check any crops destined for home-use animal feed for ergot
- Some seed treatments may have a small effect by preventing ergot germination (there are no fungicide sprays approved for use on cereals to control ergot infection)
- Sow later-flowering grass species in grass margins

A note on nutrition

Ensuring crops receive adequate nutrition, including micronutrients, can help plants withstand attack from pathogens.

The role of copper in preventing ergot infection is sometimes specifically discussed. Copper deficiency impacts many aspects of crop development, including flowering. At present, using copper specifically to prevent ergot in cereals is not a recommended practice in the UK.

Figure 2-1: Top ergot management tips on the AHDB website (2024)

The aim of this review is to gather all of the relevant literature relating to the control and management of ergot and use this information to update the AHDB Ergot Management Guidelines. Ergot has already become a significant problem in some European countries and some areas in The United States of America and Canada. It is envisaged that recent research in these countries could be applicable to UK agriculture and be incorporated into the updated guidelines.

To carry out the review, five primary research questions have been identified, to ensure that all of the relevant aspects are investigated:

1 What are the key stages of the ergot life cycle? – This includes its distribution, methods of transmission, the infection process, and possible genetic changes of Ergot (i.e. resistance and adaptations)
2 What practices can farmers deploy in temperate regions to manage ergot (e.g. seed treatments, cultivations, etc.) in commercially cultivated grasses[1]?
3 What practices can breeders deploy in temperate regions to breed or select for less susceptible varieties (e.g. open flower structure, flower timings) or ergot resistance in commercially cultivated grasses*?
4 What harvesting practices are there to decrease ergot presence in commercially cultivated grasses*?
5 What are the best practices to remove ergot from grain (i.e. sampling techniques and ergot sorting)?

[1] Commercially cultivated grasses – includes wheat, barley, rye, oats and triticale

3. Life cycle of ergot

3.1. Life cycle of *Claviceps purpurea*

Ergot is the common name for the plant disease caused by a fungal species of the genus Claviceps and is taxonomically complex. Although there are several species of Claviceps, the most common is *Claviceps purpurea* and is the species most commonly responsible for the ergot disease in the UK (Bayles *et al*., 2009, Berraies *et al*., 2024). It is likely that there are several *Claviceps spp*. which particularly infect different grass weed species to a greater or lesser extent. However, taxonomy is complex, and species delimitation currently stands at approximately 100+ species (Liu *et al*., 2022, Tanaka *et al*., 2023, Van der Linde *et al*., 2016, 2022). These may vary by location and host *spp*, but for the benefit of this report the common disease name of ergot will be used throughout and will refer to *Claviceps purpurea* being the most well documented and common species mentioned and studied throughout the literature (Berraies *et al*, 2024).

C. purpurea is a biotroph with a complex life cycle that includes both sexual and asexual reproduction. From a crop management perspective, it is important to consider that there are two key sources of inoculum which pose a risk, and which offer opportunities for disease management either via prevention or control (Figure 3.1 and Table 3,1):

1 **Primary inoculum** – this is due to ascospore release from ergots within the cropped area carried over from the previous season, via ergot infected seed introduced to the cropping area or via ergot infected home-saved seed. In addition, external sources of ergot may come from field margins and non-cropped areas (Figure 3-1, steps 1 to 5).
2 **Secondary inoculum** – this results from conidia being transferred from infected grasses within the crop or margins and infected crop plants (Figure 3-1, steps 6 to 8).

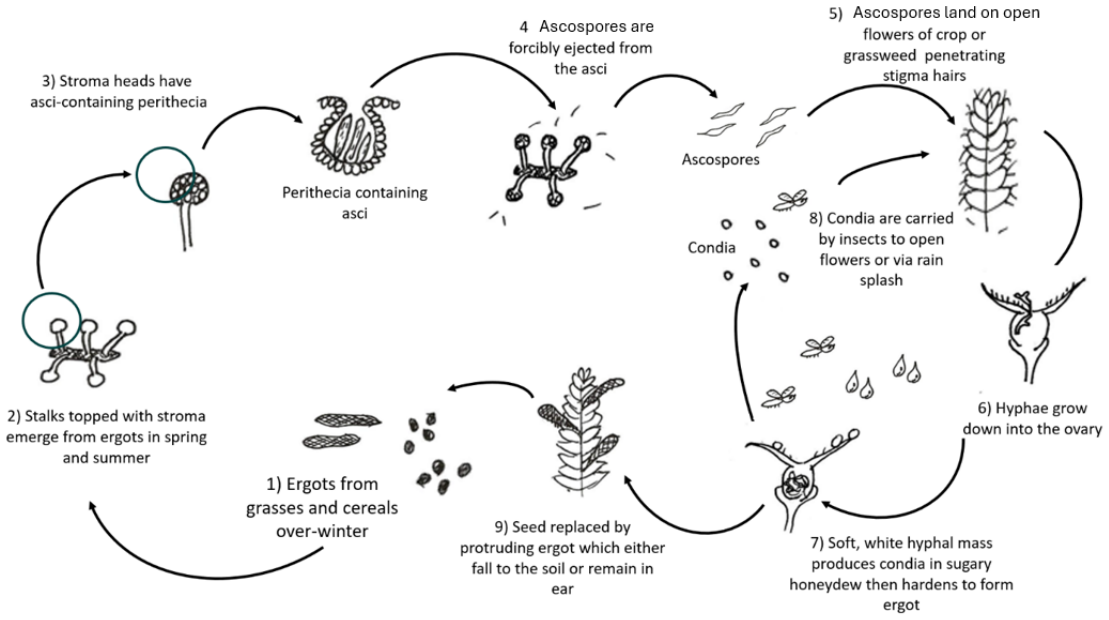


Figure 3-1: The disease life cycle of Claviceps purpurea on cereals and other grasses

Table 3-1: Explanation of the developmental stages of the disease life cycle of Claviceps purpurea on cereals and other grasses

1) Ergots from cereals and grasses overwinter in the soil or on crop debris. In addition, ergots may be present in drilled seed.	
2) After a period of vernalisation ergots germinate producing mushroom-like stalks with a stroma on top.	
3) The stroma consist of asci-containing perithecia. These asci contain ascospores which are the sexual spores that will infect the open flowers of the cereals or grasses.	
4) The ascospores are forcibly ejected into the air and land on the stigmas of flowering cereal crops or grasses.	
5) Open flowering grasses and cereals such as rye are susceptible to the ascospores.	
6) Hyphae from germinating ascospores penetrate the stigma hairs and travel down into the ovary which is rapidly taken over by mycelium.	
7) The mycelium in the ovary consists of soft, white mass which then enters the asexual stage to produce conidia in a sugary honeydew liquid which then exudes from the floret. After 10-14 days the mycelium hardens to form the recognisable ergot which has now fully replaced the grain.	
8) Conidia rich honeydew is then carried by insects to other flowering cereals and grasses or spread via rain splash. Once a floret is infected with conidia, the growth of the fungus is the same as when infection occurs with ascospores.	
9) The ergot is generally larger than the grain the pathogen has replaced and can be seen protruding from the seed head where it can be easily dislodged to fall onto the soil surface or be harvested alongside the ripe grain.	
10) Dislodged ergots may remain on the soil surface in minimum or reduced tillage situations or be incorporated into the soil with cultivations.	

Primary inoculum results from the overwintering of sclerotia (the ergots) which may either be in the soil from the previous year, added to the soil when infected seed is drilled or be present in infected grass seed heads which have overwintered either in margins or as crop debris. Ergots need a vernalisation period of 4-8 weeks near 0°C to overcome dormancy and have been found to be able to germinate over a 5-month period. They are also able to lie dormant in soil for an estimated 1-3 years when conditions are less favourable (Mitchell and Cooke (1968) and Rapilly (1968)), although there is little accurate data to support this and it could be longer (Bretag and Merriman, 1981).

The temperature optima for ergot germination is between 16-27°C, and under favourable moist and wet conditions in the spring or early summer, ergots germinate producing tiny, stalked fruiting bodies that release sexual spores (ascospores) forcibly into the air. These ascospores land on the stigma of either flowering grasses or cereals crops. The greatest release of ascospores has been found to occur at 100% relative humidity (RH) declining significantly below 30% RH (Conners, 1967, Hadley, 1968).

Ascospores of *C. purpurea* infect the female tissue of the flowering grass, replacing the seed with an ergot sclerotia. Access to the ovaries may be determined by flowering habit. There is evidence that either grass or cereal crop species that have a more open flower habit are more vulnerable to infection by ascospores – this will be covered in more detail later in the report. When the spores germinate on the stigma, they penetrate the stigma hairs and grow down the style to the transmitting tissue of the ovary (Lev-Yaden and Halpern, 2007, Tente *et al*., 2021). As a biotroph, the fungus keeps the floral tissue alive and does not induce a host necrotic response. It is estimated that within three days of the spores landing on the stigma, hyphae will have completely overwhelmed the ovary and will have begun to branch (Tente *et al*., 2021). Between 5-7 days post infection, the fungus enters the sphacelial stage with a soft, white tissue appearance that then begins to produce the asexual conidiospores. This is the stage in the life cycle where **secondary inoculum** can occur.

Within the ovaries, after approximately 2 weeks, the hyphal tissue hardens, forming the recognisable sclerotia (commonly referred to as ergots) where the seed would normally form (Tente *et al*., 2021). Ergots are generally black to dark purple in colour and vary in size and shape depending on the host. They tend to protrude from the seed head to aid dispersal. At this stage, ergots can then fall to the ground, remain in the seed head and/or are harvested with the crop grains.

As previously mentioned, **secondary inoculum** results from conidiospores (also referred to as conidia) which form prior to the hardening of the hyphae and the production of the ergot, so within a 2 week window from primary infection. Conidia exude from florets in a sugary liquid called honeydew which enables the fungal spores to disperse either via the help of insects, birds or rain splash (Miedaner and Geiger, 2015). These spores then infect other receptive flowers and is an important stage of the life cycle, as an early flowering infected grass species provide the secondary inoculum to infect a later flowering grass species. These grass species may be in margins, within crops or crop plants.

It is clear from the life cycle diagram that there are 4 key stages in the cycle which can be targeted to control or reduce the effects of ergot:

- Reduction or suppression of ergot inoculum in the soil
- Growing a crop that has a lower risk of infection
- Reduction of secondary spread
- Harvest and post-harvest grain management

The occurrence of ergot can be seasonally sporadic, and it is believed that this can largely be explained by the localised weather conditions that occur prior to and during heading of grass weed and cereal crops hosts. When a conducive environment aligns with heading of grasses or small grains, the probability of ergot increases (Mitchell and Cooke, 1968, Berraies *et al*., 2024).

Ergot spores do not spread far from the source (Berraies *et al*., 2024). In France, a 50% reduction in disease level was seen within 5m of the primary foci and 95% of ascospores spread within a 20m radius of the source (Maumene *et al*., 2012) (Figure 3.2).

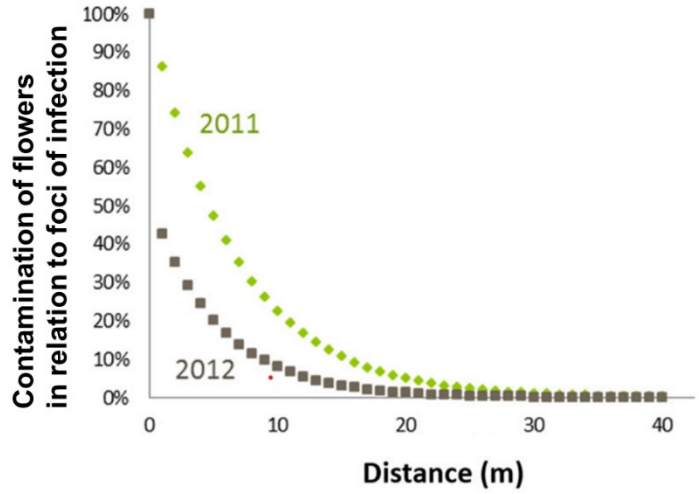


Figure 3-2: Spread of ascospores from primary foci (Adapted from from Arvalis, 2025)

3.2. Host range

C. purpurea and other *Claviceps spp*. are closely related to grass fungal endophytes in the genus *Epichloe* and have the common feature of developing symbiotic relationships with grasses (*Poaceae*) (Sung *et al*., 2007). *C. purpurea* is very broadly distributed globally and has an extensive host range including many forage grasses and cereal crop *spp*. with over 400 host species (Bové, 1970, Pažoutová *et al*., 2015).

The risk of infection in grass and cereal crop *spp*. largely depends on flowering habit. In order of risk, rye and then triticale are the most susceptible with spring wheat, winter wheat, barley and oats being less susceptible in that order (Platford & Bernier, 1976, Coufal-Majewski *et al.,* 2016, Weston and Taylor, 1942, Babic *et al.,* 2020, Menzies *et al.,* 2017) (Table 3.2, Table 3.3). Within these crop *spp*. there will also be some varieties more or less susceptible than others, again this may be based on their flowering habit or potentially other factors. Male sterile cereal lines used in plant breeding are particularly susceptible to ergot infection (Cunfer *et al*., 1975).

Table 3-2. Susceptibility of crop plants to ergot

Crop	Flowering habit	Susceptibility to ergot infection	Risk
Rye (*Secale cereale*)	Highly cross-pollinated; florets remain open for a long period of time to facilitate wind pollination	Highly susceptible due to prolonged floret openness allowing fungal spores to enter	Very High
Triticale (*x Triticosecale*)	Intermediate between rye and wheat; partial cross-pollination with some floret opening	Susceptible – more than wheat but less than rye, depending on variety	High
Wheat (*Triticum spp.*)	Mostly self-pollinated; flowers remain largely closed (cleistogamous) with brief anther exposure although varieties differ	Moderate susceptibility due to limited floral opening and rapid self-pollination – varietal flowering habit can vary (Spring wheat more susceptible than winter)	Moderate
Barley (*Hordeum vulgare*)	Highly self-pollinating; florets remain closed generally preventing fungal entry - varieties may differ in flowering habit	Lower susceptibility than wheat as florets generally closed however, like wheat, varieties can differ	Low
Oats (*Avena sativa*)	Predominantly self-pollinating, though some cross pollination can also occur, floret open briefly, and varieties vary	Low susceptibility due to closed flowering structure and self-pollination	Very Low

Table 3-3. Grass species in seed margin mixtures and other grasses, whether they are an ergot host a weed in the UK, level of ergot risk and flowering date*

a) Grasses in margin seed mixtures

Common name	Species	Ref.	Ergot risk[8]	Weed	Flowering date					
					Apr	May	Jun	Jul	Aug	Sept
Black bent	*Agrostis gigantea*	2		✓			y	y	y	
Creeping bent	*Agrostis stolonifera*	1,2		✓			y	y	y	
Meadow foxtail	*Alopecurus pratensis*	1,7,8	High		y	y	y	y		
Sweet vernal grass	*Anthoxanthum odoratum7*	8,7	Low		y	y	y	y		
Black oat	*Avena strigose*	10					y	y	y	y
Crested dogs tail	*Cynosurus cristatus*	5	Very low				y	y	y	
Cocksfoot	*Dactylis glomerata*	1,7,8	High	✓			y	y	y	y
Japanese reed millet	*Echinochloa esculenta*									
Tall fescue	*Festuca arundinacea*	8	High				y	y	y	
Sheeps fescue	*Festuca ovina*	7	Very low			y	y	y		
Meadow fescue	*Festuca pratensis*	7,8	Intermediate	✓			y	y	y	
Red Fescue /chewings fescue	*Festuca rubra commutate*	7,8	Unknown	✓		y	y	y	y	
Slender creeping red fescue	*Festuca rubra litoralis*	7				y	y	y	y	
Creeping/strong red fescue	*Festuca rubra rubra*	2,7	Unknown	✓		y	y	y	y	
Hard fescue	*Festuca trachyphylla*					y	y			
Hybrid ryegrass x fescue	*Festuolium*	5					y	y	y	
Italian ryegrass	*Lolium multiflorum*	8,9	Intermediate	✓			y	y	y	
Perennial ryegrass	*Lolium perenne*	1,7,8	Intermediate	✓		y	y	y	y	
Westerwolds	*Lolium westerwoldicum*	4								
Hybrid ryegrass	*Lolium x hybridum hausskn*									
Red millet	*Panicum miliaceum*	3								
White millet	*Panicum miliaceum*	3								
Canary grass	*Phalaris aquatica*	8,9		✓			y	y	y	
Reed canary grass	*Phalaris arundinacea*	7,8,9		✓			y	y	y	
Smaller Catstail / Small Timothy	*Phleum bertolonii*						y	y	y	
Timothy	*Phleum pratense*	1,7,8	High	✓			y	y	y	y
Smooth stalked Meadow Grass	*Poa pratensis*	3,7,8	Unknown	✓		y	y	y		
Rough stalked meadow grass	*Poa trivialis*	8	Low	✓			y	y		
Dwarf sorghum	*Sorghum bicolour*	2								
Giant sorghum	*Sorghum bicolour*	2								

b) Other grasses

Common name	Species	Ref	Ergot risk[8]	Weed	Flowering date					
					Apr	May	Jun	Jul	Aug	Sept
Common bent	*Agrostis capillaris*	8	High				y	y	y	
Orange Foxtail	*Alopecurus aequalis*	9	Not C. purpurea				y	y	y	y
Black-grass	*Alopoecurus myosuroides*	8	High	✓		y	y	y	y	
Marrram grass	*Ammophila arenaria*	8					y	y	y	
Great brome	*Anisantha diandrus*	10		✓		y	y	y		
Barren brome	*Anisantha sterilis*	7,9		✓		y	y	y		
Loose silky bent	*Apera spica venti*			✓			y	y	y	
False/Tall oat grass/onion couch	*Arrhenatherum elatius*	1,7,8	High	✓			y	y	y	y
Spring wild oat	*Avena fatua*	8		✓			y	y	y	y
Winter wild oats	*Avena sterilis ssp ludoviciana*	8		✓				y	y	y
Field brome	*Bromus arvensis*						y	y	y	
Meadow brome	*Bromus commutatus*	8	High	✓		y	y	y		
Soft brome	*Bromus hordeaceus*	8		✓		y	y	y		
Rye brome	*Bromus secalinus*	2		✓			y	y		
Wavy Hair-Grass	*Deschampsia flexuosa*	8	Low				y	y		
Barnyard grass/cockspur	*Echinochloa crusgalli*			✓						
Sand couch	*Elymus fractus*	8					y	y	y	
Common couch	*Elymus repens*	1,7,8	High	✓			y	y	y	
Yorkshire Fog	*Holcus lanatus*	1,7,8	Low	✓		y	y	y	y	
Creeping soft grass	*Holcus mollis*	1,7,8	Low				y	y	y	
Wall barley	*Hordeum murinum*	8				y	y	y	y	
Meadow barley	*Hordeum secalinum*	8					y	y		
Mat grass	*Nardus stricta*	8					y	y	y	
Lesser canary grass	*Phalaris minor*	8		✓			y	y	y	
Annual meadow grass	*Poa annua*	7,8	Low	✓	y	y	y	y	y	y
Great millet	*Sorghum bicolor*	9	Not C. purpurea							
Squirrel tail fescue	*Vulpia bromoides*	10				y	y	y		
Rats tail fescue	*Vulpia myuros*	6,9		✓		y	y	y		

*Taken from in a Kings/Cotswolds seeds websites March 2025
**References

1 Aboling et al., 2016
2 Alderman et al., 2004
3 Anastoff, 1920
4 Cagaš et al., 2006
5 Dabkevicius, 1998
6 Marudarajan et al., 1950
7 Pažoutová et al, 2002
8 Bayles et al., 2009
9 Tanaka et al., 2023
10 Walker, 2004

3.3. Toxin production during Claviceps purpurea life cycle

Despite ergots replacing grains in cereal crop *spp*. the impact on the quantity of harvested grain is minimal (Harper and Seaman, 1980). However, ergot infection in cereal crops is very serious due to the presence of mycotoxins in the form of alkaloids and other toxins in the ergots which then contaminate the grain when harvested. The ergots have very different biochemical and physical properties compared with healthy grains, with these differences affecting processing, milling and grain end-use quality (Bryla *et al*, 2019, Merkel *et al*, 2012).

The effects of ergot contamination in grain, particularly rye, and the resulting toxic and hallucinogenic effects have been recorded over millennia and are even mentioned in the bible (Schiff, 2006 provides an interesting historical overview). Alongside wheat rust, it is probably one of the most recorded and historically mentioned of the cereal diseases. Ergot contamination, alongside Fusarium head blight (FHB) (*Fusarium graminearum*) does still pose a significant threat to both human and animal health when grain, and processed grain, either as animal feed or in the food chain, is consumed. Again, these effects are extremely well documented in the literature and are reviewed by Bhatnager, Yu and Ehrlich, 2002, Ramos *et al*., 2011, Pandey *et al*, 2023 and Berraies *et al*, 2024 among many others. As fungal diseases, both Fusarium and ergot have had millennia to adapt and co-evolve with the development and evolution of cereal crops globally.

There are approximately 300-400 fungal species that are known to produce mycotoxins (Bhatnager, Yu and Ehrlich, 2002). The term mycotoxin is a generic term for any toxic substance produced by a fungus but in reality, covers a vast range of chemical compounds. These toxic compounds produced during the life cycle of a fungus are secondary metabolites which have distinct origins, structures and effects. The table below (Table 3-4) summarises the most common mycotoxin producing pathogens found in an agronomic environment (Pandey *et al*, 2023).

Table 3-4. Summary of agronomically occurring fungal pathogens producing mycotoxins (adapted from Pandey et al*., 2023)*

Pathogen	Mycotoxin
Claviceps spp. (e.g. *C. purpurea*)	Ergot alkaloids e.g. ergotamine
Fusarium spp. (e.g. *F. graminearum, F. verticillioides*)	Trichothecenes e.g. deoxynivalenol (DON), T-2 toxin, fumonisins, zearalenone
Aspergillus spp. (e.g. *A. flavus, A. parasiticus, A. ochraceus*)	Aflatoxins, e.g. ochratoxins etc.
Alternaria spp. (e.g. *A. alternata*)	Alternariol, tenuazonic acid

C. purpurea is perhaps unusual compared with other fungal pathogens occurring in the agronomic environment, in that they produce alkaloids as a secondary metabolite, which are more commonly associated with plants. Alkaloids are naturally occurring organic compounds that contain nitrogen (Roy, 2017). The reason that they are toxic when processed with grain such as in flour production or as animal feed is due to their pharmacological effects, however, these attributes have also been exploited to develop novel and effective pharmacological treatments for a very wide range of conditions. From plant species, notable examples include galantamine from *Narcissus spp*. used to treat Alzheimer's and physostigmine from the Calabar bean (*Physostigma venenosum*) used for

the treatment of glaucoma (Roy, 2017). It is perhaps also interesting to note that caffeine is an alkaloid (Arnaud, 1987).

The alkaloids produced during the life cycle of *C. purpurea* have been found to interfere with the plant's hormonal signalling, helping the pathogen to establish the infection during the penetration and establishment phase within the host plant. They are synthesized and then accumulate during the sclerotia (ergot) forming phase of the life cycle when the mycelium hardens into the ergot in the ovary. Alkaloids remain stable in the ergot for protracted periods of time and only start to decline once the ergot starts to germinate.

It is hypothesised that the production of alkaloids by *C. purpurea* confers an evolutionary advantage to the pathogen by deterring herbivores from consuming infected plants (Wäli *et al*, 2013). In addition, it has also been shown that the alkaloids produced by the fungus protect it from bacterial or fungal competitors in its environment which may help its longevity in the soil.

The main alkaloids found in the ergot are structurally related to lysergic acid and have a strong impact on the nervous and vascular system due to their effects on neurotransmitters such as dopamine, serotonin and norepinephrine, making them both powerful toxins as well as useful drug treatments in clinical settings. Alkaloids produced by ergot include ergotamine, ergocristine, ergocryptine, ergocornine, ergotmetrine and ergotvaline (Schardi *et al*., 2006). Of these, ergotamine can be used to treat migraine, dihydroergotamine is used to treat migraine and vascular headaches and ergometrine can induce labour and prevent post-partum haemorrhage. Total alkaloid concentrations in harvest samples of milling wheat, feedwheat, wheatfeed, feed barley, malting barley, food oats, food barley, feed oats and oatfeed are shown in Figure 3.3. This shows the difference in alkaloid concentrations between crop species, and also the large effect of different weather conditions each year on alkaloid levels. The regulatory framework around the levels of ergot contamination and alkaloids in food stuffs is outlined in Chapter 4.

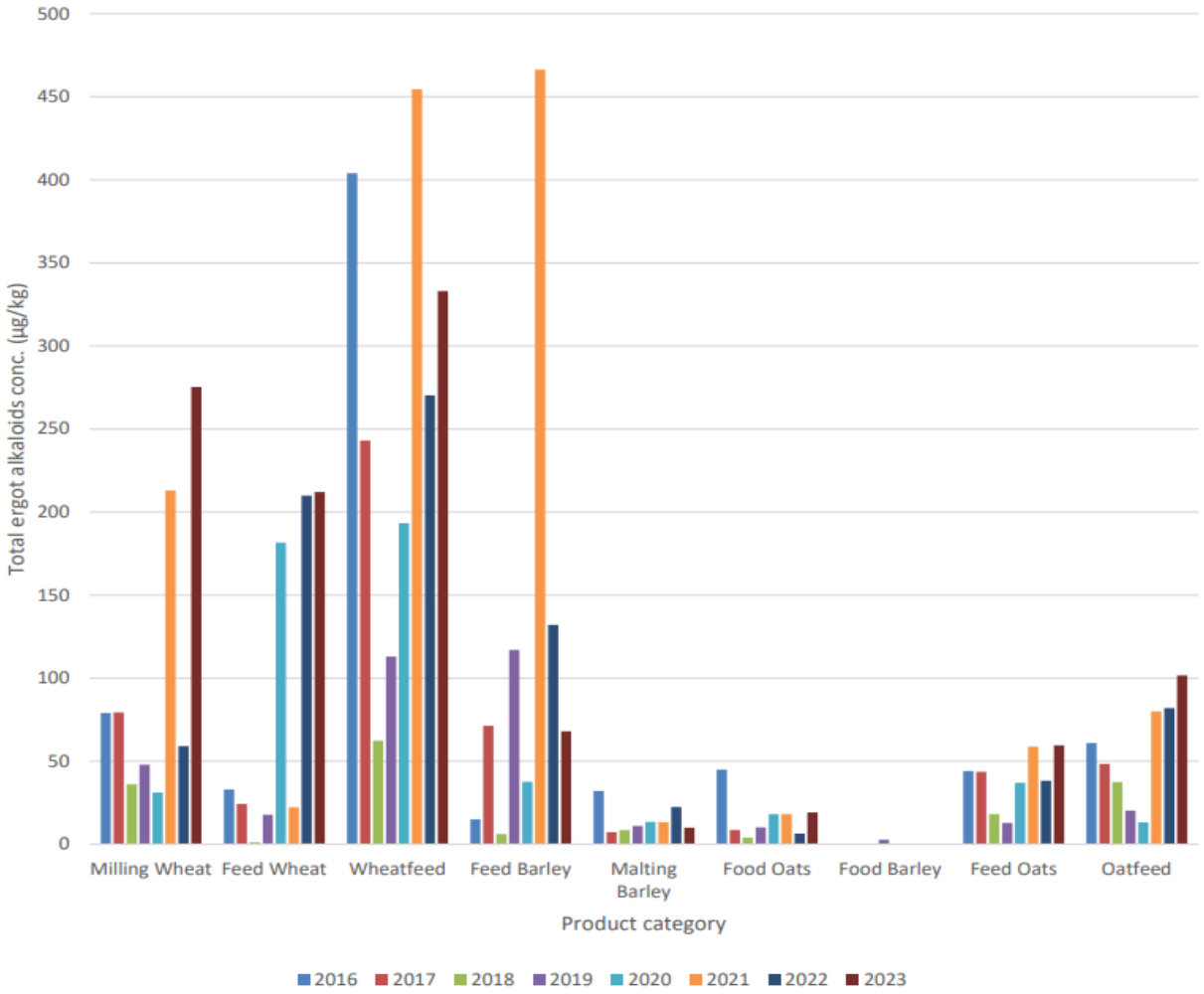


Figure 3-3: Mean total Ergot Alkaloid levels in harvest samples (µg/kg by product) (AHDB, 2024)

3.4. Weather factors and forecasting ergot risk

The occurrence of ergot can be seasonally sporadic, depending on the environmental conditions through the spring and summer (Mitchell & Cooke, 1968, Berraies *et al*., 2024). Ergot germination in the spring is favoured by moist or wet soil conditions and warm temperatures (ideally between 16-27ºC). Ascospore infection at flowering is highest where relative humidity is close to 100% (Conners, 1967, Hadley, 1968). Cool conditions at this time can also extend flowering and extend the period of infection.

Conditions in 2024 were particularly conducive to the development of ergot. Daily rainfall and air temperatures were generally above average in March, April and May. This was particularly evident during March and the first half of April, which provided near ideal conditions for the germination of ergot sclerotia. However, this was then followed by a period of exceptionally cool and showery weather during the first 3 weeks of June when cereal crops would have been flowering (Figures 3.4 and 3.5). This would have provided the perfect conditions for ergot ascospore infection, with high relative humidity to aid infection, whilst the cool conditions prolonged flowering which gave a longer period for infection.

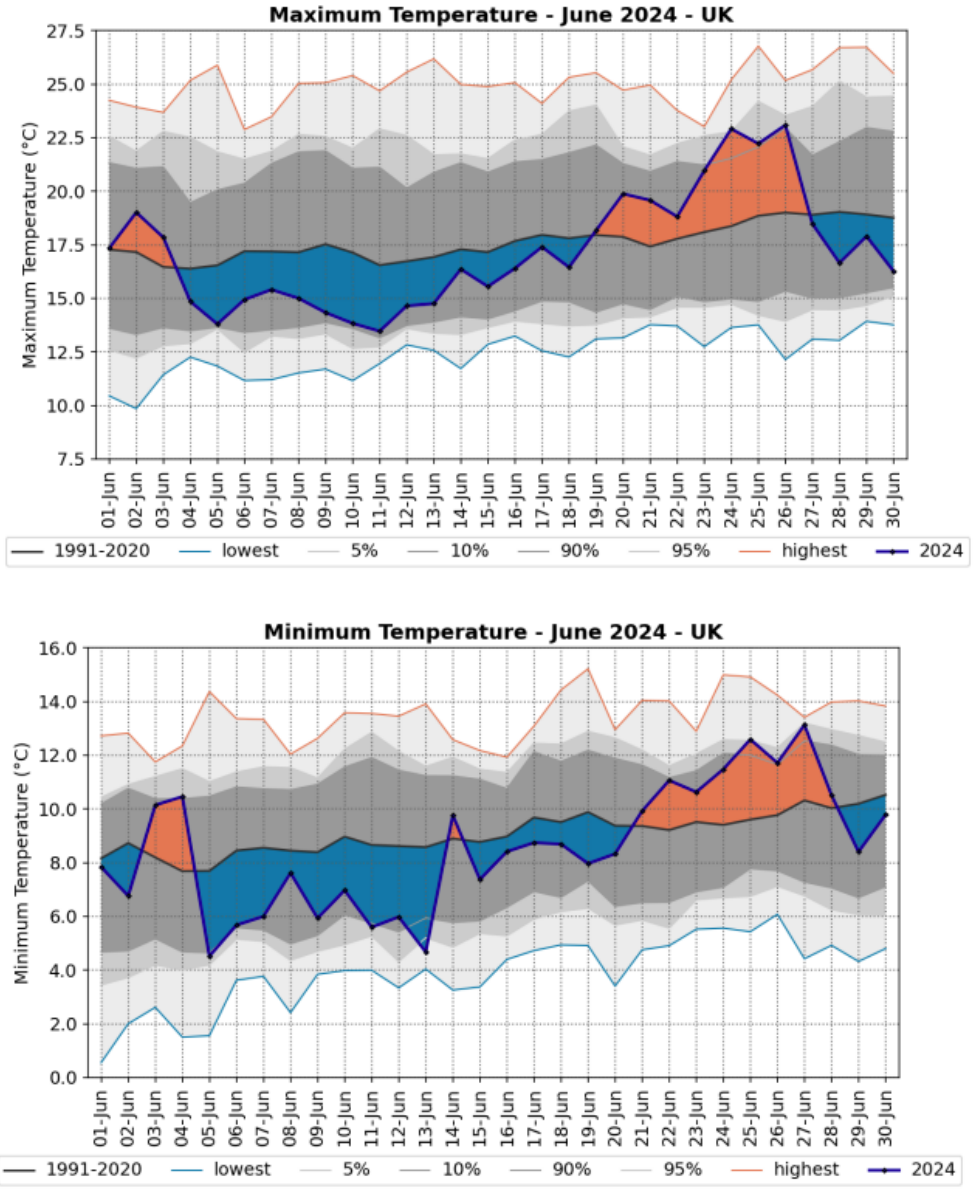


Figure 3-4: Daily maximum and daily minimum temperature averaged across the UK in June 2024 compared the 1991-2020 average. Source: Had UK Grid 01/07/2024

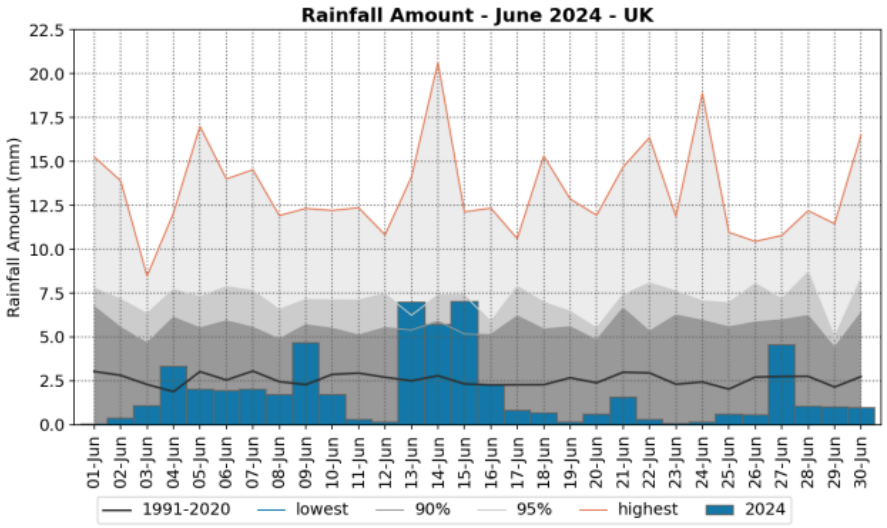


Figure 3-5: Daily rainfall amount averaged across the UK in June 2024 compared the 1991-2020 average. Source: Had UK Grid 01/07/2024

There has been an intensification of weather variability in recent years as a result of climate change, and in turn, this can have a large impact on ergot sclerotia germination and host infection. In addition, the increasing frequency of weather-related stress may also affect pollen viability, particularly in cereals (Peloso, 2024). It is expected that climate change will increase the frequency of extreme weather events and therefore the effects of ergot infection pressure.

For the control of ergot, there is potential to assess and model the relationships between the environment, host susceptibility/resistance and pathogen populations. The collection of data from a large number of specific fields over time, followed by analysis of ergot incidence and severity could help model the complex relationships to different cereal species, variety, weather parameters, management practices and geography. This could be used to enable the prediction of ergot occurrence, aided by modern techniques such as artificial intelligence and machine learning. As the weather is known to be such a crucial factor in the development of ergot, disease modelling and forecasting could be used to support an integrated control strategy and identify the correct control measures for each individual situation (Berraies et al, 2023). Potentially, this could allow the forecast of the ergot risk in the following year or even longer. Radar-rainfall data has been combined into weather-based ergot severity models which have been successfully used to predict sorghum ergot severity in multiple areas of the Texas Panhandle. It is possible that technologies like this could be used to predict ergot severity to provide timely disease warnings for any potential management applications such as application of fungicides (Workneh and Rush, 2006).

Rapid diagnostic tests for predicting the risk of ergot are not well established but would be useful for helping to understand the disease pressure on a field-by-field basis. The establishment of soil tests to identify ergot sclerotia levels in the soil could give a useful indication of potential risk levels for the coming season. Another measure that would be useful for establishing risk is monitoring *Claviceps purpurea* spore levels from a network of spore traps, in much the same way that this is already used in the control of sclerotinia in oilseed rape. Insect testing to determine the proportion of insects carrying spores would be another useful tool that could support decision making. This key area of detection, surveillance and rapid diagnostics is an area of increasing interest in plant disease control and is an area that requires developing further.

4. Ergot regulations

This section of the review examines the current UK regulatory framework around ergot for grain to be used in human consumption, animal feed and seed for sowing. Guidelines are based around maximum ergot sclerotia weights in a grain sample and maximum alkaloid concentrations. Advancements in analytical methodologies have greatly improved the detection and quantification of ergot alkaloids and can ensure that even low levels of contamination can be reliably detected (Kowalczyk *et al*., 2016, Kowalczyk and Kwiatek, 2023).

4.1. Current regulatory framework in the UK

4.1.1. Human consumption

The legal limits for ergot sclerotia and ergot alkaloids for grain and grain products for human consumption are different between Great Britain (GB) and the European Union (EU)/Northern Ireland (NI). NI is subject to EU food safety law. The EU reduced the limit for ergot sclerotia in grain on 01 January 2022, and at the same time introduced maximum limits for ergot alkaloids in processed cereal as part of Regulation (EC) No 1881/2006. This change occurred just after GB left the EU. Regulation (EC) No 1881/2006 EU was repealed on 25 April and replaced with Regulation (EU) 2023/915, which has since been amended on 01 July 2024 with Regulation (EU) 2024/1808. For human food products, the UK still adheres to Regulation (EC) No 1881/2006, which sets maximum limits for contaminants, including ergot sclerotia.

Table 4-1. Summary of GB and EU/NI regulations for ergot sclerotia in cereals for human consumption

Ergot sclerotia limit	GB limit	EU and NI limit
Unprocessed cereals (with the exception of maize, rye and rice)	0.5g/kg (0.05%)	0.2g/kg (0.02%)
Unprocessed rye	0.5g/kg (0.05%)	0.2g/kg (0.02%) from 01.07.25
Feed grains	1g/kg (0.01%)	1g/kg

Table 4-2. Summary of GB and EU/NI regulations for ergot alkaloids in cereals for human consumption

Ergot alkaloid limit	GB limit	EU and NI Limit
Milling products of wheat (with an ash content lower than 900mg/100g)	No limit set	100µg/kg until 30.06.28 50µg/kg from 01.07.28
Milling products of barley, spelt and oats (with an ash content lower than 900mg/100g)	No limit set	50µg/kg
Milling products of barley, wheat, spelt and oats (with an ash content equal to or higher than 900mg/100g)	No limit set	150µg/kg
Barley, wheat, spelt and oat grains placed on the market for the final consumer	No limit set	150µg/kg
Rye milling products and rye placed on market for final consumer	No limit set	500µg/kg until 30.06.28 250µg/kg from 01.07.28
Wheat gluten	No limit set	400µg/kg
Processed cereal based food for infants and young children	No limit set	20µg/kg

Although the EU ergot and ergot alkaloid limits do not apply directly to GB, many grain merchants or end users set their specifications in line with the EU limits, as it is difficult for customers in GB to segregate the products that they are using. In practical terms, they treat the EU and GB markets as one, and so the EU regulations have a significant impact on the GB market. The majority of mills in GB have stricter limits for ergot sclerotia in the grain than 0.02% and many mills have a zero-tolerance approach. The Agricultural Industries Confederation (AIC) in the UK state in their Contract for Grains and Pulses No.2/16 that “grain shall not contain more than 0.01% ergot by weight for feed grain and zero tolerance for all other grain”.

It is very difficult to control ergot alkaloids below the very low legal limits set out by the EU, and there currently appears to be a conflict between the ergot sclerotia limits and the ergot alkaloid limits. As a result, there have been product recalls in many European countries due to high alkaloid levels in processed cereal products. This will become even more challenging from 01 July 2028 when the permissible alkaloid concentration for milling products of wheat will be reduced from 100 µg/kg to 50 µg/kg and the upper limit for rye milling products and rye placed on the market for the final consumer will reduce from 500µg/kg to 250 µg/kg.

A correlation analysis carried out by Arcella *et al.* (2017), found that there was a strong and significant linear relationship between the content of ergot sclerotia and the levels of ergot alkaloids analysed in wheat, barley, rye and triticale (Figure 4.1). However, at the point on each graph where ergot and ergot alkaloid levels are at or below the allowable levels, there is a larger degree of variability in the data. It can therefore be quite easy for a grain sample to be below the maximum ergot level but above the maximum ergot alkaloid level.

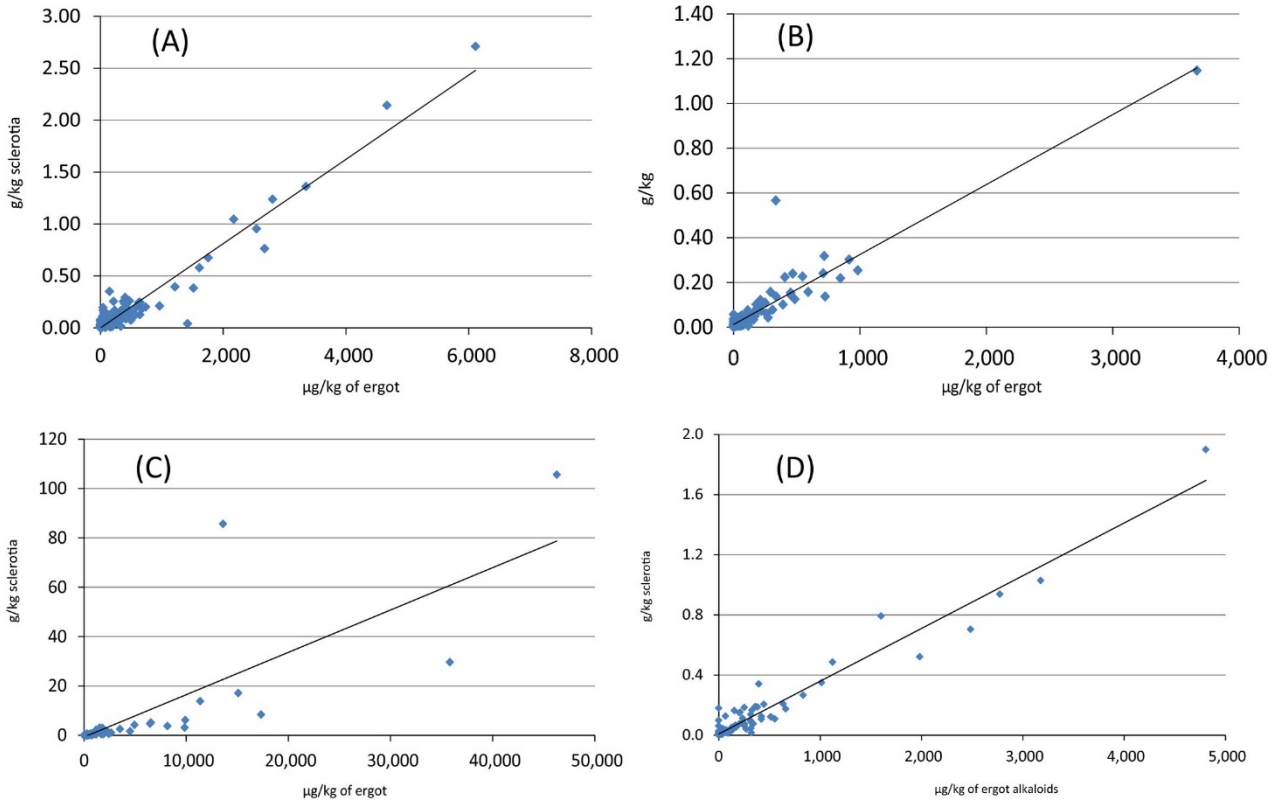


Figure 4-1. Relationship between the amount of ergot sclerotia and ergot alkaloids in samples of (A) wheat, (B) barley, (C) Rye and (D) Triticale. Source: Arcella et al (2017)

Based on the average level of alkaloids in a wheat sclerotia observed by Gorden *et al.* (2019), if wheat contaminated with 0.02% ergot sclerotia was milled into flour, it would have an alkaloid content of around 377ppb, which is well over the EU legal limit of 100ppb. A study carried out by UK flour millers spiked wheat grain that was completely clean of ergot with 0.02% ergot sclerotia and milled it into a white flour. This flour was tested for alkaloids and found to have a content of 347ppb which is again well above the legal EU limit of 100ppb. Also, this limit is to drop to 50ppb on 01 July 2028. Research carried out by Malysheva *et al*. (2014), raised a similar point regarding the discrepancy between ergot sclerotia limits and maximum alkaloid concentrations.

4.1.2. Animal feed

The UK follows European Union regulations concerning ergot levels in animal feed, specifically Directive 2002/32/EC, which sets the limits for ergot contamination in animal feed. The limits for rye ergot in feed materials and compound feed containing unground cereals are set at: 1000 mg of rye ergot per Kg of feed. This limit applies to feed with a moisture content of approximately 12% and is intended to ensure that ergot contamination, which can lead to adverse effects in livestock due to the presence of ergot alkaloids, remains within levels deemed acceptable for animal health.

UK regulations do not currently provide more detailed limits for individual ergot alkaloids in animal feed, and there are no specific allowable levels for processed animal feed products. This means that reliance on physical sclerotia content as a marker remains the primary standard for contamination thresholds in feed materials in the UK. This is in contrast to some European Union countries where more comprehensive standards for ergot alkaloids in feed ingredients are set. Elsewhere in the world, ergot alkaloid levels in animal feeds have been set for some time. In

Canada, maximum levels of ergot alkaloids have been established at 6 mg/kg in pig feed, 3 mg/kg in cattle, sheep and horses and 9 mg/kg in chicks. Guidance in Uruguay states that ergot alkaloids should not be detectable in feed for pigs with a guidance level of 0.45 mg/kg in other feed. A German monitoring study from 2012–2014 revealed that ergot alkaloid levels, rather than ergot mass alone, are more closely associated with adverse effects in animals (Schwake-Anduschus *et al*., 2020). The discrepancy between ergot sclerotia and ergot alkaloids was also highlighted in a wider grain study in animal feed where the number of sclerotia differed vastly between physical presence and ergot alkaloids (Schwake-Anduschus *et al*., 2020).

4.1.3. Seed regulation standards

Under the Seed Marketing Regulations 2011 (No. 463) in the UK, specific tolerances for ergot sclerotia in certified seed are established to maintain seed quality. For Basic Seed, a zero-tolerance policy is applied, with no ergot sclerotia allowed in 1000 grams of seed. For the C1 and C2 classes, the regulatory minimum standard for the number of ergot pieces is up to three pieces per 500g by visual inspection. There is also a higher voluntary standard of one piece per 1000g. These strict thresholds are designed to ensure that only high-quality seed is marketed, thereby reducing the risk of ergot sclerotia being introduced to the soil as part of the drilling process.

It is advisable that seed for the following season should be taken from fields harvested with the lowest ergot pressure. Where home saved seed contains ergot, bulk colour separation or modified gravity cleaning can be effective ways of removing ergot and other contaminants. Further information on growing farm saved seed is available at ahdb.org.uk/knowledge-library/top-tips-for-growing-farm-saved-seed

Whilst there are some wheat and rye varieties which have been shown to be less impacted by ergot than others (Tente *et al*., 2022, Miedaner *et al*., 2021), they are not widely distributed in the cereal market. Breeding or selection of varieties with ergot resistance may be useful for the future and will be discussed further in section 8.

5. Agronomy

The recent increase in the prevalence of ergot has been attributed to recent changes in farming systems, chiefly the introduction of grass margins in arable fields, poor control of grass weeds due to herbicide resistance, shorter rotations and the move towards minimum tillage or zero tillage systems. Changes in recent years from area-based subsidy payments to the Sustainable Farming Incentive where growers are financially rewarded for environmental practices has accelerated the uptake of measures such as establishment of field margins, beetle banks or grassy field corners or blocks. Prevention is the most effective management strategy for the control of ergot, as once it is observed in the field it is too late to control, and steps can only be taken to limit the level of contamination of the grain (Shumann and Uppala, 2017). There are a range of crop management practices which can be used to influence the incidence of ergot infection, although no single control measure has been found to be completely effective when used on its own. The control of ergot therefore relies on an in an integrated approach that employs a range of management practices (Berraies *et al*., 2024, Agriopoulou, 2021).

5.1. Rotation

Rotation has always been the cornerstone of good husbandry. Crop choice is partially dependent on location and soil type, but as optimum farm structure is market-driven, conventional cropping patterns are usually determined by the most profitable crops.

Surveys of cereal crops in France (2012-2014) showed that ergot incidence was higher in triticale and rye than in other cereal crops (Orlando *et al*. 2017) (Figure 5-1). Previous work agrees that rye and triticale are the most susceptible crops (Platford and Bernier, 1976, Weston and Taylor, 1942). Triticale and rye are cross pollinated and so flowers remain open for longer than other species resulting in increased susceptibility to infection compared to self-pollinated wheat, barley and oats.

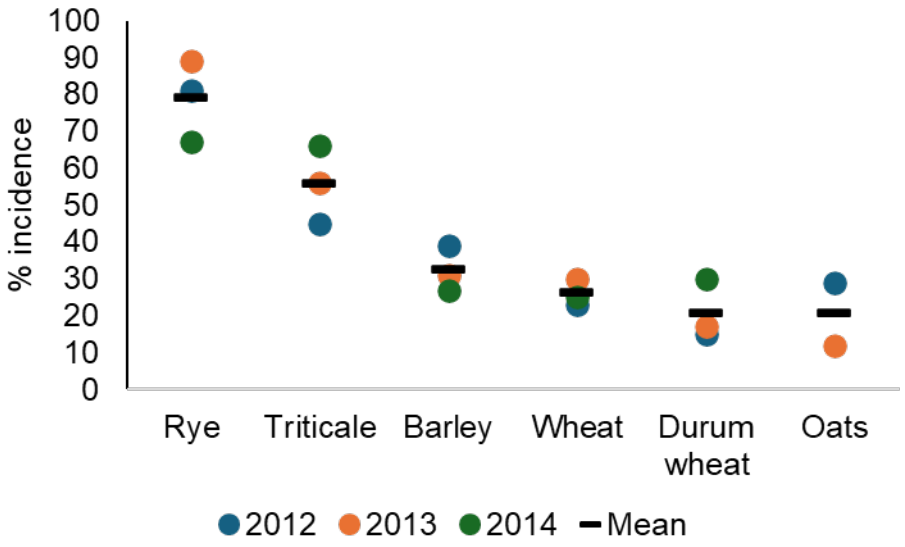


Figure 5-1 Incidence of ergot sclerotia in France by crop and harvest year (Orlando et al., 2017)

Duration of ergot survival is not well understood. Sclerotia generally survive for a single year, although survival for up to 3 years has also been recorded (Maunas and Leclere, 2013, Mitchell and Cooke, 1968, Raphilly, 1968). Sclerotia will germinate within a non-susceptible crop but the

lack of presence of a suitable host will prevent completion of the ergot life cycle. Spores can still be released in non-cereal crops and blown onto susceptible crops. A crop rotation containing non-susceptible crops will reduce the number of viable sclerotia but good control of grass weeds is required. This has been identified as an issue with the cropping of oilseed rape infested with grass weeds (Orlando *et al*., 2017).

In UK agriculture, the shift to simplified rotations, particularly of continuous winter wheat established by minimal cultivations has exacerbated the problem of annual grass-weeds, notably *Alopecurus myosuroides* (Moss, 1980a, b).

Several agronomic factors have been identified as influencing total ergot alkaloid concentrations (Orlando *et al.,* 2017). The most important factors identified were host plant, followed by previous crop (crop rotation), grass weed presence, and tillage system. Within the rotation ergot alkaloid levels were higher following cereal crops and crops infested with grass weeds such as oilseed rape.

5.2. Cultivations

In recent years, increasing size of farms, the drive for cost cutting and a move towards conservation agriculture has led to a reduction in the time allocated for cultivations; leading to a reduction in ploughing and an increase in non-inversion tillage and direct drilling (Jones *et al*., 2006, Townsend *et al*., 2016, Alskaf *et al*., 2019).

Cultivations can play a significant role in the control of ergot both directly by burying ergot sclerotia and indirectly through the control of grass weeds. Sclerotia are unable to germinate when buried to a depth of 5cm or deeper and hence unable to release ascospores into the air (Maunas and Leclere, 2013). Studies in France, investigated the effect of different cultivation systems on the distribution of sclerotia in the top 20cm of the soil. Ergot sclerotia were scattered on the surface and then the effects of cultivation were investigated over the following two seasons. It was found that ploughing in year 1 lowered the number of sclerotia in the top 10cm, with 85% of sclerotia found below 10cm (Figure 5-2). However, shallow cultivation with a Lemken tine cultivator working to 10cm in year 1 kept 65% of the sclerotia in the top 0-5cm layer. Ploughing for a second consecutive year brought sclerotia back up to the soil surface, with up to 60% of sclerotia in the top 10cm. Ploughing once in the two years kept the majority of the sclerotia in below 10cm by the end of the second cultivation, with 81% below 10cm where the ground was ploughed then shallow cultivated, and 64% where the ground was shallow cultivated then ploughed (Figure 5-2). (Maumene *et al*., 2016),

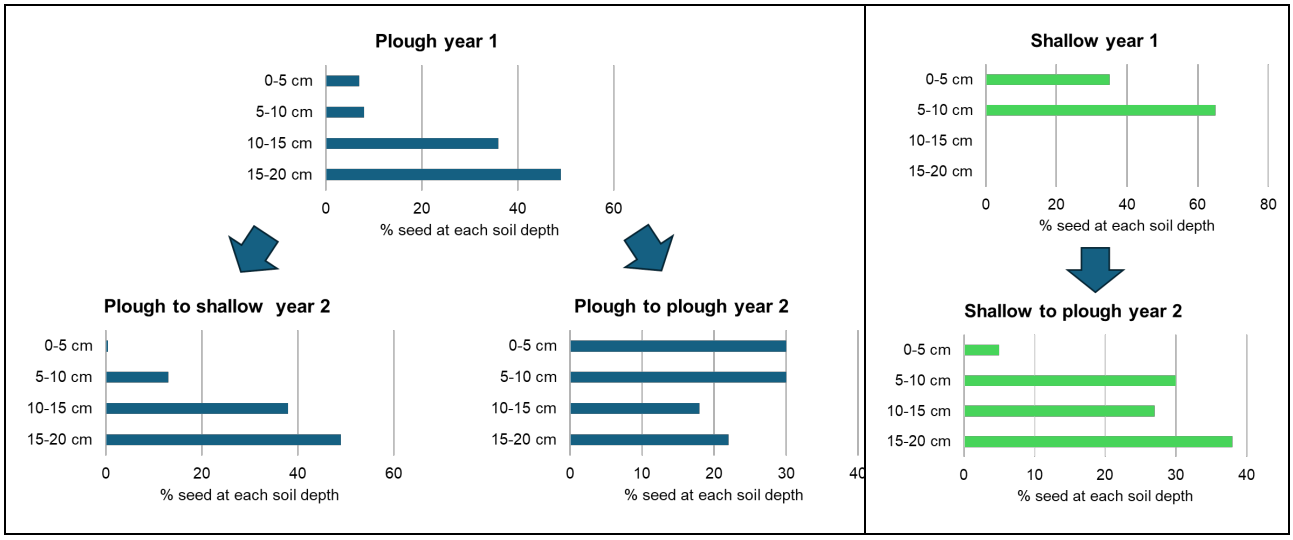


Figure 5-2: Cultivation options and their effect on ergot sclerotia and their position within the soil profile

Additional work in France compared cultivation practices with grain sampled at harvest which was subsequently tested for ergot alkaloids. The results showed that there was less contamination after deep cultivation rather than shallow cultivation, although the difference was not significant. Ploughing did bury the sclerotia preventing the production of spores in the field but other sources of infection such as sclerotia in the field margin or in the seed were unaffected by field cultivations (Orlando *et al*., 2017).

The situation with ergot is similar to the situation with freshly shed weed seeds whereby seeds fall onto the soil surface and cultivation can move or bury them (Figure 5.3). Ploughing inverts soil, burying up to 95% of shed seed to 15-20cm deep, and shallow till mixes the upper layer to the depth of working rather than burying the seed. With no-till there is very little mixing (AHDB, 2017).

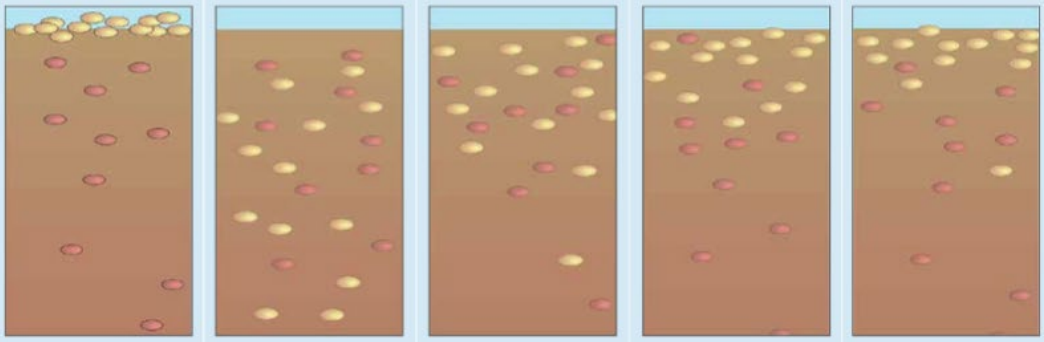
Cultivation	After harvest	Plough	Deep till	Shallow till	No-till
Soil movement	Not applicable	Inversion	Deep	Little	No mixing
Cultivation depth	Not applicable	Over 5 cm, inverted	Over 5 cm	Under 5 cm	None
Example	Not applicable	Plough	Discs over 5 cm	Discs under 5 cm	No-till drill
		Many old seeds brought to surface, most new seeds buried	Fewer old seeds brought to surface, some new seeds buried	Very few old seeds brought to surface. Few seeds added to the seedbank	A few seeds may change layers
Soil depth 5 cm 30 cm					

Figure 5-3. Cultivation options and their effect on freshly shed seed and the weed seedbank (AHDB, 2017)

Work using plastic beads in lieu of weed seeds showed that ploughing buries 86% of beads below 6cm (out of the germination zone) but non-inversion cultivations leave between 50 and 70% of beads in the top 6cm of the soil (Mohler *et al.*, 2006). These are representative of ergot likely to germinate in the following season. Although this makes it clear that minimum tillage would not be as effective as ploughing for burying ergot sclerotia, minimum tillage is still burying between 33% and 52% of the plastic beads deeper than 5cm, depending on the depth of working. Compared with direct drilling which would bury very few, if any, sclerotia below 5cm, it can be assumed that minimum tillage would result in less ergot sclerotia germination than direct drilling.

The inclusion of ploughing in the rotation is a key tool for control of black-grass, each year there is a 70% decline in viable seed in the seedbank. Including ploughing on a rotational basis, once in 3-6 years results in few viable seeds being bought back to the surface (AHDB, 2017).

In the UK, Cussans *et al*., (1979) found that Annual meadow grass (*P. annua*), wild oat (*A. fatua*) and black-grass (*Alopecurus myosuroides*) were all favoured by non-ploughing techniques. In experiments over 9 years using different primary cultivations in a vegetable crop rotation, there was a pronounced effect on seed numbers of *P. annua* (Roberts, 1965). At the end of the experiment, seed numbers were 7, 11 and 23 million per acre respectively for deep ploughed (14-16 ins), shallow ploughed (6-7 ins) and rotary cultivations (6-7 ins).

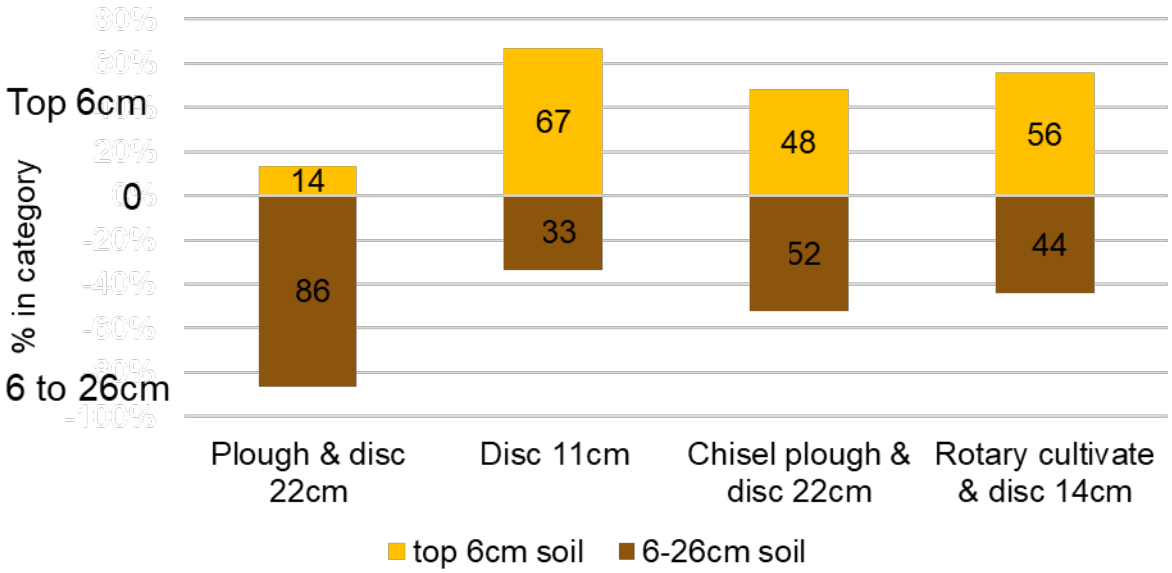


Figure 5-4: The effect of cultivations on beads on the soil surface (from Mohler et al., 2006)

5.3. Sowing and sowing date

Sowing at an even depth into a well-prepared seedbed will promote a uniformly developing crop (Menzies and Turkington, 2015). This can reduce the number of late-developing tillers, which tend to be the tillers that are most severely infected by *C. purpurea* (Bayles *et al.,* 2009). Correct sowing depth is crucial for cereal crops to ensure proper seedling development and plant growth. The seed should be placed deep enough to have access to adequate moisture and yet shallow enough to emerge as quickly as possible. Seeds too close to the surface absorb moisture but are at risk of dying because roots cannot reach moisture quickly enough to sustain the germination and seedling growth. Deeper seeding can reduce stand density and plant vigour because of the inability of the coleoptile to reach the surface. On average, oats are the most tolerant cereal to be placed deeper than the optimum, whilst barley is the least tolerant. Under most conditions, the recommended sowing depth for cereals is around 3-4cm, at which any ergot sclerotia could germinate and release ascospores. The stipes of germinating sclerotia would be unable to break the soil surface if the sclerotia were buried to a depth of at least 5cm, preventing the release of ascospores (Bretag and Merriman, 1981). Brown (1947) reported ergot sclerotia could not extend their stromata when sclerotia with rye seed were planted 3 inches [7.6cm] deep. Therefore, deeper drilling to at least 5cm could help reduce the viability of any ergot sclerotia introduced with the grain at drilling. Pascual *et al.* (1999) investigated sowing wheat at a range of different depths as a tool for reducing risk to birds from treated seeds. In this situation on light fenland soils, deeper sowing (46-50mm) gave better yields than shallower sowings (20-36mm). Therefore, on some soil types, it may be an option to increase sowing depth as a way of reducing the germination of ergot sclerotia, although this will depend on cereal type, variety, seedbed quality and soil type.

The use of sowing date as a tool to reduce the incidence of ergot has not been extensively studied, and adjusting sowing date can have large effects on other factors such as other diseases, weed and pest pressure. Delaying sowing can reduce grassweed pressure and reduce gout fly pressure, both of which can help reduce the severity of ergot. Drilling date affects flowering date, but so do environmental conditions, so it is not possible to predict the best sowing date for ergot control.

Sowing date can also influence the degree of open or closed habit of flowering, although this is not easy to predict (Oxley *et al.,* 2019).

Trials investigating the effects of three sowing dates on the incidence of ergot in spring Durum wheat in North America, found the intermediate sowing date to have the highest incidence of ergot compared with early and late sowing (Gargouri Jbir *et al*., 2022). However, ergot infection rates are a result of complex interactions between pathogen availability, weather, host pollination, and insect spread of honeydew. It is therefore not easy to predict how often sporadic changes in weather patterns will affect each of these factors and what effect this will have on the optimum sowing date. In UK conditions, spring sown crops are more susceptible to ergot infection due to their later flowering coinciding with high levels of secondary infection. Anecdotal comments from farmers and agronomists mention that late drilling of spring wheat should be avoided as this makes the crop far more vulnerable to gout fly damage which could in turn increase susceptibility to ergot, and late sowing invariably means an extended flowering and more opportunities for ergot infection.

5.4. Planting clean seed

The use of uncontaminated seed for drilling is a vital step in preventative action that can be taken to reduce the risk of ergot. The minimum regulatory standard for the maximum number of ergot pieces in certified seed is up to three pieces per 500g, with a higher voluntary standard of 1 piece per 1000g. The use of farm saved seed with high ergot infection levels can cause inoculum to build up and spread within and across fields. Seed that is badly contaminated with ergot sclerotia should not be used for sowing. If contaminated seed cannot be avoided the seed should be cleaned thoroughly to remove the ergots. Gravity sorters or colour sorters are the most effective ways of cleaning home saved seed for sowing.

5.5. Fungicide seed treatments

Treating cereal seed with some fungicides can reduce the viability of sclerotia, although evidence of this being tested in the field is limited. Seed treatments can have the effect of preventing germination of the ergot sclerotia, delaying the germination of sclerotia, or reducing the number of fruiting stalks (clavae). Preventing germination is clearly the preferred mode of action as late germinating sclerotia could still result in ergot developing in grass hosts, late cereal tillers or a spring-sown crop nearby. However, any delay in germination may still contribute to a lower risk of ergot if there are fewer disease cycles each season. The full list of fungicidal cereal seed treatments registered for use in UK is shown in table 5.2. Treatments containing prothioconazole + tebuconazole and ipconazole + imazalil are the only products which currently mention activity to suppress the germination of ergot on the label. Whilst seed treatment can be a useful option for reducing the germination of sclerotia from contaminated seed, it clearly has no effect on the germination of sclerotia already in the soil. However, there is some evidence that under favourable conditions viable sclerotia may still germinate and produce spores even where the seed was treated with a fungicide (Wegulo and Carlson, 2011).

Table 5-1: Commercially available cereal seed treatments in the UK and their activity against ergot

Active ingredient	Product	Crops	Ergot activity mentioned on product label
fludioxonil	Beret Gold	wheat, barley, oats, rye, triticale	
fludioxonil	Prepper	wheat, barley, oats, rye, triticale	
fludioxonil, tebuconazole	Fountain	wheat, barley, oats, rye, triticale	
difenconazole, fludioxonil	Celest Extra	wheat, oats, rye	
difenconazole, fludioxonil	Difend Extra	wheat	
difenconazole, fludioxonil, tebuconazole	Celest Trio	wheat, barley, oats, rye, triticale	
ipconazole, imazalil	Rancona i-MIX	wheat, barley	Suppression of germination of *Claviceps purpurea*
prothioconazole, tebuconazole	Redigo Pro	wheat, barley, oats, rye, triticale	Limited evidence suggests Redigo Pro reduces the germination of ergot particles in contaminated seed stock
sedaxane, fludioxonil	Vibrance Duo	wheat, barley, oats, rye, triticale	
fluopyram, prothioconazole, tebuconazole	Raxil Star	barley	
fludioxonil, fluxapyroxad, triticonazole	Kinto Plus	wheat, barley, oats, rye, triticale	
silthiofam	Latitude	wheat, barley	
silthiofam	Latitude XL	wheat, barley, spelt, triticale	

Fungicide seed treatments have been shown to vary in their activity on the germination and clavae emergence from rye ergot (Dabkevicius *et al.,* 2002). In this work, Fludioxonil gave a significant reduction in mean germination and number of emerged ascosarps, whilst tebuconazole only gave a significant reduction in number of emerged clavae.

The inhibitory effects on rye ergot sclerotia germination of fungicidal seed treatments, Baytan-Universal 19.5 WS (triadimenol + fuberidazole + imazalol), Panoctine 35 LS (guazatine), Divident Star 036 FS (difenoconazole + cyproconazole), Premis 25 FS (triticonazole), Kinto 80 FS (prochloraz + triticonazole) and Jockey 198 FS (fluquinconazole + prochloraz) have also been tested in laboratory and field conditions (Debkevicius *et al.,* 2006). All these seed treatments showed a significant suppression of sclerotia germination under field conditions, although efficacy was significantly lower than under laboratory conditions.

The effects of three seed treatments on the spring germination of wheat ergot sclerotia was investigated by Maunas *et al*. (2013). A seed treatment containing prochloraz + triticonazole gave the highest level of control with an 89% reduction in clavae production and 84% reduction in sclerotia germination. A mixture of carboxine + thiram gave a slightly lower level of control with 76% reduction in clavae production and 65% reduction in germination rate. A mixture of fludioxonil, difenoconazole and sedaxane gave a lower level of control with an approximately 50% reduction in clavae production and a 35% reduction in sclerotia germination.

Ergot sclerotia burial trials that have been carried out by ADAS alongside this review have found that they take 6 weeks to germinate once they have received adequate cold conditioning. Whilst there have been a number of laboratory, glasshouse and field experiments looking at the effect of seed treatments on the germination of ergot sclerotia, there is a lack of field trials data where the sclerotia are buried at conventional autumn sowing dates (September – November) and monitored for germination in the spring, 5-7 months later. It would be worthwhile investigating this with a range of cereal seed treatments that are currently registered for use in the UK, under a range of sowing dates. To aid growers in the control of ergot, it is recommended that the AHDB wheat and barley seed treatment charts are updated to include a column for label suppression of ergot (ahdb.org.uk/knowledge-library/foliar-fungicide-activity-and-seed-treatment-options-for-wheat and ahdb.org.uk/knowledge-library/foliar-fungicide-activity-and-seed-treatment-options-for-barley).

5.6. Foliar and soil applied fungicides

Applying foliar fungicides for the control of ergot is not commonly practiced, with the main limitation of contact fungicides being the difficulty in getting the compounds to reach the plant's ovary (Evans *et al.,* 2000). The ergot fungus infects the ovaries and for most of the time the ovaries are tightly enclosed and protected by the glumes. The only time when the ovaries are accessible to fungicide sprays is when the florets are open to allow cross pollination. The flowers of cereals usually open for relatively short periods and not simultaneously, making it difficult to time an effective fungicide application. This is particularly the case in fields that are not homogenous and have variation in flowering time, or if the crop produces many tillers which have a more spread-out flowering period which offers a longer period for infection.

The are currently no fungicides approved in the UK for application as foliar sprays to control ergot. In Canada, Miravis Ace (pydiflumetafen + propiconazole) has a label claim for the suppression of ergot in wheat (spring, winter and durum), barley and oats. Prosaro Pro (prothioconazole + tebuconazole + fluopyram) is available in some countries and also has suppression of ergot on the label in wheat (spring, durum and winter). Application of Prosaro Pro for the control of fusarium head blight and ergot is recommended at early flower using forward and backward facing nozzles or nozzles that have a two directional spray. The fungicides azoxystrobin and azoxystrobin + propiconazole are also labelled for the control of ergot for grass grown for seed in the pacific northwest (Alaoufi *et al.*, 2023).

Several studies have demonstrated that properly timed fungicide applications can reduce the severity of ergot in Kentucky bluegrass (Alderman, 2006). For optimum effect, fungicides must be applied at the beginning of flowering and have been shown that they can reduce the severity of ergot, however it is not clear whether there is an economic benefit from fungicide application in this case. Kaur *et al.* (2015) investigated the activity of five different fungicides to protect perennial ryegrass flowers from ergot infection during anthesis. These were applied as three applications made at weekly intervals. Applications of flupoyram + prothioconazole, azoxystrobin + propiconazole and pyraclostrobin + fluxapyroxad during anthesis gave a significant reduction in the number of perennial ryegrass heads with ergot honeydew. These treatments also gave a significant reduction in ergot severity along with the other treatments penthiopyrad and benzovindiflupyr. *In vitro* screening has also been used to test a range of fungicides in their efficacy against *Claviceps purpurea* (Yarham, 1996). In this work, fenpropimorph and difenoconazole showed the most consistent activity against isolates of *C. purpurea* from both wheat and barley. Also, a bio-assay of ovules dissected from ears in a field trial suggested that

uptake of the active ingredients into the vulnerable organs of the inflorescence was only very limited because fungicides do not move to the ear systemically (Yarham, 1996).

In vitro tests may also be a poor indicator of field performance. Work by Gladders *et al.* (2001) investigated opportunities for the control of ergot using fungicides under laboratory, glasshouse and field conditions. 34 fungicides were tested, and while many of them showed activity against *C. purpurea in vitro* and in glasshouse trials, field performance was poor and inconsistent. Significant reductions were sometimes obtained with azole fungicides applied close to flowering, but these were too inconsistent to justify commercial use. It was concluded that fungicide sprays are unlikely to provide commercially acceptable levels of ergot control, and in some cases, fungicides may even aggravate the problem. It was therefore recommended that control of ergot will continue to rely on rotations, cultural control, and avoiding susceptible crops on high-risk sites.

Research on ergot in male sterile hard red spring wheat in North Dakota by Alaoufi *et al.* (2023),evaluated the efficacy of four fungicides; Sphaerex (prothioconazole + metconazole), Miravis Ace (pydiflumetafen + propiconazole), Quilt (azoxystrobin + propiconazole), and Priaxor (fluxapyroxad + pyraclostrobin) in field trials on resultant sclerotia characteristics and ergot alkaloids. All four fungicides gave a significant reduction in total ergot body weight, with the fungicide premixture of pydiflumetafen + propiconazole giving a significantly lower weight than the other fungicide treatments. Treatment effects on ergot alkaloids were less clear, with fluxapyroxad + pyraclostrobrin the only treatment giving lower ergot alkaloid levels than the untreated, although this was not significant.

Field trials in North Dakota have been investigating the use of Sphaerex (112.5 g/l metconazole + 187.5 g/l prothioconazole), Prosaro Pro (167 g/l prothioconazole + 84 g/l tebuconazole + 84 g/l fluopyram) and Miravis Ace (125.1 g/l pydiflumetafen + 104.4 g/l propiconazole) for the control of ergot (Friskop, 2024). Prosaro Pro and Miravis Ace both have suppression of ergot on the label in North Dakota, whilst Sphaerex does not. Field trials in 2022 and 2023 used a male sterile line of spring wheat which would be extremely susceptible to ergot. Fungicide sprays were applied at either half ear emergence or full ear emergence, and activity was measured in terms of grams of ergot bodies collected from the plots and total ergot alkaloids (0.5 grams of ergot placed in 80 grams of wheat). Miravis Ace applied at half ear emergence and full ear emergence gave a significant reduction in the weight of ergot bodies (Figure 5.5). Although not significant, the full ear emergence application appeared to give a greater reduction than the half ear emergence application. Sphaerex and Prosaro Pro did not give any reduction in weight of ergot bodies, and no fungicide treatments were able to reduce the level of total alkaloids (Figure 5.6).

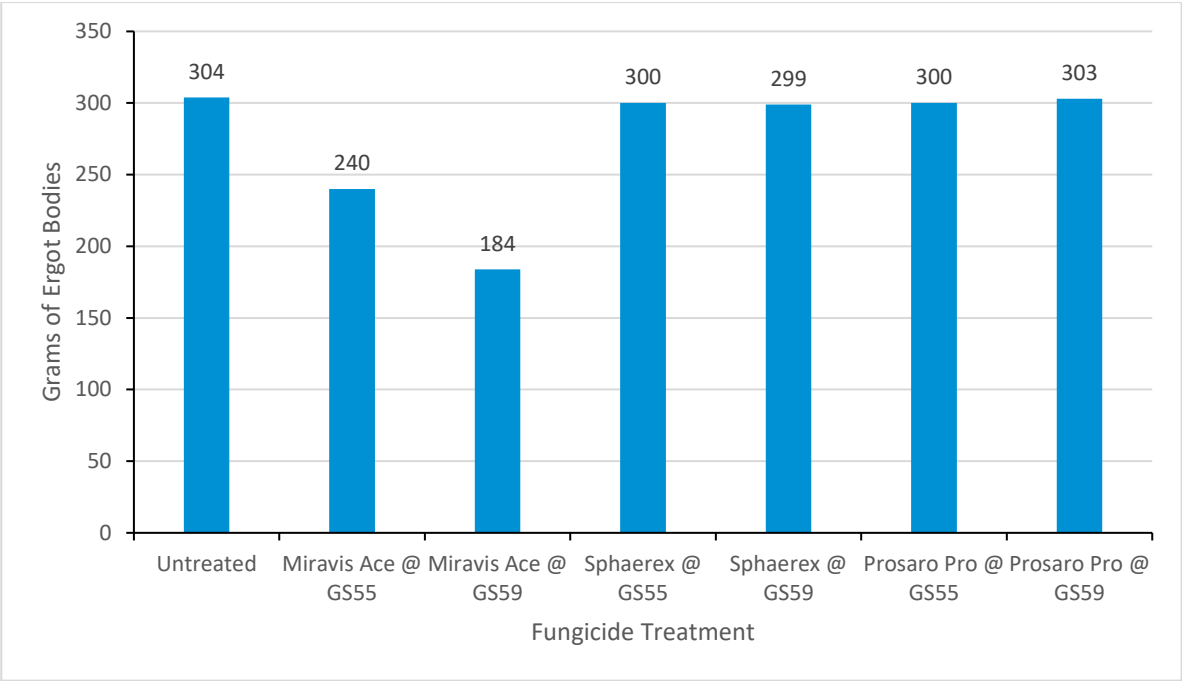


Figure 5-5 Grams of ergot bodies recovered from spring wheat plots treated with Miravis Ace (1.0 l/ha), Sphaerex (0.53 l/ha) and Prosaro Pro (0.75 l/ha), applied at half ear emergence (GS55) and full ear emergence (GS59) (Friskop, 2024)

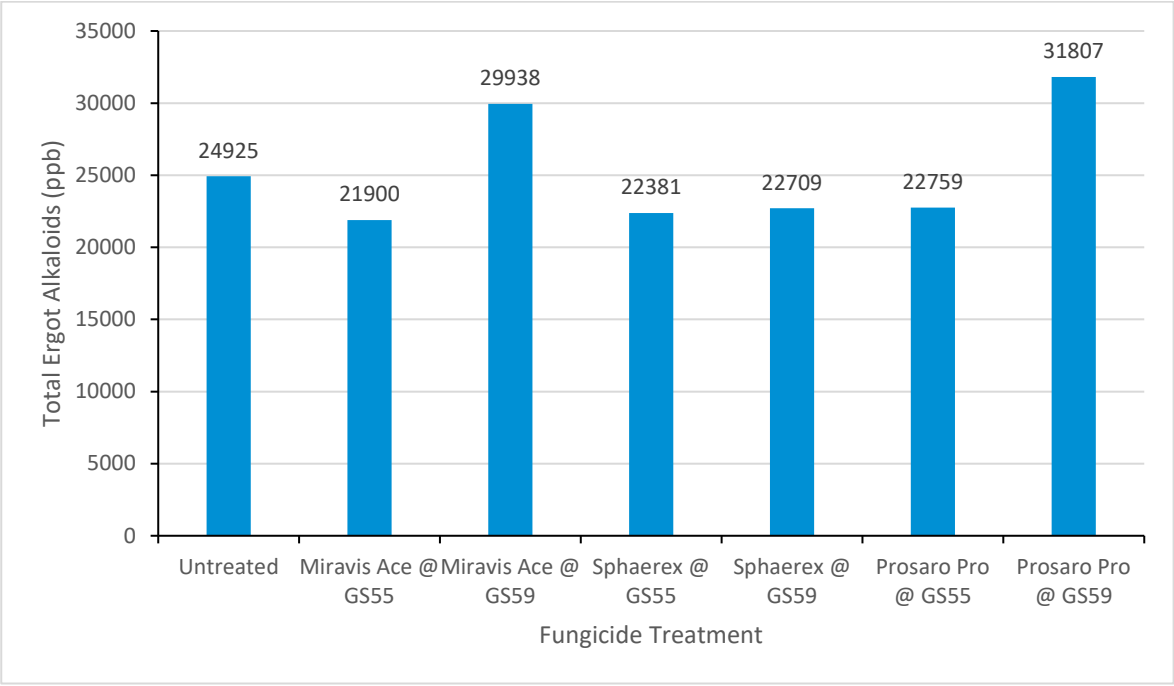


Figure 5-6 Total ergot alkaloids (0.5 grams of ergot placed in 80 grams of wheat) for grain from wheat plots treated with Miravis Ace (1.0 l/ha), Sphaerex (0.53 l/ha) and Prosaro Pro (0.75 l/ha), applied at half ear emergence (GS55) and full ear emergence (GS59) (Friskop, 2024)

Trials with soil-applied fungicides have investigated the potential for reducing the germination of ergot sclerotia in perennial cool-season grass seed production systems (Dung *et al*., 2018). Lab experiments *in vitro* tested eight fungicide treatments, showing reduced sclerotia germination and capitula formation from applications of azoxystrobin + propiconazole and picoxystrobin + cyproconazole. In field experiments, autumn applications of fluopyram + prothioconazole reduced the area under capitula production curve (AUCPC) values by 59, 72 and 73% in 2014, 2015 and 2016 respectively. Azoxystrobin, azoxystrobin + propiconazole and pyraclostrobin reduced AUCPC values by 34-42% over three years of field trials. These results indicate that there may be potential to reduce sclerotia germination and capitula (ergot fruiting bodies) production of *C. purpurea* by using soil applied fungicides, although this approach does carry the risk of affecting native beneficial microorganisms. Other work has investigated the efficacy of soil applied fungicides to reduce ergot sclerotia germination in Kentucky bluegrass seed production. Autumn, spring and autumn + spring applications of 12 different fungicides were applied to the soil, although none of them were registered for soil application. There were no statistically significant reductions in sclerotia germination from application of any fungicide treatments, although autumn and autumn and spring applications of fluopyram + prothioconazole and azoxystrobin appeared to reduce AUCPC values (Kaur *et al*., 2015).

5.7. Biological control

There is some evidence that biocontrol agents could be used to reduce or delay germination of sclerotia on the soil, or to try and control infection within the ears.

The products Contans (*Coniothyrium minitans*), Trichopel (*Trichoderma harzianum*) and SoilGard (*Gliocladium virens*) were tested in a lab assay to evaluate their efficacy for the inhibition of germination of perennial ryegrass sclerotia (Kaur *et al.,* 2016). These all gave a significant reduction in area under capitula production curve compared to the water-treated control. Serenade (*Bacillus subtilis*) appeared to give a reduction in area under capitula production curve compared to the control, although this was not significant. Additional testing of these and other biocontrol products is required to prove their effectiveness in the field.

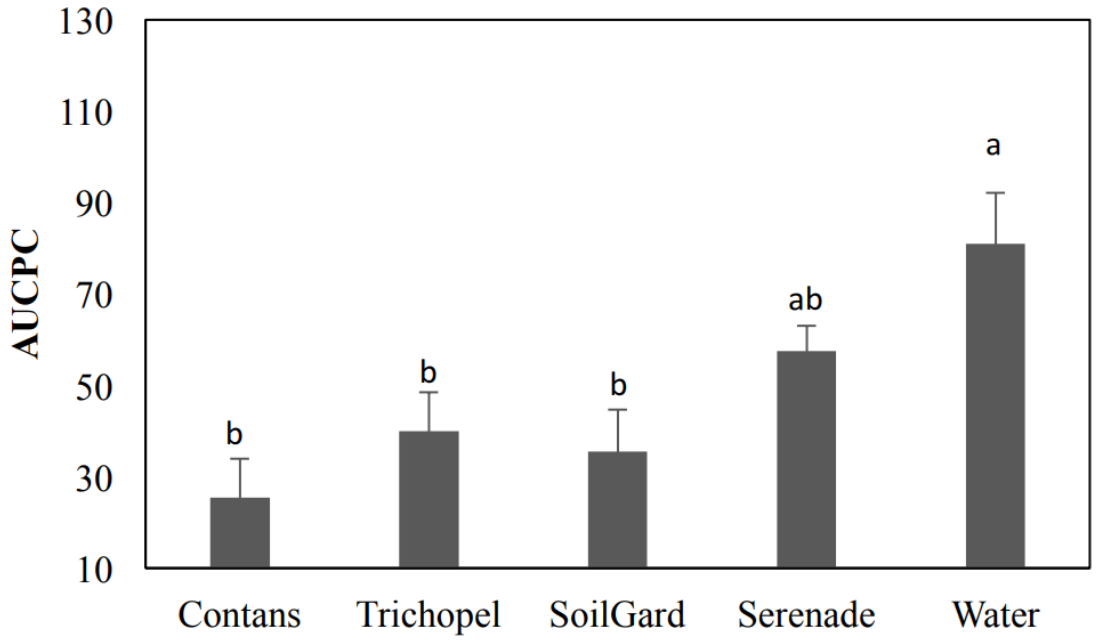


Figure 5-7: Mean area under capitula production curve (AUCPC) values in experimental petri plates containing ergot sclerotia treated with various biocontrol fungicides. (Kaur et al., 2016)

A wide range of *Trichoderma spp.* were also tested more recently in Germany against *C. purpurea in vitro* of infected rye in glasshouse trials (Stange *et al.,* 2023). The *Trichoderma* isolates *T. harzianum 20770* (B)*, T. atroviride* 20780 (C), *T. atroviride* 20781 (D), *T. hamatum* 20784 (E), and *T. harzianum* WM24a1 (G) showed the most robust ability to inhibit the growth of *C. purpurea.* The glasshouse trials showed a trend for protection against ergot when *Trichoderma spp.* was used as a rhizosphere treatment of the rye. It was concluded that *Trichoderma* could provide an alternative and sustainable disease management strategy for controlling ergot infection, although this needs further investigation and testing under field conditions. Dabkevicius *et al.* (2002) investigated the effects of the fungus *Trichoderma lignorum* and the bacteria *Pseudomonas aureofaciens* applied as a seed treatment on the germination of winter rye ergot sclerotia. Neither treatment had any significant effect on sclerotia germination and ascocarps formation.

Little work here has focused on the biological control of ergot alkaloids.

5.8. Weeds

The presence of grass weeds has been identified as a key source of ergot, due to the wide host range present in and around cereal fields (Orlando *et al*., 2017 and Bayles *et al*., 2009). French researchers investigating the occurrence, pattern and agronomic practices for managing ergot identified weeds in the top three agronomic factors that resulted in the highest levels of ergot alkaloid content in harvested grain (figure 5.8).

The flowering period of grass weeds, which is earlier and longer than for cereals, generally coincides with the germination period of ergot sclerotia and they can be infected by ascospores. Approximately 7 days after infection by ascospores, honeydew is produced by the plant in response to the fungus. This contains fungal conidia that can further infect both weeds and the crop as it flowers (Campbell, 1957). Sclerotia produced by grass weeds then return to the soil or are harvested with the crop.

Weight of ergot sclerotia from black-grass was directly related to populations in the field. In France Bonin *et al*., (2013) showed a significant relationship between the weight of harvested ergot sclerotia (from wheat or black-grass) and the number of black-grass heads (*A. myosuroides*). The presence of weeds does not guarantee infection of ergot but is a significant contributory factor. Infection also depends on the presence of inoculum and other contributory factors such as weather conditions. Sclerotia produced by black-grass (*A. myosuroides*) are ten times lighter than those produced by wheat but are equally capable of germinating and producing spores (Arvalis, 2020).

The number of herbicides for the control of grass weeds has decreased and the levels of herbicide resistance have increased, making control of grass weeds within crops more difficult (Orlando et al, 2019, Cook *et al*., 2023). Less complete control of grass weeds will lead to an increase in the levels of ergot seen.

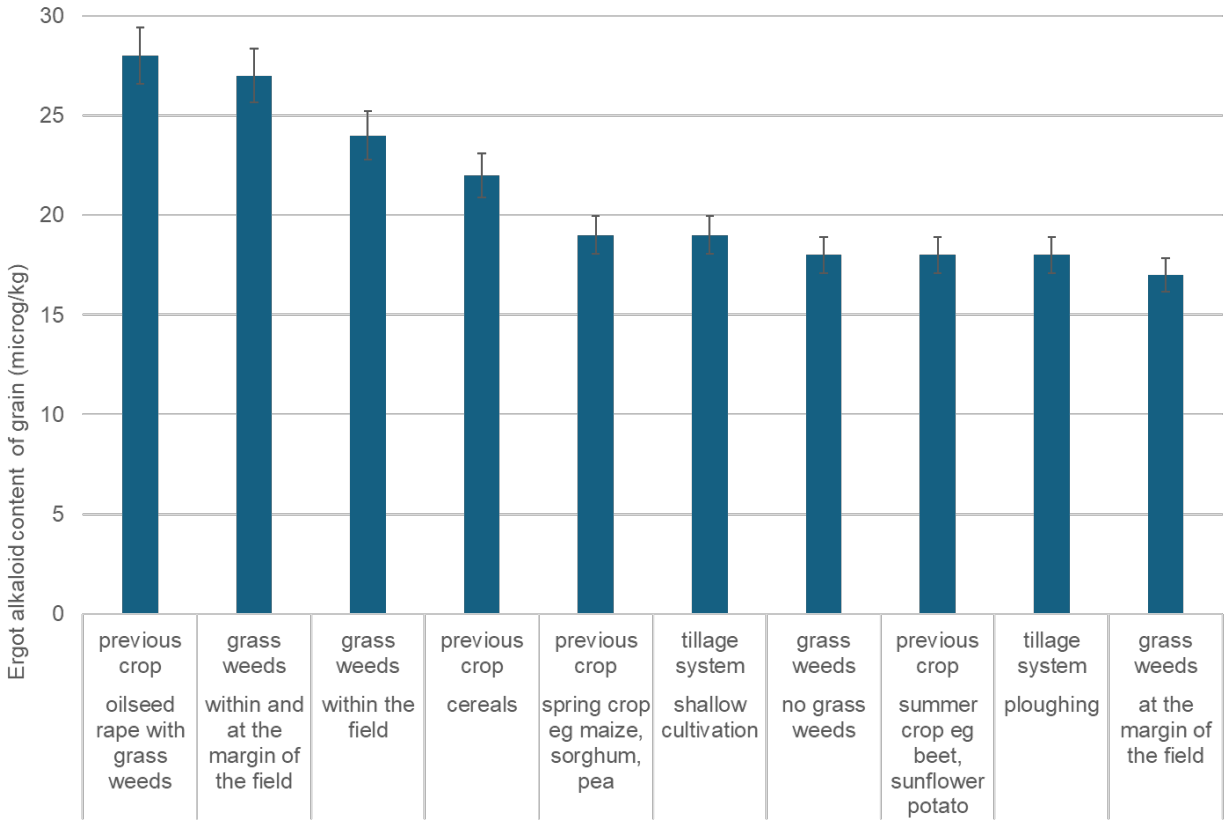


Figure 5-8 Effect of agronomic factors on total alkaloid content of harvested grain (from Orlando et al., 2017)

Weed control is key to prevention and spread of ergot within a cereal crop (Berraies *et al*., 2024, Orlando et al., 2017). In the UK there has been much research on the control of grass weeds in the rotation, as loss of key herbicides has led to the development and uptake of more integrated control measures (AHDB, 2017, Lutman *et al*., 2013). Herbicides are still widely used with predominance of pre-emergence product use in wheat and barley crops (Cook *et al*., 2019). Herbicide availability is much reduced for crops with a smaller area grown such as oats, rye and triticale and this is an issue for effective grass weed control. The AHDB have a wide range of

guidelines for weed control either in the rotation, in a crop, or for a particular weed species such as black-grass and brome (AHDB, 2025).

It is possible that using an instrument such as the Zurn Top Cut Collect which is capable of collecting and removing grass weed heads showing above the crop could prevent them from acting as a primary point of infection (as conidia infected honeydew) and lessen the secondary spread of ergot within the crop.

5.9. Pests

The honeydew produced by infected ears contains conidia of ergot which can be spread from cereal crops and grasses predominantly by insects and rain splash but can also be from head-to-head contact or any other means; animal, human or mechanical that transfers the sticky honeydew from one flower to another. The relative importance of insects and rain splash for spreading honeydew is not well understood. Insects, particularly flies and moths are attracted to ergot honeydew as a food source. As these insects crawl around a seed head they can pick up and transfer honeydew to other flowers, contributing to disease spread. However, quantitative information on the role of insects in ergot epidemiology is lacking. It is not known if control of insects would reduce secondary spread of ergot (Alderman, 2006).

The conidia of *C. purpurea* have been found on a diversity of insects, including moths, flies, leafhoppers and thrips. Butler *et al.* (2001) investigated the association between insects in crops of Kentucky bluegrass in Central Oregon grown for seed just before harvest. Up to 100% of moths and 75% of flies collected from some fields carried conidia of *C. purpurea.* However, there was no correlation between ergot honeydew present in a field and number of insects with conidia of *C. purpurea.* Other work has found a significant positive correlation between insect abundance and ergot incidence in perennial ryegrass fields (Kaur *et al*., 2019) whereby the author investigated the association between insect abundance and ergot disease incidence in a range of perennial ryegrass seed fields in 2014 and 2015. This work reported *C. purpurea* spores being detected on 39% and 36% of dipteran insects collected in 2014 and 2015 respectively. Similarly, 44% and 18% of lepidopteran insects tested positive for the presence of *C. purpurea* spores in 2014 and 2015 respectively. Lemon (1992) investigated the dispersal of *C. purpurea* spores by flies or beetles in tall fescue. The beetle *Acylomus* sp. was not found to be a spore dispersal vector of *C. purpurea,* whilst the fly *M. lupulina* carried spores on the bodies and in their gut, and transferred the spores to their surroundings. Anecdotal reports have linked the percent of aphids in crops around flowering with ergot severity. Although it is conceivable aphid movements could spread infections, such a link remains unproven. Further work is required to determine the role of insects in the transfer of ergot infected honeydew from one plant to another in UK cereal crops, and the relative importance of different insect species.

Anecdotally, some farmers and agronomists have noticed a link between spring gout fly damage and the occurrence of ergot in cereal crops (Ergot expert group pers comms). The second generation of gout fly in May and June can affect the ear emergence and development in spring wheats and late formed tillers of winter wheat. This gout fly larval grazing around the base of the developing ear and sometimes on the ear itself can result in poorly developed ears, with immature grains spoiled on one side. It is possible that these ears are predisposed to attack from ergot if the weather conditions become conducive.

5.10. Crop nutrition

Ensuring adequate nutrient availability can help the crop to have an even stand and a short flowering period. This can reduce the likelihood of secondary infection of late formed tillers. Poor fertility may delay maturity and create a more open floret physiology that is susceptible to infection (Menzies and Turkington, 2015). Deficiency of either copper or boron in plants has also been linked with more severe cases of ergot infection (Menzies and Turkington, 2015).

The relative susceptibility of cereal crops to copper deficiency is in the order: barley>oats>wheat (McAndrew *et al.,* 1984). Wheat and barley primarily rely on self-pollination rather than cross-pollination. However, copper deficiency causes pollen sterility, preventing self-pollination and causing the flowers to open in an attempt to cross pollinate. These open flowers are more likely to become infected with ergot. Copper deficiency has been recorded in only a few specific soil types in the UK, namely organic and peaty soils, reclaimed heathland sands, and shallow, organic chalk soils (with 6 to 12% organic matter) in South England (Archer, 1985). The most extensive areas of copper deficient soils are on the shallow chalks of southwest and southeast England, on peats and heathland soils. In Scotland, copper deficiency occurs in soils derived from acid schists and granite rock, as well as peaty soils. Chalmers *et al.,* (1999) suggested that the incidence of copper deficiency is higher in Scotland than the rest of the UK. Winter cereals are less susceptible than spring cereals to drought-induced copper deficiencies as their root structure is better developed, allowing them to exploit micronutrients which sit lower in the soil (Roques *et al.,* 2013).

Boron deficiency has also been linked to high levels of ergot. Boron is involved in the metabolism of carbohydrates and phenolic acids, which are crucial for growth of pollen tubes. This can mean that although the pollen has germinated, the pollen tubes are unable to reach the ovary resulting in fertilisation failure. It has often been seen that reproductive growth, mainly flowering, fruit and seed set and seed yield is particularly sensitive to boron deficiency (Bariya *et al.,* 2014). Availability of boron decreases as soil pH increases, and high rates of lime application can therefore induce boron deficiency (Roques *et al.,* 2013). There is also a strong association between boron and soil organic matter, with boron availability reducing with increasing organic matter content (Roques *et al.,* 2013). Boron deficiency is most likely to occur on soils derived from acid igneous rocks and, especially sandy soils which inherently contain little boron. Boron can be toxic to cereals at levels only slightly above those required for optimum growth and so care must be taken to ensure that excessive amounts of boron applied to correct potential deficiency in one crop do not present a potential toxicity risk to the following crop (Roques *et al.,* 2013).

Copper is an essential micronutrient for plants and plays a role in various physiological processes. However, using copper to prevent ergot in cereals is not a common or recommended practice (Omex, 2024). Copper and boron are not included in a standard soil analysis, but it may be worth including them, if deficiency is suspected. Alternatively, other services, such as YEN nutrition, can analyse harvest grain samples and use benchmarks to identify potentially yield-limiting nutrient deficiencies. However, the application of copper and boron does not eliminate the risk of ergot, as other factors, such as cool or hot weather at flowering, or improperly timed herbicide applications may lead to pollen sterility and therefore increase the risk of ergot (Menzies *et al.,* 2015).

Mielke (1993) investigated the effects of applying calcium cyanamide on the germination of winter rye ergot sclerotia laid out on the ground. This showed that spring applications of calcium cyanamide reduced the germination of ergot sclerotia by 40-50%. However, calcium cyanamide, commonly sold under the product name of Perlka, is registered for use as a fertiliser, not a plant protection product.

5.11. Margins, grassland, grass breaks, hedge bottoms, beetle banks and buffer strips

Field margins have been widely proven as a source of inoculum (Berraies *et al,*. 2024, Bayles *et al*., 2009), but any sown or naturally occurring piece of grassland, beetle bank, buffer strip or hedge bottom can also act as a source. The inoculum can be as overwintering sclerotia which supply the primary inoculum (ascospores) for the season and as a source of secondary inoculum (conidia) that can infect the susceptible crop as honeydew.

Field edges provide a source of secondary inoculum from infected grasses. This may be exacerbated by the higher frequency of late tillers on the field edge (Bayles *et al*., 2009).

Ascospores infect early flowering grasses, the subsequent honeydew has been seen as a key source of inoculum for spring wheat crops (Bayles *et al*., 2009). Surveys in France have shown that there was no indication that margins were the main source of ergot, but sown margins were of lower risk than unsown/wild areas. Margins contribute to the overall reservoir of ergot inoculum in the arable environment, and they may also provide a local source of secondary inoculum from infected grasses which poses a risk to wheat at the crop/margin interface. Margin age, type of margin and crop cultivation practices (ploughing or minimum tillage) had little effect on ergot incidence in margins. Ergot numbers were higher close to the hedge or next to the crop (Orlando *et al*., 2017).

5.11.1. Mowing

Repeated mowing will prevent grass weeds from flowering and as a consequence prevent infection with ergot.

Mowing of field margins can reduce the production of honeydew for secondary spread and of sclerotia for overwintering (Berraies *et al*., 2024). Bayles *et al.* (2009) conducted a mowing experiment where plots were either mown once on 31st May or mown twice on 31st May and mid-July. Mowing reduced fertile tillers significantly and repeating mowing reduced fertile tiller number to near single figures, although this was dependent on season and species. Mowing reduced ergot levels but did not eradicate it.

Grasses show a staggered ear emergence. Shield and Godwin (1992) showed that at a mid-May cutting date, black-grass (*A. myosuroides*) had tillers ranging in growth stage from GS31 to GS57. As a consequence, after mowing, flowering tillers could reappear after 4 days. The authors also showed the response of Sterile brome (*Anisantha sterilis*) to mowing Figure 5-9), as a consequence, the height of the fertile tillers reduced at each mowing, leaving the latest tillers below the height of the mower. Black-grass growth also followed this pattern and volunteer wheat only recovered from the first mowing. First cuts should be mown as high as possible to remove the heads only. Subsequent mowings should be at lower heights.

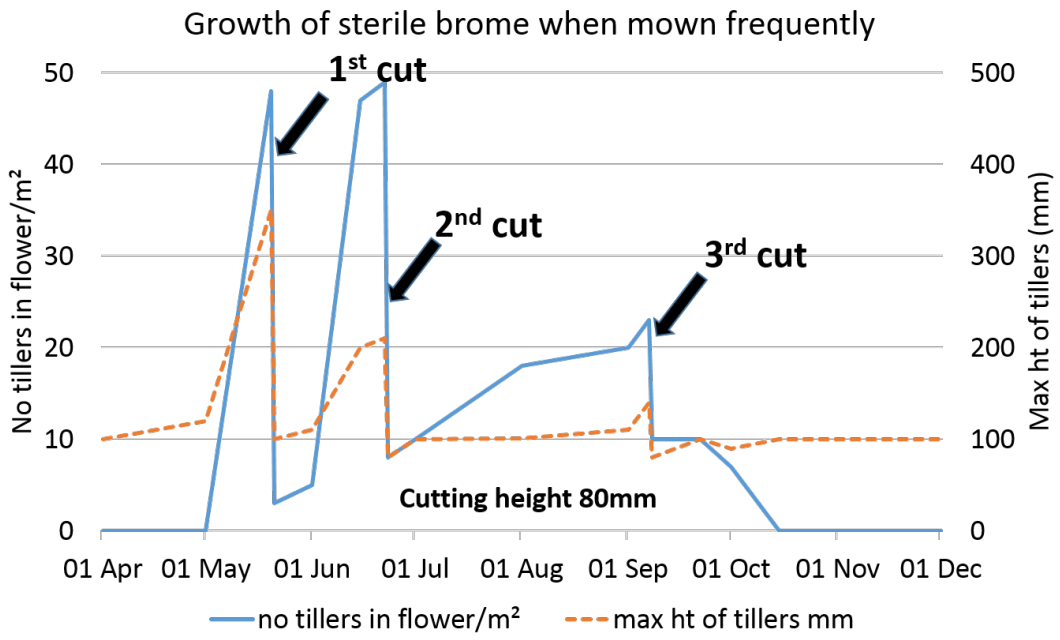


Figure 5-9: Growth of sterile brome when mown frequently (from Shield and Godwin, 1992).

5.11.2. Other management of margins

Sowing of less susceptible grass species is an option. In a four year study in the UK, Bayles *et al.* (2009) identified ergot in 37 grass species and presence of the pathogen was more common in areas of weedy grass and natural regeneration than in sown margins. The authors identified that ergot from different grass species differed in their infectivity for wheat and there was also variation between ergots from the same grass species. It was concluded that grass species which combine low infectivity for wheat with late flowering should minimise the risk of spread of ergot to adjacent crops. The predominant sources of ergot were couch, cocksfoot, black-grass, perennial ryegrass, tall oat grass, Italian ryegrass, timothy, tall fescue and Yorkshire fog. They identified sweet vernal grass (*Anthoxanthum odoratum*) and creeping soft grass (*Holcus mollis*) as low infectivity and crested dog's tail (*Cynosurus cristatus*) as a low-risk species.

Herbicides could be used in margins to control some grass species, but the species affected are very limited. Cycloxydim can be used on green cover on land not being used for crop production. Species reported as susceptible on the cycloxydim label (Laser MAPP 17339) include loose silky bent (*Apera spica venti*), perennial ryegrass (*Lolium perenne*), sterile brome (*Anisantha sterilis*), soft brome (*Bromus hordeaceus*), black bent (*Agrostis gigantea*), false oat grass (*Arrhenatherum elatius*) and creeping bent (*Agrostis stolonifera*). Black-grass and Italian ryegrass are reported as being susceptible but due to high levels of resistance to Herbicide Resistance Action Committee (HRAC) group 1 herbicides (Cook *et al.*, 2023), the level of control of these species is expected to be low. Tolerant species include red fescue (*festuca* spp.), annual meadow grass (*Poa annua*) and rough stalked meadow grass (*Poa trivialis)*.

Wavy hair grass (*Deschampsia flexuosa)* and Yorkshire fog (*Holcus lanatus*) have both been identified as having low ergot infectivity, so are desirable species in margins (Bayles *et al.*, 2009) however, both have also been identified as being susceptible to cycloxydim (Willoughby and Forster, 2021).

5.12. Management of crop uniformity

A uniform crop that flowers over a shorter time period is at lower risk from ergot infection. Late tillers and side shoots flowering outside the pollination period of the main stand are more affected by ergot than the main shoots (Wegulo and Carlson, 2011). The most important factor to ensure a uniform crop is to avoid sub-optimal plant population and avoiding an uneven plant population. Both of these factors would result in tillers at a wide range of developmental stages. The starting point for a consistent crop is to sow seed with good germination potential at an appropriate seed rate, into a well-prepared seedbed at a consistent depth (Wegulo and Carslon, 2011). This will result in uniform crop development that will in turn prevent a prolonged flowering period. Controlling establishment pests is also vital in establishing an even and consistent crop. Adopting precision farming techniques for variable rate application of inputs such as seed, phosphate and potash can be effective ways of increasing crop uniformity across the field. It is possible that some varieties may be more prone to producing more late formed tillers, and it may be worth avoiding such varieties.

5.13. Hygiene

Good hygiene is the first defence against the introduction of soil borne diseases into clean land. Howard et al., (2014) reported that hundreds of kilograms of infected soil and crop debris can be moved from field to field on farm machinery. Machinery that is used in infested fields should be power washed before use in uninfected fields, and soil should be at least knocked off from boots and tools. Clean fields should be visited first in the sequence of crops so that cleaning down of equipment can be done at the end of the day. Thorough cleaning of combines after harvesting badly ergot infected fields can also reduce the risk of spreading ergot sclerotia from one field to another, in much the same way that this is used as a mitigation tool for grassweed control.

5.14. Forage crops and risk to livestock by direct poisoning

In addition to risk from feeding livestock with ergot infected grain, there is also the risk that grazing animals can consume ergot infected pasture directly or via infected conserved forage (Canty et al, 2014). A significant challenge in identifying the exact effects of ergot alkaloids on livestock is the highly variable animal response to exposure. Issues can therefore range from often-unpredictable acute outbreaks of gangrenous ergotism to more subtle and chronic decreases in livestock productivity (Klotz, 2015). The full range of effects from ingestion of ergot alkaloids by livestock can include poor weight gain, reduced fertility, hyperthermia, convulsions, gangrene of the extremities and even death (Dewell and Ensley, 2024). As with cereal grains, the incidence and severity of ergot alkaloids in grazed grass and conserved forage will vary with climatic conditions and sward species. Since the ergot fungus is only in the seed head, grazing of infected pasture before the seed head develops is advised (Dewell and Ensley, 2024). Field inspection is vital each year to determine presence and severity of ergot, and where ergot sclerotia are identified in a grazing field, the livestock should be removed. Grass that has developed a seed head and has an issue with ergot can be topped before allowing livestock to graze. Conserved forage produced from ergot infected grass may be toxic as well. Although the sclerotia can often drop off the grass as it is being handled in the process of haymaking or haylage making, it should be inspected before feeding to ensure that it does not contain sclerotia (Dewell and Ensley, 2024). Delayed harvesting of grass hay due to rain means that late cut hay can be more at risk of infection, and so extra vigilance will be required. Longer term, selecting grass species when replacing pastures that have greater ergot resistance and lower infectivity could lower the risk of ergot alkaloid poisoning.

6. Harvest mitigation strategies

6.1. Delaying harvesting badly affected areas

Delaying harvest of an ergot infected crop can reduce the amount of ergot sclerotia in harvested grain as they can be shaken from the ears by the wind (Menzies and Turkington, 2015). Although this will result in fewer ergot sclerotia in the harvested grain, it will have the knock-on effect of leaving more ergot sclerotia on the soil surface which continues the cycle of infection and may exacerbate the problem in subsequent seasons.

6.1.1. Harvesting headlands and field separately

Scouting fields before harvest to identify areas heavily infected with ergot and then harvesting these separately from the rest of the field can be a useful way of managing an infestation at harvest (Wegulo and Carlson, 2011). Typically, higher levels of ergot occur around field edges due to the proximity of grass margins and late developing tillers where crops are shaded by hedges. Harvesting these areas separately can be an effective strategy for minimising ergot contamination.

6.1.2. Harvest weed seed control attachments

At harvest time, weeds that are still present in the crop have seeds held in the seed head. These seeds are harvested with the crop and the majority exit the harvester and are spread with the straw and chaff. Harvest weed seed control (HWSC) has been successfully adopted by farmers in Australia (Akhter et al., 2022). The strategy is to collect and/or destroy the weed seeds in the chaff material during harvest using methods such as chaff carts, bale direct system, integrated impact mills, windrow burning, chaff tramlining and chaff lining or other methods of targeting the chaff material containing the weed seeds. UK trials with an integrated impact mill resulted in 85% reduction in weed seed return (Bofin, 2025). As ergot are present in the seed heads at harvest there is the possibility that these methods could be used to destroy or remove ergots from the field.

7. Sorting and removal of ergot from grain

7.1. Best sampling practices

It is important to monitor the quality of grain going into and out of the shed to reduce the likelihood of claims and rejections and any associated charges. An accurate sampling process at harvest will allow the grower to have a complete picture of what grain is in the shed. The challenge of sampling grain is to obtain a representative sample that will accurately reflect the characteristics of the bulk sample, whilst adhering to the best practice in health and safety. Best practice is to take a series of incremental samples for different parts of any given lot, blend them thoroughly and then take a subsample for analysis. The best time to do this is when filling the store at harvest, as this allows regular incremental samples to be taken from each trailer load. This will invariably give a better representation of the bulk of the grain than samples obtained by spearing the heap.

Further information on grain sampling can be found in the AHDB Grain sampling guide (AHDB, 2025a).

7.2. Best sorting practices

Ergot sclerotia can be removed from infested grain by using mechanical sieves, gravity sorters or optical-electric colour sorters. However, it may not be possible to sufficiently clean heavily infested grain, and cleaning processes can be timely and costly. If farmers are not members of a grain store, cleaning ergot from a contaminated sample can cost up to £18/tonne, although there may be a discount where they are members. Cleaning ergot sclerotia and ergot sclerotia fragments from the grain can significantly reduce the alkaloid content of the grain sample but does not produce a grain sample that is free from alkaloids. This is because there is the potential for alkaloid transfer onto clean grain during post-harvest processing, loading and transportation (Byrd *et al.,* 2014). Gordon *et al.* (2019) investigated the potential for ergot alkaloids to be spread by physical contact to clean seed from ergot sclerotia. It was found that ergot alkaloids could be readily transferred from both intact ergot sclerotia, as well as broken particles of sclerotia, with the broken particles resulting in more alkaloid transfer. Cleaning contaminated grain as early as possible to reduce sclerotia breakage and further alkaloid contamination can help reduce alkaloid concentrations in the cleaned sample. Ergot sclerotia on grass species tend to be smaller and more easily breakable and so contamination with black-grass sclerotia during harvest presents a greater risk of physical transfer of ergot alkaloids during transportation of the grain. The same project also found that ergot alkaloids can transfer to healthy grain that develop above and below flowers that are infected with *C. purpurea.*

7.2.1. Mechanical sieves and rotary cleaning

Ergot sclerotia can be very difficult to remove from a grain sample by mechanical cleaning, due to the many different sizes and shapes that they come in. However, where grain is contaminated with grassweed ergot sclerotia which are much smaller and thinner than the cereal grains, it may be possible in some cases to remove them with a standard sieve cleaner which sorts according to size and density (Gilbard, 2024). Bulk rotary cleaners are a simple and fast way of separating out oversized and/or undersized contaminants from good grain. Research by Arvalis in 2015 found that cleaning wheat samples using a dual cleaner comprising a rotary drum and aspirator removed 43% of ergot sclerotia with a low/reduced flow rate and optimised settings. Mobile bulk rotary cleaning systems can typically clean approximately 20-25 tonnes of wheat per hour.

7.2.2. Gravity separation

Gravity separation can be used for grading components in a grain sample by specific weight of products with very slight differences in size and/or weight which cannot be separated by screening (width), aspiration (weight) or by indented cylinders (length). Gravity separation, aided by an air stream separates the ergot sclerotia of lower specific gravity than the grain. Most systems work on a fluidized bed principle where air is forced through the deck causing the light fraction to float above the heavy fraction. The deck is reciprocated causing the heavy fraction to move uphill, while the light fraction floats downhill. Variations in deck speed, air volume, deck material, deck angle and take-off points allow fine adjustments to be made in the degree of separation. Mobile gravity cleaning operations can typically clean 8-10 tonnes per hour.

7.2.3. Colour sorting

Optical electric colour separation is particularly effective for ergot removal in cereals. Colour sorters drop the grain by gravity onto a shoot which is then inspected by a series of digital cameras that can recognise any defect in the grain. Once the defect has been recognised, a blow of compressed air deflects it to a waste collection area. Colour sorters are able to cross recognise both size and colour, giving a double evaluation which can help limit processing waste and increase the final quality of the product. Costs of this equipment are high and the process greatly reduces flow capacity during milling. However, colour sorters work with very little waste; as little as one tenth of gravity separators.

Modern mobile seed cleaning and treatment units often have optical colour sorting devices installed on them, allowing ergot to be cleaned from the seed on farm, with a typical output of 12 tonnes per hour. However, it can cost approximately £18/t to clean ergot from infected seed, which is a significant cost (Gilbard, 2024). There will also be a cleaning weight loss of around 2% during the cleaning process, although this may be higher in heavily contaminated grain.

8. Breeding

As already highlighted in Chapter 3 (and 3.2) different grass weed and crop species vary in their susceptibility to *C. purpurea*. Rye and then triticale are the most susceptible with oats, wheat and barley being less so, although male sterile barley has a less complex flowering structure and is highly susceptible to ergot infection. At the species level, these differences are due to the physical mechanisms by which the pathogen can infect the flower and therefore relates to a) when the flower emerges and for how long and b) flower morphology (Berraies *et al*., 2023). These macro differences in susceptibility have already been highlighted in order to support the management strategy recommendations and coincide with the phases of the pathogen life cycle. So, for example, avoid growing rye and triticale in a high ergot risk area, if at all possible, and avoid agronomic practices that result in poor establishment and hence unevenness of flowering timing.

When breeding for *C. purpurea* resistance within a crop species such as wheat or barley, it is clear that selecting varieties with positive avoidance traits such as more closed flowers, less secondary tillering (which will result in asynchronous flowering timing) and shorter flowering periods would confer an advantage when trying to limit infection and hence levels of ergot (Wood and Coley-Smith, 1982, Menzies and Turkington, 2015). It has been shown that breeding for differences in flowering development can significantly reduce disease levels for both open pollinating and self-pollinating crops. An interesting example has been highlighted by Miedaner *et al*., (2021) who showed that a reduction in levels of ergot in rye could be achieved through breeding for high pollen shedding as the fungus ended up competing with the pollen for the exposed stigma, reducing infection. Conversely, a very good example of an unintended consequence from plant breeding occurred with the introduction of the variety Rialto, which was launched in 1991. Unlike most wheat varieties, Rialto had a tendency for more open flowering (chasmogamy) which meant that the florets remained open for longer which increased the window for ascospores or conidia to enter and infect the ovary. In addition, it was found that Rialto exhibited delayed pollen shedding which meant that there was a lag between floret opening and fertilisation leaving an opportunity for the pathogen to infect (Gordon *et al*., 2015, Menzie and Turkington, 2015). The emergence of Rialto as a high-risk wheat variety for ergot was a surprise to the industry and caused a great deal of concern at the time. Ergot resistance was not a plant breeding target and was an unintended consequence of breeding for foliar disease resistance and yield. Indeed, despite its ergot risk, Rialto has been in the parentage of several subsequent wheat varieties over the years due to its other positive traits.

Currently, information on the flowering habit, morphology and duration of modern wheat and barley varieties is limited and not easily available to either farmers or growers (Ergot expert group pers comms). It is true that flowering characteristics within a variety are likely to vary to some extent based on sowing date, soil type, nutrient availability and weather, however, it is also a genetic trait of a particular variety and should be measurable within certain limitations and should be considered as additional necessary information within the Recommended List.

An alternative approach to breeding for variety resistance in key crops such as wheat is via selection of generic traits which provide active resistance once infection has occurred, thus developing a form of host immunity. Before using this as a useful breeding target it is important to more fully understand the molecular mechanisms by which the plant immune system may be able to defend itself against *C. purpurea*. However, there is very little information about the genes that confer resistance in, for example wheat, to ergot (Tente *et al*., 2021). The first reports of partial resistance to ergot in both hexaploid and durum wheat were reported in the 1970s when Platford

and Bernier, 1976 demonstrated a reduction in honeydew production as well as a reduction in the size of ergots in some varieties (Platford *et al*, 1977).

More recently, the most significant finding has been in the cv Greenshank which is a durum wheat line described by Menzies, 2004, and Menzies and Turkington, 2015. It was found that Greenshank not only produced fewer and smaller sclerotia (ergots) but also had much lower levels of honeydew, and hence conidial production. Subsequent mapping of quantitative trait loci (QTLs) associated with ergot resistance by Gordon *et al.,* 2020 demonstrated that cv Greenshank carried ergot resistant alleles on chromosomes 1B, 2A, 5A and 5B. These findings encouraged the development of further lines based on Greenshank with Ruan *et al*., (2021) developing a new durum wheat line that was found to be highly resistant to ergot. Despite infection by the *C. purpurea* fungus, little to no honeydew was produced and very few sclerotia were formed.

To date, few similar mapping studies in hexaploid wheat have been carried out and breeding for ergot resistant varieties has not been a key target. However, work reported by Tente *et al*., 2021 has investigated the role of host hormone biosynthesis and signalling pathways in the host:pathogen relationship as a possible future target for plant breeding or novel control methods. Their work demonstrated that infection with *C. purpurea* resulted in changes in the expression of the host wheat genes which were associated with hormone metabolism and signalling as well as a wide range and number of genes related to host defence. This supports many other similar studies where plant hormones have been identified as having a key role to play in the regulation of immune responses to pathogens (Pieterse *et al*., 2012). The work described by Tente *et al*., (2021) indicates that the pathogen is able to rapidly alter hormone levels *in planta* effectively “co-opting” the hosts hormone homeostasis and/or signalling mechanisms to facilitate infection. If these alterations or triggers could be suppressed within the plant and/or modified chemically, then there could be a useful opportunity to reduce or prevent infection by the pathogen.

9. Conclusions and recommendations

9.1. Key findings from the review

Ergot in cereals caused by *C. purpurea* has been around since the Middle Ages and has been characterised by its sporadic nature. The increase in frequency of occurrence that has been seen in recent years can be attributed to a combination of weather conditions and the fact that many modern farming practices are actually conducive to the development of ergot. Modern farming practices combined with cool, wet conditions during flowering are the perfect combination for a high level of ergot infection. Although there are a number of different management methods for the control of ergot, it is difficult to completely eliminate the risk, as there is no one control method that is entirely successful in controlling ergot on its own. Therefore, the control of ergot relies on an integrated approach that uses a range of strategies. The AHDB has a set of guidelines that are available to growers to help them control ergot. The purpose of this review was to examine all of the available literature on ergot from around the world and update the guidelines for the UK based on the findings of the review. It was never anticipated that the review would uncover any single revolutionary method for the control of ergot. It was hoped that some of the research and development that has been carried out since the guidelines were last updated could be used to add new methods which may contribute to the control of ergot. It was also hoped that the information could be used to give a weighting to each of the control methods so that growers are more aware of the likely impact from each of the control measures.

The life cycle of *C. purpurea* is complex as it includes both sexual and asexual reproduction. In terms of crop management, there are two key sources of inoculum that can provide a risk to the host plant – primary inoculum and secondary inoculum. Whilst reviewing the life cycle, it was clear that there are four key stages in the life cycle where growers can intervene to try and control ergot:

1. Control of ergot sclerotia inoculum in the soil
2. Establishment and management of a cereal crop that is less susceptible to ergot
3. Control of secondary spread of ergot via grasses
4. Harvest and post-harvest practices to limit the level of contamination and remove ergots from the grain

Extending the crop rotation is a very effective way of controlling ergot. In some cases, ergot sclerotia have been shown to survive in the soil for up to three years, and so ideally a break from cereals for two or more years in high-risk situations would be an effective way of reducing the risk from ergot. Where a cereal must be grown, selecting one of the less susceptible species such as wheat, barley or oats rather than rye or triticale would be an effective way of reducing ergot levels.

Ploughing to bury ergot sclerotia at least 5cm deep so that they cannot emerge above the soil surface is an effective way of reducing ascospore production in the spring. However, it is important to think of the ergot sclerotia bank in the soil in the same way as a grassweed seedbank is considered. After ploughing, it is important to use shallow cultivations in the subsequent year. Ploughing for a second year in a row would have the effect of bringing a significant proportion of the ergot sclerotia back up to the soil surface. Research suggests that non-inversion tillage could bury a proportion (33% to 52%) of ergot sclerotia to deeper than 5cm, depending on the depth of working. In this case, minimum tillage may reduce ergot sclerotia germination more than direct drilling. This area needs further work to establish whether minimum tillage has a benefit over direct drilling for managing ergot sclerotia germination. Drilling into a good seedbed at an even depth can help the development of a uniform crop that is less susceptible to ergot. Where soil type allows,

drilling deeper than 5cm could reduce the germination potential of ergot introduced with the seed at drilling, although care needs to be taken to avoid sowing the cereal seed too deep.

Every effort should be made to ensure that uncontaminated seed is used for drilling. This can be achieved by using cleaned and certified seed, or if using home saved seed ensuring that it is taken from an uncontaminated seed stock. Where home saved seed is intended to be sown and contains ergot sclerotia, the seed should be cleaned, preferably with a gravity separator or colour sorter. Treating seed for sowing with a seed treatment that has suppression of ergot on the label could help reduce the germination of ergot introduced with the seed at drilling. There are currently two seed treatments on the market in the UK that have suppression of ergot on the label. There have been a number of trials carried out to investigate the effects of seed treatments on the germination of ergot sclerotia. However, very few of these were actually carried out in the field, and the ergot were generally sown in November/December rather than the normal drilling time of September/October. Further investigation is required to determine the effect of cereal seed treatments on the germination of ergot sclerotia in the field. The sclerotia should be buried at the standard drilling time of September/October to investigate their effect on germination 5-7 months later.

Applying fungicides for the control of ergot is not commonly practiced due to the challenges of getting the products to reach the plant ovaries where infection is taking place, and the relatively short window of opportunity for the application. There are currently no fungicides registered for the control or suppression of ergot in the UK. Whilst laboratory and glasshouse experiments have often shown good activity from fungicides against *C. purpurea*, field performance has often been inconsistent. Recent trials in North Dakota have shown a reduction in ergot body weight from applying fungicides at half ear emergence or full ear emergence, although effects on alkaloid levels were less clear. Miravis Ace (pydiflumetafen + propiconazole) gave the most effective reduction in ergot body weight. More work is required to investigate the effects of current fungicides applied at ear emergence on the level of ergot infection. Soil applied fungicides have shown some success in reducing the germination of ergot sclerotia, although there are currently no fungicides in the UK registered for soil treatment. This approach also risks affecting beneficial microorganisms.

The use of biocontrol agents to control ergot has not been extensively studied. Lab assays have shown *Coniothyrium minitans*, *Trichoderma harczianum* and *Gliocladium virens* to give a reduction in germination of ergot sclerotia, whilst glasshouse trials showed a trend for *Trichoderma* to inhibit the growth of *C. purpurea*. More work is required to investigate the effectiveness of biocontrol agents to inhibit the germination of ergot sclerotia and to control ergot infection in the cereal ear.

Grassweeds are a key source of ergot, and so their control within the crop is critical for effective control of ergot. Grasses flower earlier and for a longer period of time than cereals, and so are flowering as the ergot sclerotia are germinating. Approximately 7 days post infection, honeydew is produced which, via insects and rain splash, spreads to further infect weeds and the crop as it flowers. Grassweed control is becoming increasingly challenging in cereals due to less herbicides being available and levels of herbicide resistance having increased. Growing spring cereals is an effective way of reducing grassweed pressure. However, spring cereals are more susceptible to ergot due to a flowering habit and later time of flowering which provides a greater opportunity of infection with ergot spores.

Honeydew containing ergot conidia is spread from cereal crops and grasses mainly by insects and rain splash. However, the relative importance of these methods of transfer are not well understood. Further research is required to determine the role of insects in the transfer of honeydew, and the

relative importance of different insect species. Infection of late formed tillers of winter wheat or later flowering spring wheats with second generation gout fly in May and June can damage ears and affect flowering. This could make ears more vulnerable to ergot infection.

Adequate levels of crop nutrition are vital to ensure a consistent and even crop which flowers for a shorter period of time and is less susceptible to infection with ergot. Also, poor crop fertility can delay maturity and make the crop more open flowering which leaves it more open to infection. Copper deficiency can cause pollen sterility in wheat and barley which causes the flowers to open up, making them more susceptible to infection from ergot. Reductions in ergot levels have been seen from applying copper in copper deficient situations, although copper deficiency has only been recorded a few specific soil types in the UK. Monitoring at risk fields and correcting this with soil or foliar applications of copper could help reduce ergot levels. Boron deficiency has also been linked to ergot, as boron is important for the growth of the pollen tubes. As boron availability decreases as soil pH increases, it would be advisable to monitor both boron level and pH on soils prone to boron deficiency. There is a lack of UK field trial data to prove the value of adequate copper and boron levels for limiting the development of ergot. This is an area which requires further investigation. Due to soil variability, small plot trials may not be the best way of investigating this. Tramline trials where different tramlines are treated with copper and/or boron could be a more effective way of investigating the effects on ergot levels. Spring applications of calcium cyanamide have shown a reduction in germination of winter rye ergot. The value of this in other cereals for reducing ergot levels requires further investigation.

The shorter the flowering period of a cereal crop, the less opportunity there is for ergot to infect the grain site. Establishing and growing a uniform crop can be an effective way of shortening the flowering period. A patchy, thin crop will develop many late tillers which extends the flowering period. Factors that can help establish a uniform crop are sowing high quality seed with high germination potential at an appropriate seed rate, at a suitable sowing depth into a well-prepared seedbed. Controlling establishment pests and using precision application of seed and crop inputs can also help ensure a more uniform crop.

Good hygiene with cultivation and harvesting equipment could help lower the risk of spreading ergot sclerotia from heavily infected fields to cleaner fields. Although this has not been extensively studied in terms of ergot control, there are no reasons why the hygiene principles applicable to grassweed control should not apply to ergot and add to the integrated approach.

Where a high level of ergot infestation is identified in specific field areas, harvesting these areas separately can be a very effective way of containing the level of ergot contamination. In the future, the use of harvest weed seed control attachments could be a useful way of reducing the return of ergot sclerotia to the soil, although this area requires further research.

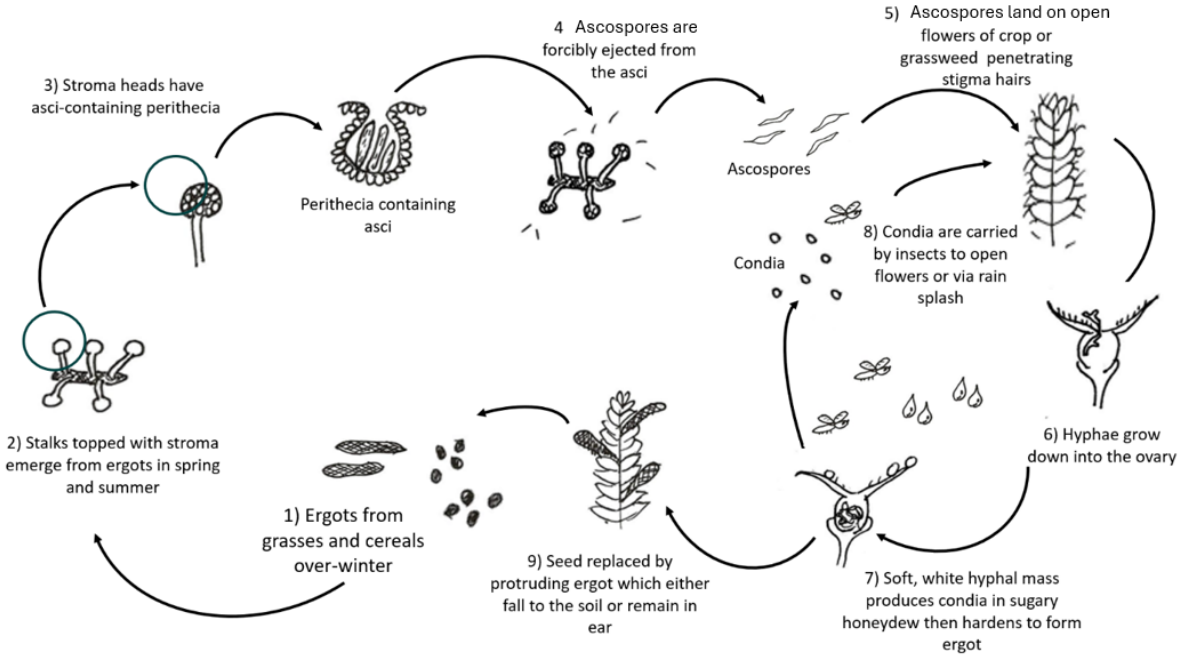
Taking representative grain samples at harvest can be a useful way of identifying any problem fields and keeping this separate from the bulk of the grain. Where grain is contaminated with ergot, cleaning grain with colour sorters or gravity separators can be an effective way of reducing the level of contamination, although this does not ensure that the grain sample is free from alkaloids.

To date, breeding for ergot avoidance or resistance has not been a key target, when compared with some of the potentially yield reducing foliar diseases. Selecting varieties that have a short flowering period, more closed flowering habit, and high pollen shedding ability could be a useful tool to reducing ergot levels. However, this information is not readily available and so it is recommended that ways of assessing these traits are investigated with a view to incorporating the

information in the Recommended Lists. Also, avoiding varieties that are prone to producing a lot of late tillers could be an effective way of reducing the length of the flowering period. This type of information is currently anecdotal, and so again it would be useful to incorporate a scoring system into the Recommended List. Alternatively, as there are several factors that might affect varietal susceptibility, screening existing varieties in inoculated trials may usefully identify differences of value. Longer term, breeding for ergot resistant varieties would be a highly effective way of reducing ergot levels.

9.3. Key guidelines for farmers

9.3.1. Ergot life cycle diagram



9.3.2. Interventions and their impact

Higher-impact interventions:

1. Crop rotation
2. Cereal species
3. Drill clean seed
4. Stale seedbeds (to control grass weeds)
5. Cultivate (until at least 5 cm)
6. Avoid early sowing (to control grass weeds)
7. Herbicides (to control grass weeds)
8. Varietal choice (length of flowering, openness of flowering)*
9. Harvest infected areas separately and keep grain separate

*Limited evidence available.

Moderate-impact interventions:

1. Keep records of infestations
2. Appropriate seed rate
3. Good quality seedbed
4. Control of pests at establishment
5. Adequate crop nutrition
6. Grass-weed control in non-host crops
7. Sow late-flowering, low-infectivity species in grass margins
8. Mow grass margins (if permitted)

9. Scout fields before harvest to identify problem areas
10. Monitor grain contamination as it enters the grain store
11. Seed treatments*

*Limited evidence available.

Lower-impact interventions (still useful when integrated with other measures):

1. Cultivator hygiene
2. Combine hygiene
3. Spring cropping (to control grass weeds)
4. Monitor copper, boron and pH levels
5. Minimise the handling of infected grain before sieving/sorting

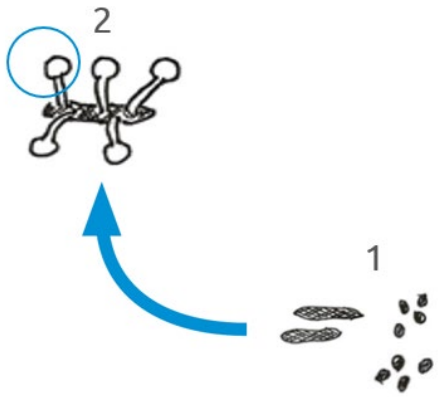
9.3.3. Interventions (in life cycle sequence)

Reduction of ergot inoculum

Life cycle:

1. Dormant ergots (from grasses and cereals) on or in the soil or crop debris over the winter

2. Stroma-topped stalks emerge from ergots near/on the soil surface in spring and summer (which develop and eventually release ascospores)



Reducing risk (main options):

- Cultivations:
    - Cultivate to bury ergots to a depth of at least 5 cm
    - Ploughing is best and minimum tillage is more effective than direct drilling
    - Avoid cultivations that may bring ergots to the soil surface in the following year
- Drill high quality, clean seed. Either:
    - Certified seed or
    - Clean, home-saved seed (via gravity separator/colour sorter)

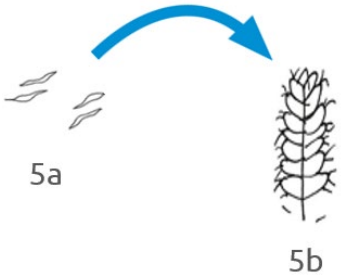
Reducing risk (other options):

- Use seed treatments that cite suppression of ergot on the label
- Clean machinery after working in infected fields
- Control weeds in non-host and host crops
- Keep records of fields with previous ergot infestations

Reduction of infection risk

Life cycle:

5. Ascospores (5a) land on open flowers of crop or grass weed (5b) and penetrate stigma hairs.



Reducing risk (main options):

- Rotation
  - Grow a non-cereal crop in high-risk areas
  - Select a cereal crop that is less susceptible (oats < barley < wheat < triticale < rye)
- Establish a uniform crop:
  - Use an appropriate seed rate
  - Use variable seed rates, where applicable
  - Sow into a good seedbed at a consistent depth
  - Control establishment pests
  - Ensure crop nutrition is adequate
- Choose lower-risk varieties*:
  - Avoid open-flowering varieties
  - Avoid varieties with a long flowering period
  - Avoid varieties with prolific late tillering

*Limited evidence available.

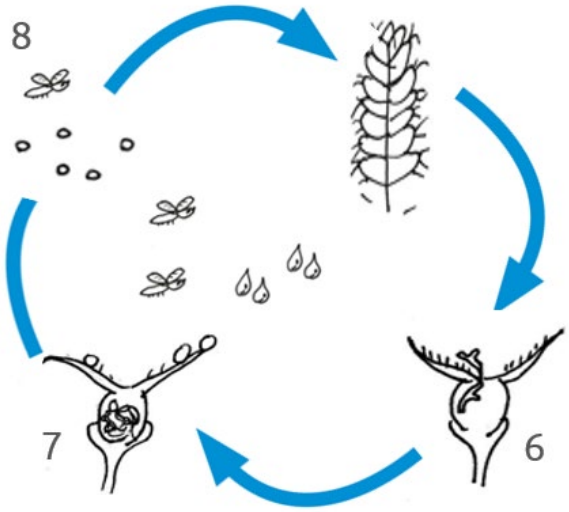
Reducing risk (other options):

- Manage factors that affect the time of flowering:
  - Monitor copper levels on high-risk soils by soil or grain analysis (copper deficiency can cause pollen sterility)
  - Monitor boron levels on high-risk soils by soil or grain analysis
  - Monitor soil pH (high pH reduces boron availability)

Reduction of secondary spread

Life cycle:

6. Hyphae grow down into the ovary
7. Soft, white hyphal mass produces condia in sugary honeydew, which hardens to form ergot
8. Conidia are carried by insects to open flowers or via rain splash or physical contact



Reducing risk (main options):

- Control grass weeds:
    - Use appropriate cultivations to manage weed seeds in the soil seedbank
    - Create stale seedbeds
    - Delay sowing
    - Consider spring cropping
    - Consider herbicides

Reducing risk (other options):

- Manage margins, buffer strips and beetle banks:
    - Sow later-flowering species with lower infectivity*
    - Mow or top grasses (if permitted)

*Limited evidence available.

Harvest and post-harvest management

Life cycle:

9. Seed replaced by protruding ergot, which either remains in the ear or falls to the floor

Reducing risk (main options):

- Identify and pay attention to high-risk fields (e.g. fields with grass-weed issues or high-risk crops, such as rye or triticale)
- Scout fields and grass margins to identify problem areas prior to harvest
- Harvest infected areas separately and segregate from other grain
- Sample and monitor grain as it enters the store
- Store infected grain separately
- Check grain intended for animal feed use
- Clean contaminated grain (via gravity separator/colour sorter)
- Update records to flag higher-risk fields/areas

Reducing risk (other options):

- Clean equipment after harvesting infected grain
- Minimise infected grain handling before cleaning, where possible

9.4. Knowledge gaps – areas for future research

- The benefit of minimum tillage versus direct drilling for burying ergot sclerotia below 5cm, at which point they can no longer germinate.
- The use of biological control agents for controlling ergot sclerotia germination as a soil application and controlling ear infection as a foliar application.
- The use of products for suppression of ergot sclerotia germination, such as calcium cyanamide (Perlka).
- The use of fungicide and biofungicide seed treatments for suppressing the germination of ergot sclerotia by burying treated ergot sclerotia in September/October and monitoring germination in the spring.
- The use of modern fungicides applied as a spray application at ear emergence for the control of ergot in high pressure situations. This should be combined with modern nozzle technology techniques which have the potential to get more of the fungicide treatment to the target site in the ovary.
- The effect of correcting copper and/or boron deficiency on the severity of ergot infection. This could be done by using a high-pressure situation such as rye grown on a potentially copper/boron deficient soil type and treating different tramlines to monitor effects on ergot levels in grain samples.
- The effectiveness of harvest weed seed removal techniques to prevent ergot sclerotia being returned to the soil at harvest.
- Testing of grass species to identify differences in their infectivity for ergot.
- Investigate the effects of mowing grasses on ergot infection, such as best mowing techniques, including optimum cutting height and frequency of cutting.
- Quantify and validate the contribution of IPM practices to the control of ergot.
- Investigate the impact of geographical location and local microclimates.
- Identify ways of measuring flowering characteristics of cereal varieties, such as degree of open flowering, length of flowering and propensity for late tillering.
- The ability for ergot sclerotia and fragments to contaminate clean grain with alkaloids is well documented. The route of transfer of alkaloids from infected flowers to healthy grain is less clear. It is important to find out precisely how the ergot alkaloids move from the infected flowers to healthy grain, where in the healthy flowers and grain the alkaloids are deposited and when in the life cycle this occurs.
- Quantify the alkaloid content of different grass weed seeds.
- Develop an ergot forecasting or risk model for the UK.
- Develop field monitoring and detection tests for ergot.

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11. Appendix 1: Literature review methodology

This chapter details the Rapid Evidence Assessment (REA) which was undertaken with the aim of reviewing the current state of ergot (Claviceps purpurea) research with the aim to provide better management guidelines for the disease in cereal crops.

THE REA was carried out following standard methodology (Defra, 2015). Section 2 of this report outlines the research questions and search terms used to complete the REA.

11.1. Research questions

The primary research question for this REA was:

1. What are the key stages of the ergot life cycle? – Distribution, Ergot transmission, Infection process, Genetical Changes of Ergot (i.e. resistances, adaptations)
2. What practices can farmers deploy in temperate regions to manage ergot (i.e. seed treatments, cultivations, etc.) in commercially cultivated grasses?
3. What practices can breeders deploy in temperate regions to breed (i.e. Open flower structure, flower timings) for ergot resistant varieties in commercially cultivated grasses?
4. What harvesting practices are there to decrease ergot presence in commercially cultivated grasses?
5. What are the best practices to remove ergot from grain (i.e. sampling techniques and ergot sorting)?

For the purpose of this review, which is primarily focused on the United Kingdom, the commercially significant grass species that are susceptible to ergot infection and hold substantial economic value have been identified as follows:

- Wheat
- Barley
- Rye
- Oats
- Triticale

Specific countries with temperate climates comparable to that of the United Kingdom, which align with the focus of this review, were identified.

Additionally, countries with well-documented expertise in ergot were included. These countries have been incorporated into the review search criteria as follows:

Ireland, France, Belgium, Netherlands, Denmark, Germany, Luxembourg, Austria, Czech Republic, New Zealand, Czechia, Northern Spain, Poland, Canada, USA.

11.2. Methodology

11.2.1. REA process

The REA process followed the following key steps:

1. REA Protocol design
    a. Search term generation
    b. Inclusion / exclusion criteria

Suggested search terms are captured in this document; however, a scoping stage took place at the start of the searches to ensure the search terms were delivering relevant evidence and to offer an opportunity to revise the search terms where necessary.

2. Conducting the REA following PRISMA recording Protocol
    a. Systematic searches

Search terms were applied using the key words outlined below. The project team documented the date of each search, noting the number of articles returned. The top 50 titles (when sorted in order of relevance) and other relevant article information for Web of Science searches were recorded for each research question.

    b. Evidence Screening 1: RAG Screening titles

RAG (Red-Amber-Green) rankings were used to screen the evidence based on title, ranking it as ‘clearly relevant’ (Green), ‘clearly not relevant’ (Red) or ‘uncertain’ (Orange). Evidence that was ‘clearly not relevant’ was discarded and evidence that was ‘clearly relevant’ or ‘uncertain’ was recorded and carried through to the second screening stage. To avoid the duplication of work, searches were combined at this stage and duplicate titles removed.

    c. Evidence Screening 3: RAG Screening Abstracts

Working in an ascending fashion through the ‘Green’ titles, the abstract, executive summary or introductory and/or concluding paragraphs (depending on availability) were RAG evaluated. ‘Green’ abstracts were moved through to the full reading stage whilst ‘Amber’ abstracts were checked by a second reviewer for secondary evaluation, before being carried forward or removed.

    d. Complete Data Extraction

Where the content was clearly relevant (‘Green’), data was extracted. Due to time constraints a time suitable REA protocol was developed. This meant the number of relevant titles taken forward to full data extraction was limited to 50 per research question.

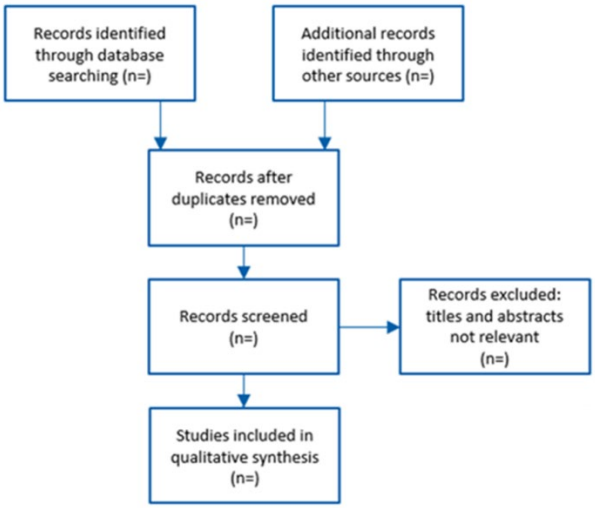

Figure 11-1. PRISMA diagram displaying the REA recording process

11.2.2. Search criteria

The systematic searches outlined below were conducted using Web of Science and Google Scholar. Relevant search terms for each question were identified in consultation with AHDB. Grey literature was obtained by conducting searches using ‘Google’, ‘OpenGrey’ and ‘Defra Science’ and also by requesting relevant information from project stakeholders.

Research question	Key search terms
1 – ergot life cycle	Life cycle
	Infection
	Honeydew
	Ascospores
	Sclerotinia
	Spread
	Distribution
	Transmission
	Genetics
	Resistance
	Adaptation
2 – ergot management	Seed treatment
	Fungicide
	Pesticide
	Treatment
	Biocontrol
	Fertilizer
	Nutrition
	Bio-fungicide
	Biological
	Boron
	Copper
	Cultivation
	Blends
	Margins
	Management
	Tillers
	Hygiene
	Lodging
	Ploughing
	Rotation
	Weeds
	Margin Species

	Beetle Banks
	Grassweeds
	SFI
3 - Breeding	Breeding
	Varieties
	Winter
	Spring
	Flowering
	Sterile
	Hybrid
	Resistant
4 – Harvest practices	Harvest
	Varieties
	Winter
	Spring
	Flowering
	Sterile
	Hybrid
	Resistant
5 – Ergot removal from grain	Grain
	Sampling
	Sorters
	Sieving
	Colour
	Colour Sorter
	Gravity Separation

11.2.3. Search terms

Searches were conducted using Boolean search terms. The operator ‘AND’ was used to combine key words together, producing relevant search results, whilst ‘OR’ was used to broaden search results by including synonyms.

In total 10 Search strings were produced by combining search terms. Key search terms were identified for the pathogen of interest, each research question, commercial crop of interest and region. Splitting the searches into research questions ensured that a range of relevant material was sourced.

Table 11-1. Key search terms identified and used in search strings for each question

Pathogen of interest	Commercial crop of interest	Region
Ergot	Cereal	Ireland
Claviceps	Wheat	France
	Barley	Belgium
	Rye	Netherlands
	Oat	Denmark
	Triticale	Germany
	Grassland	Luxembourg
	Grass	Austria
		Czech Republic
		New Zealand
		Czechia
		Northern Spain
		Poland
		Canada
		USA
		America

11.3. Evidence screening

To ensure that the review focused on the most relevant material to UK crops and cropping systems, exclusion criteria were developed. Articles were excluded which were:

- Studied based on crops not listed in Table 11.1
- Studies of ergot/Claviceps species not relevant to UK agriculture. For example, *Claviceps tandae* has not been included in the review as it hasn't been found in the UK.
- Studies of the impact of ingestion of ergot by livestock and human consumption.

In total 20,834 papers were sourced of which 455 were taken to the title reading stage and 362 were taken to the full reading stage.

11.3.1. Data extraction

All evidence identified as suitable for full data extraction was collated in an evidence extraction Excel database. For each relevant publication the following information was captured:

- Article title
- Abstract/Synopsis
- Author(s)
- Source Title/Journal

- Publication Year
- Author keywords
- Language
- Referencing details (DOI)

11.3.2. Quality Assessment of Evidence

A database of relevant publications was created in a systematic way, to ensure that data extraction was consistent. To assess the quality of evidence, information was collected on:

- Type of evidence (e.g. research paper, review paper)
- Research design (e.g. field, laboratory or glasshouse)
- Crop(s) studied
- Geographical context

The researchers made a professional judgement, based on the below principles of credible research enquiry in Table 11.2 to ensure that only high-quality evidence was included in the REA (REA,2014). A score of 1-5 (1 being not at all, 5 being completely) was assigned for each paper based on the quality categories (transparency, appropriateness, cultural sensitivity, validity, reliability, and cogency). Papers which were given a score of <2 on the overall quality were excluded from the review write-up.

Table 11-2: Principles of credible research.

Principles of quality	Associated questions
Transparency	Does the study present or link to the raw data it analyses? What is the geography/context in which the study was conducted? Does the study declare sources of support/funding?
Appropriateness	Does the study identify a research design? Does the study identify a research method? Does the study demonstrate why the chosen design and method are well suited to the research question?
Cultural sensitivity	Does the study explicitly consider any context-specific cultural factors that may bias the analysis/findings?
Validity	To what extent does the study demonstrate measurement validity? To what extent is the study internally valid (within the sample)? To what extent is the study externally valid (within the wider population)? To what extent is the study ecologically valid (within the environment)?
Reliability	To what extent are the measures used in the study stable? To what extent are the measures used in the study internally reliable? To what extent are the findings likely to be sensitive/changeable depending on the analytical technique used?
Cogency	Does the author 'signpost' the reader throughout? To what extent does the author consider the study's limitations and/or alternative interpretations of the analysis? Are the conclusions clearly based on the study's results?

11.4. REA Result

The total number of studies included in the REA for each of the crop groups and research questions is summarised in Table 11.3

Table 11-3: Summary of REA article screening and data extraction. Where WOS stands for 'Web of Science' and GS stands for 'Google Scholar'

Question number	Question	Search String	Total results WOS	Saved results WOS	Total results GS	Saved results GS	Total results sum	Saved results sum	Total results once duplicates removed	Total results once R removed
1	What are the key stages of the ergot life cycle? – Distribution, Ergot transmission, Infection process, Genetical Changes of Ergot (i.e. resistances, adaptations)	1	134	50	20,700	50	20,834	100	145	115
		2	59	50	28,900	50	28,959	100		
		3	133	50	23,700	50	23,833	100		
2	What practices can farmers deploy in temperate regions to manage ergot (i.e. seed treatments, cultivations, etc.) in commercially cultivated grasses?	4	169	50	29	29	198	79	142	103
		5	38	38	26,600	50	26,638	88		
		6	11	11	31	31	42	42		
3	What practices can breeders deploy in temperate regions to breed (i.e. Open flower structure, flower timings) for ergot resistant varieties in commercially cultivated grasses?	7	25	25	9,640	50	9,665	75	47	41
4	What harvesting practices are there to decrease ergot presence in commercially cultivated grasses?	8	18	18	9,830	50	9,848	68	19	16
5	What are the best practices to remove ergot from grain (i.e. sampling techniques and ergot sorting)?	9	55	50	4,330	50	4,385	100	102	87
		10	9	9	15	15	24	24		

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