Impacts of changing climate and agronomic factors on fusarium ear blight of wheat in the UK

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Climate change will have direct impacts on fusarium ear blight (FEB) in wheat crops, since weather factors greatly affect epidemics, the relative proportions of species of ear blight pathogens responsible and the production of deoxynivalenol (DON) toxin by two *Fusarium* species, *F. graminearum* and *F. culmorum*. Many established weather-based prediction models do not accurately predict FEB severity in the UK. One weather-based model developed with UK data suggests a slight increase in FEB severity under climate change. However, severity of the disease is likely to increase further due to increased cropping of grain maize, since maize debris is a potent source of inoculum of *F. graminearum*. Further research on forecasting, management options to reduce mycotoxin production and breeding for resistant varieties is a high priority for the UK. Management must also consider factors such as tillage regime, wheat cultivar (flowering time and disease resistance) and fungicide use, which also influence the severity of FEB and related toxin production.

Keywords: food security, mycotoxins, risk prediction, wheat scab, fusarium head blight, deoxynivalenol (DON)

Introduction

Climate change can increase the range and severity of plant disease epidemics (Garrett *et al.*, 2006). Such increases can threaten global food security if they affect staple food crops in agricultural ecosystems especially in the developing world (Chakraborty *et al.*, 2000; Anderson *et al.*, 2004; Garrett *et al.*, 2006; Schmidhuber & Tubiello, 2007). Crop disease epidemics cause instability in food supply, which can lead to famine, conflicts and mass-movement of people to more favoured areas (Stern, 2007). Climate change can directly affect plant pathogens by providing a climate that is more or less favourable to the pathogen (for infection, colonisation, reproduction or dispersal). Several successive years of favourable climate can potentially cause a build-up of inoculum, leading to epidemics that are much more severe than when a single favourable year occurs. Furthermore, climate change can indirectly affect crop diseases, for example by provoking adaptation strategies that involve changes to crop rotations to include new crops that are additional hosts to particular pathogens.

The weather in the UK is relatively variable compared to that of continental European locations, with large differences in monthly rainfall typically occurring during a year despite the long term average monthly rainfall at any given location being almost the same each month. Figure 1 shows the annual mean temperature in different regions of the UK, which varied more with location than with year over the period 1914-2004. UK Climate Impacts

Programme (UKCIP; www.ukcip.org.uk/) projections of future weather vary depending on which of many climate change scenarios are used but the general consensus is that the UK is predicted to have a warmer climate (e.g. +2 ºC in winter to +4 ºC in summer), with slightly wetter winters and drier summers (Semenov, 2009; Fig. 2). The UK is also predicted to experience much more intense weather events. These are the best estimates of future climate change available, although some alternative scenarios have been suggested.

Figures 1 and 2 here.

The UKCIP projected weather would advance the date of onset of wheat anthesis (by approximately 2 weeks by 2050) and maturity for harvest (by 3 weeks) (Semenov, 2009; Madgwick *et al.*, 2011). ‘Mediterranean-type’ wheat cultivars, which respond to different environmental cues determining the time of flowering, typically flower 2 weeks earlier than current UK cultivars. Adoption of this kind of cultivar in the UK has been proposed as an adaptation strategy to avoid heat stress at flowering could advance the time of flowering by at least another week to mid-May in southern England.

One serious disease of small grain cereals under the influence of climate change is fusarium ear blight (FEB), also known as fusarium head blight or scab, caused by a complex of many different species in the genera *Fusarium* and *Microdochium* (Xu & Nicholson, 2009). Of these, two species, *Fusarium graminearum* (Schwabe) (teleomorph, *Gibberella zeae*) and *Fusarium culmorum* (Smith) Sacc. (no known teleomorph) are of concern in the UK because they produce a range of toxins that can contaminate grain, particularly deoxynivalenol (DON) (Fernandez & Chen, 2005; Parry *et al.*, 1995). Due to health concerns, EU legislation limits DON levels at 1250 µg kg^{-1} in unprocessed wheat, with lower limits for various processed foods. DON concentrations of up to 600 mg kg^{-1} in grain caused by natural infections have been reported (Sinha & Savard, 1997), hence two or three heavily-infected grains per 1000 grains can make a batch close to the rejection limit. In the UK, in most years, few grain samples exceed DON thresholds in the UK [e.g. 0-5% of loads have exceeded thresholds since 2001, except in 2008 (10.2%) (http://www.hgca.com/)]. Furthermore, the toxin zearalenone is also produced by *F. graminearum* and *F. culmorum,* while toxins such as HT2 and T2 are produced by other species of *Fusarium* and there are indications that strains or species that are favoured by warmer climates are more likely to produce some of these toxins (Jestoi *et al.*, 2009).

Problems associated with FEB are three-fold. Firstly, diseased ears that senesce prematurely (Fig. 3a) leads to shrivelling of infected grain (Fig. 3d) and substantial yield losses, ranging from 5-75% (Lin *et al.*, 2004; Parry *et al.*, 1995). There is also often an associated stem-base infection, fusarium foot-rot, caused by the same pathogens (Bateman *et al.*, 2007; Fig. 3c) that can contribute to these yield losses and act as a source of inoculum for ear infection. Secondly, the bread-making quality of infected wheat grains is also reduced due to their decreased protein and starch content (Parry *et al.*, 1995). Severely infected batches of grain may be rejected by millers on grounds of poor quality. The third effect is the contamination of grain by a range of mycotoxins, which is of great concern for safety of human food and animal feed (Wei *et al.*, 2005; Kostelanska *et al.*, 2009). In commercial practice, the lightest grains, which can be heavily infected, are usually removed at combining. However, despite post-harvest methods, such as optical sorting (Champeil *et al.*, 2004a) to reduce the impact of infected grain, FEB and contamination by mycotoxins remain major concerns.

Figure 3 here*************

DON is produced primarily during infection of the ear by *F. culmorum* and *F. graminearum* when water availability is high, which in the UK is usually before harvest, rather than in storage as farmers store grain at <15% (Gilbert & Tekauz, 2000; Jennings *et al*., 2004a;b; Hope *et al*., 2005; Chakraborty & Newton, 2011). A delay to harvest, caused by wet weather can substantially increase DON production (Anon 2009b). DON is thought to play a role in virulence (Jansen *et al*., 2005; Proctor *et al*., 1995; Maier *et al*., 2006) and possibly (along with other trichothecenes) in competition against other fungi.

FEB disease occurs throughout the wheat growing regions of the world, with epidemics recorded in major cereal growing areas (McMullen *et al.*, 1997; Parry *et al*., 1995). The two main DON-producing species, *F. graminearum* and *F. culmorum*, have slightly different temperature optima for growth, 24-28°C for *F. graminearum* and 20-25°C for *F. culmorum* (Doohan *et al*., 2003; Brennan *et al.*, 2003). This small difference may explain why *F. graminearum* predominates in regions with relatively hot summers, such as the USA, Canada, Australia and parts of continental Europe, whereas *F. culmorum* is found in cooler maritime regions such as north western Europe (Moss, 2002; Parry *et al*., 1995). However, in the UK, there appears to be no trend associated with mean temperature for years when *F. graminearum* has predominated over *F. culmorum* and vice versa (Anon. 2010). In the UK, these two species interact with other species responsible for FEB, principally *F. poae*, *F. avenaceum*, *Microdochium nivale* and *M. majus*, and there are other interacting species worldwide, many of which produce mycotoxins (Xu & Nicholson, 2009). Disease surveys in the UK have shown that the incidence of fusarium ear blight in the UK has been sporadic but has increased over the past decade (Fig. 4). Additionally, the incidence of *F. graminearum* has started to increase substantially since 2002 (www.cropmonitor.co.uk; Jennings *et al*., 2004b). During the 2006/2007 season, there was an unusually high incidence of FEB in the UK, with the principal causal agent being *M. nivale* (Fig. 4). A wet summer in 2008 was associated with a relatively severe FEB epidemic and associated DON contamination, with more *F. graminearum* than *F. culmorum*. Before then, FEB had not been considered to pose a serious risk of DON contamination in the UK, particularly if good farming practices were followed. This review investigates the potential direct and indirect impacts of climate change on fusarium ear blight and subsequent mycotoxin contamination in the UK, particularly impacts of altered farming practices.

Figure 4 here.**********

Disease-cycle of FEB

F. graminearum and *F. culmorum* survive the inter-crop period on infected seed and crop debris in the field (Bateman *et al*., 2007). For both *F. graminearum* and *F. culmorum*, asexually-produced macroconidia (Fig. 3b) formed in sporodochia are dispersed by rain splash, to infect florets at anthesis either directly from inoculum sources on the ground or via infections on intermediate leaf layers, that lead to secondary sporulation (Beyer *et al.*, 2005; Parry *et al*., 1995; Paul *et al.*, 2004; Schmale *et al.*, 2005). Additionally, *F. graminearum* develops a sexual stage when conditions are warm and humid, forming blue or black ascospore-bearing perithecia on the surface of colonised debris such as chaff, grain and leaf litter, giving a ‘scabbed’ appearance (Doohan *et al*., 2003; Sutton *et al*., 1980; Goswami & Kistler, 2004; Kang & Buchenauer, 2000; Parry *et al*., 1995). These discharge ascospores into the air in the spring for long-distance dispersal when the air temperature is decreasing and relative humidity (RH) increasing (i.e. typically in the evening) but not when RH is extremely high (Doohan *et al*., 2003). Maldonado-Ramirez *et al*. (2005) assessed concentrations of viable *F. graminearum* propagules in air by impaction onto selective agar plates on remotely operated pilotless drone aircraft. They found that airborne inoculum (of *F. graminearum*/*G. zeae*) was abundant and well dispersed in air above New York state throughout the wheat flowering period (May/June) in each of four years. There was a homogeneous spatial pattern of propagule deposition detected by samplers located over a 1 km scale (Schmale *et al*., 2006).

Infection occurs when spores are deposited on the flowering wheat ear during periods of wetness or high humidity, with ideal conditions 25°C and 100% relative humidity for 24 hours post inoculation (Abramson *et al.*, 1987; Parry *et al*., 1995). Wheat plants are most susceptible during anthesis but infection can occur up to the soft dough stage (Windels, 2000). Mycelium is able to infect florets in humid conditions by growing along the surface of spikelets and particularly on the anthers as they are extruded from the wheat ear during flowering. The initial symptoms of FEB are pale brown water soaked lesions on infected spikelets and at this stage there is often a substantial area of asymptomatic infection ahead of the visible disease symptoms (Brown *et al*., 2010). Visible symptoms vary according to the species and to some extent the toxins produced by the infecting pathogen. In most cases the diseased areas of discolouration expand, causing spikelets to turn prematurely light brown. Bleaching that may occur on florets above the infection point (Fig 3a); is associated with DON production in some species (Maier *et al.*, 2006). Individual florets may become sterile, leading to poorly filled, shrivelled grain. Infected grains may have a chalky, floury interior and may show salmon-pink patches of conidia (Fig. 3d) along the edges of the glume and the base of the spikelet and the peduncle beneath the infected ear darkens (Ruckenbauer *et al*., 2001, www.scabusa.org).

Factors affecting severity of FEB and DON production

Weather factors

Weather has been investigated as a factor affecting FEB in a number of studies. Xu *et al.* (2008) suggested that *Fusarium poae* was associated with relatively dry and warm conditions, *F. graminearum* with warm, humid conditions, *F. avenaceum* and *F. culmorum* with cool, wet or humid conditions, while two *Microdochium* species were associated with cool to moderate temperatures and frequent rain showers. Some forecasting models suggest that occurrence of rain and high humidity approximately one week before anthesis increases FEB risk and this is thought to be because this stimulates sporulation (de Wolf *et al*., 2003; Hooker *et al.*, 2002; Moschini *et al*., 2001). In addition, rain and, or high humidity at anthesis has been highly correlated with FEB incidence (Bateman *et al*., 2007; de Wolf *et al*., 2003; Moschini *et al*., 2001) but not with DON production (Hooker *et al.*, 2002). Warm (i.e. 15ºC to 30ºC), wet weather at anthesis not only promotes infection but also encourages vegetative spread of mycelium to more florets (Parry *et al*., 1995; deWolf *et al*., 2003). However, in continental European locations, where hotr conditions can occur, concentrations of DON decreased with increase in days exceeding 32°C (Hooker *et al.*, 2002). Weather factors (rain) contributing to a late harvest were also associated with increased DON contamination (Eiblmeier *et al.*, 2007).

A recent study that investigated impacts of climate change on Fusarium ear blight in the UK combined a crop growth model and a weather-based disease model with simulated future climate data (Madgwick *et al*., 2011; Figure 5). The incidence of fusarium ear blight was related to rainfall during anthesis and temperature during the preceding 6 weeks. It was projected that, with climate change, wheat anthesis dates will be approximately two weeks earlier than at present. As a result, the rain-related risk of infection at anthesis did not decrease, as would have been predicted if anthesis had remained in mid-June (rainfall is projected to be almost unchanged in May but substantially reduced in June). Due to wetter and warmer conditions in spring, the model predicted a slight increase in severity of fusarium ear blight epidemics by the 2050s, particularly in southern England (Madgwick *et al.*, 2011). This predicted slight increase reflected purely the weather-related risk and did not include effects of other indirect factors discussed in the following sections.

Fig 5 near here********

In the long-term, climate appears to influence the predominant *Fusarium* species occurring in a given location. Bottalico (1998) suggests that differences in the predominant mycotoxin-producing *Fusarium* species present in cereals between northern and southern Europe are primarily due to differences in their survival on different substrates and timing of spore release relative to wheat anthesis. Furthermore, warm dry weather from autumn to early spring in the UK appears to increase risk by increasing inoculum build-up (Anon 2007). In northern Europe, climate change may be a factor responsible for a recent shift from *F. culmorum* to *F. graminearum* as the main cause of FEB (Waalwijk *et al.*, 2008). A similar change has been observed in maize, where the predominant *Fusarium* species was *F. graminearum* but increasingly the predominant species are others with favoured by warmer conditions, such as the *Gibberella fujikuroi* complex: *F. verticillioides, F. proliferatum* and/or *F. subglutinans*, which produce several mycotoxins (Waalwijk *et al.* 2008). However, changes to the climate of the UK and northern Europe have been only very slight over the past 30 years (Fig. 1). Although greater changes are predicted for the future, it seems that other factors, such as tillage, maize cultivation, fungicide use and cultivar resistance appear most likely to have contributed to the change in prevalence of *F. graminearum* and *F. culmorum* reported since 2002 (Anon 2010).

Inoculum availability and crop cultivation

In the UK, the incidence and severity of FEB epidemics on wheat varies from year to year but there has been a trend for the disease to increase in importance over the last decade (www.cropmonitor.co.uk; Fig. 4). In the UK, FEB is associated with a range of species in the genera *Fusarium* and *Microdochium.* Severe epidemics of FEB occur when there is a coincidence of a large amount of inoculum, suitable weather for infection and host plants at a susceptible growth stage, i.e. at flowering. The amount of inoculum is enhanced by increased cultivation of cereal hosts, especially maize, and by increased use of direct drilling or minimal tillage (Bateman *et al*. 2007; Eiblmeier *et al*., 2007), which provides the pathogen with more plant residues on the soil surface on which to over-winter and sporulate (Teich & Hamilton, 1985; Windels, 2000; Champeil *et al.*, 2004b; Šíp *et al.*, 2007). Weather influences inoculum availability; perithecia of *G. zeae* were reported to develop on debris and grains (of maize or wheat) on the soil surface (requiring light for development) at temperatures between 15-30°C (Gilbert & Fernando, 2004; Trail *et al*., 2002), while *F. culmorum* conidia are also produced on debris on the soil surface (Bateman *et al*., 2007). Conidia (both macro- and microconidia) are also produced on fusarium foot (stem-base) rots or from superficial infections on leaves (Anon 2010). These factors, other climatic factors and geology (soil type) affect each of the FEB-causing species and their interaction with the host in different ways; this then affects the relative amounts of inoculum of each species.

Due to different responses of the ear blight fungi to weather (see previous section), in any season the coincidence of spore release and wheat flowering may favour one species over another. This fits with the principle of competitive exclusion (Gausse, 1934), which states that two species occupying the same niche cannot coexist indefinitely, while those occupying different niches can coexist. DON contamination of grain is most severe in wheat crops that are preceded by grain maize (Eiblmeier *et al.*, 2007). This is thought to be because the large mass of infected crop debris that remains on the soil surface after harvesting of grain maize has a substantial capacity for production of wind-dispersed ascospores of *G. zeae* (*F. graminearum*) and persists in soil for a long time (Beck & Lepschy, 2000; Bateman *et al.*, 2007). Since airborne inoculum of *F. graminearum* was found by Maldonado-Ramirez *et al.* (2005) to be dispersed regionally in the planetary boundary layer, it follows that regions with intense wheat and, or maize cultivation are likely to have greater concentrations of airborne inoculum. In the UK, grain maize is restricted to Southern England and the greatest density of forage maize crops is in areas of livestock production, especially the southwest where there are more cattle (Figs 6a and 6b). Climate change is predicted to cause the summer months to become warm enough for grain maize to be economically viable over a larger area of the UK (Kenny & Harrison, 1992). Provided that suitable spring weather promotes sporulation, additional maize cropping has potential to cause a substantial increase in FEB on UK wheat due to increased inoculum availability.

Figure 6 here.

Crop and crop-protection factors

In addition to maize cultivation and minimal tillage, other agronomic and crop-protection factors influence the amount of FEB and the predominant species occurring. Commercially available fungicides can reduce the incidence of FEB by 50-70% when applied at the correct time, during flowering (Jennings 2002; Jennings *et al.*, 2000). However fungicide applications at a sub-optimal time may result in little effect (Jennings *et al.*, 2000). D’Mello *et al*. (1998) found increases in DON and other mycotoxins occurred after sub-lethal exposures to MBC and triazole fungicides *in vitro*, while others suggest that some strobilurin (QoI) fungicides may increase DON production (Eiblmeier *et al*., 2007; Blandino & Reyneri, 2009; Jennings *et al*., 2000; Edwards *et al*., 2001; Simpson *et al*., 2001). Even when fungicides are applied to protect most wheat ears at the correct time, ears of late-developing tillers are likely to be missed. These late tillers also tend to be shorter and are therefore in a more humid microclimate within the crop canopy, which increases the probability of infection. Furthermore, recent European legislation (EC No 1107/2009 repeal of directive 91/414/EEC) will mean that fewer fungicides are available to control FEB in the future.

Cultivar resistance affects the severity of FEB and toxin production and is classified into five main types: type I is resistance to initial infection, type II is resistance to the spread of the pathogen after the initial infection, types III - V refer to the resistance to DON accumulation and tolerance of the disease (reviewed by Champeil *et al*., 2004a; Buerstmayr *et al*., 2009). One of the best known sources of resistance is the Chinese variety Sumai 3, which shows excellent type II resistance (Bai & Shaner, 2004) and a much lower level of DON accumulation in the harvested grain. Numerous other sources of resistance to FEB have also been identified and the underlying QTL identified (reviewed by Buerstmayr *et al*., 2009). Generally the difference in disease severity due to resistance that is currently available in UK varieties is relatively small with none completely resistant (Anon 2009a). Further research is in progress to improve and understand the different mechanisms of host resistance, which have great potential in the integrated management of FEB.

Cultural practices and chemical treatments that affect canopy density and crop height may affect spore dispersal and deposition on wheat ears (particularly for rain-splashed conidia) and the presence of certain weeds may influence the amount of inoculum and the predominant FEB species since several common weeds are hosts of *F. culmorum* and *F.*

graminearum (Champeil *et al*., 2004a). Additionally, Grewal *et al*. (1996) reported that zinc deficiency in soil reduced resistance to foot rot (crown rot) caused by *F. graminearum* in wheat, which may increase inoculum availability for FEB. Other mineral deficiencies may prolong flowering in wheat due to poor pollination success and this could also increase susceptibility to FEB.

Integrated risk assessment

A mycotoxin risk assessment tool that is available for UK growers integrates some of these different factors affecting fusarium mycotoxin risk. It can assist early decision-making about crop management, such as tillage or fungicide regime, and allow farmers to indicate the relative fusarium risk for a field according to region of production, previous crop, cultivation method, cultivar resistance, anthesis-applied fungicide (application time known as T3 in the UK), rainfall at flowering and pre-harvest rainfall (Anon 2009b). Acceptance of risk assessments by industries such as millers could reduce the need for mycotoxin testing in most cases, i.e. where risk is predicted to be small.

Conclusions: impacts of climate change on FEB

Disease surveys in the UK have shown that *F. graminearum* is becoming more common on wheat ears than *F. culmorum*, with the incidence of *F. graminearum* in the UK exceeding that of *F. culmorum* since 2002 (Anon 2010; Jennings *et al*., 2004b; Gosman *et al*., 2007). However, such changes in prevalence of *Fusarium* species have occurred too recently to conclude that they are due to climate change (see Fig. 1). Although it is clear that weather influences epidemics of different *Fusarium* species in different ways, many changes in farming practices, such as tillage regime, maize cultivation and fungicide use, have also occurred recently. It is likely that climate change will have direct impacts on the prevalence and severity of FEB and associated DON production in wheat crops as weather is one of the main factors affecting the severity of epidemics and the relative proportions of different ear blight pathogens responsible. The UK is in a unique situation due to its very variable climate and complex of several interacting species of FEB pathogens. There are indications that the predominant species have changed recently in association with a range of cultural changes and possibly weather-related factors. It is unclear whether *F. graminearum* and *F. culmorum* and other FEB fungi will respond to changes in climate in terms of inoculum production exactly to coincide with the advancement in wheat flowering date predicted as a result of UKCIP climate projections (Semenov, 2009).

Predicted drier summers may, despite the continued presence of FEB, result in reduced DON contamination, because there will be a decrease in pre-harvest rainfall (from GS 87 or hard-dough stage to harvest). Preharvest rainfall can increase DON production substantially (Anon 2009b). However, this conclusion is based on a long term predicted rainfall trend, while in practice there will be considerable variation in summer rainfall from one year to another in the UK.

Furthermore, an indirect effect of climate change will be enhanced grain maize cropping, which will substantially increase the capacity for inoculum production. It seems likely that one reason why the occurrence of *F. graminearum* is much greater in North America and continental Europe than in the UK is that the density of grain maize is much greater in these areas and that maize debris provides a potent source of *F. graminearum* ascospores for infecting wheat crops. The culture-based assessment method used by Schmale *et al.* (2006) and Maldonado-Ramirez *et al.* (2005) did not identify the airborne inoculum source, which could be ascospores, conidia or hyphal fragments, but it did show the presence of inoculum dispersed evenly over the entire region. In contrast to the situation in North America, a lack of a homogeneous regional air-spora of *F. graminearum* (*G. zeae*) due to sparse occurrence of infected debris is thought to explain why weather-based disease models developed in other parts of the world frequently overestimate observed disease in the UK (Madgwick *et al.*, 2011). If inoculum availability is heterogeneous in the UK, then disease forecasting schemes that include a component of inoculum detection will be important.

The impact of climate change on FEB is likely to have implications for breeders, growers and policy makers. Strategies to breed for resistance and to develop methods to reduce inoculum (crop debris), combined with effective crop protection products will continue to be needed to maintain a safe supply of grain. Forecasting schemes to target control options (fungicides applied at anthesis) to high risk seasons and, or locations would avoid unnecessary fungicide applications in low-risk sites. Further research to understand crop exposure to pathogen inoculum could allow a climate- or direct inoculum-based disease forecast to be issued in time to guide spray applications at anthesis. Disease forecasting and further research to improve crop protection solutions for growers must aim to mitigate the increased risk of FEB predicted under climate change.

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Figure Legends:

Fig 1 - Annual mean temperature from 1914 to 2004 for different regions of the UK, smoothed with a triangular kernel filter with 14 terms on either side of each target point. © Crown copyright 2006, the Met Office, used with permission.

Fig 2 - Baseline 30-year (1971-2000) monthly mean rainfall and temperature at Rothamsted, UK (51° 48' 0" N, 0° 21' 0" W) and projected monthly means for 2050 according to the high emission (2050HI) climate scenario HadRM3 climate model.

Fig 3 - Fusarium ear blight in a winter wheat crop, cultivar Hereward, Rothamsted field experiment, July 2007 (A); *Fusarium graminearum* macroconidia (B); fusarium foot rot (C); comparison between healthy harvested grain (left) and *Fusarium* infected grain (right) (D).

Fig 4 - Incidence (% crops affected) of fusarium ear blight on winter wheat at GS 75 in England and Wales. Results from the CropMonitor survey of winter wheat crops (1991 - 2008, http://www.cropmonitor.co.uk/)

Fig 5 - Maps showing the projected average fusarium ear blight incidence (% plants affected) generated by a fusarium ear blight model and based on advanced anthesis dates for three weather scenarios; baseline, 2020 high emission scenario (2020HI), and

2050 high emission scenario (2050HI). The baseline scenario is based on weather from 1960-1990. The maps were produced by spatial interpolation between the 14 sites. Adapted from Madgwick *et al*. (2011).

Fig 6 - Relationship between number of cattle and area of maize grown in counties of England in 2008 (A) and maize distribution in England in 2008 as a percentage of the total arable area in each county (B). Maize is a potent source of ascospores of *Gibberella zeae* (*F. graminearum*). Data (www.defra.gov.uk); no data were available for arable areas in Scotland and Wales (shaded grey).

Figure

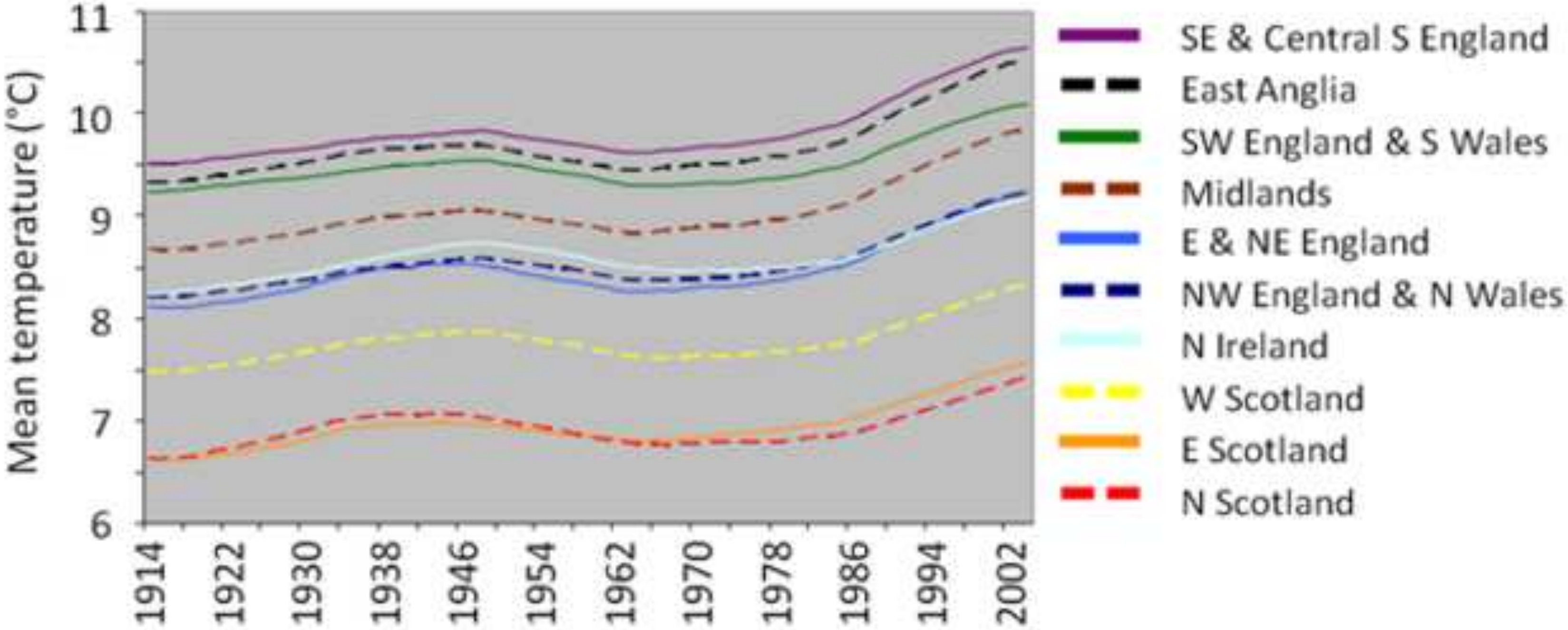

Mean temperature (°C)
11
10
9
8
7
6
1914
1922
1930
1938
1946
1954
1962
1970
1978
1986
1994
2002
SE & Central S England
East Anglia
SW England & S Wales
Midlands
E & NE England
NW England & N Wales
N Ireland
W Scotland
E Scotland
N Scotland

Figure2

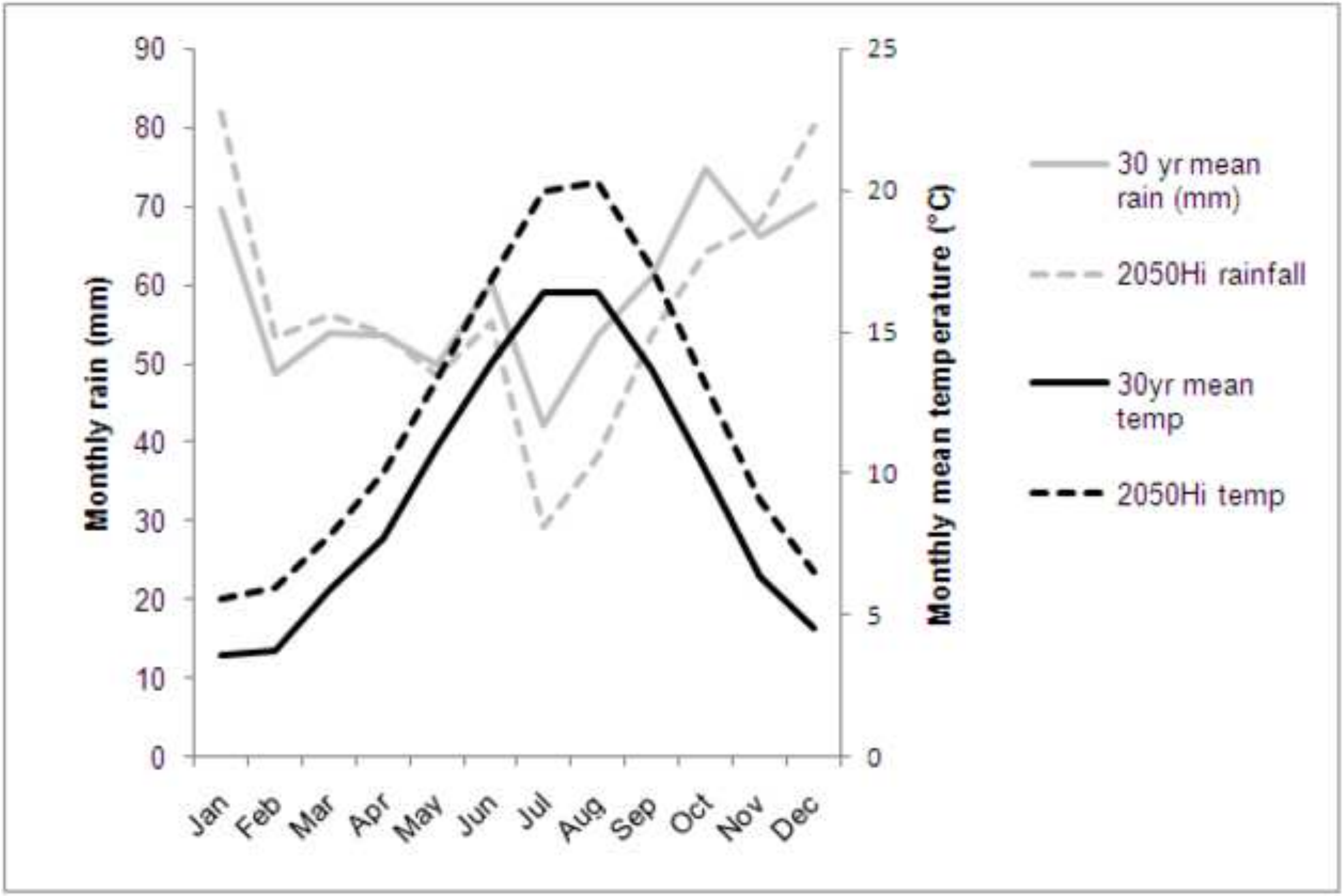

Monthly rain (mm)
90
80
70
60
50
40
30
20
10
0
Monthly mean temperature (°C)
25
20
15
10
5
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
30 yr mean rain (mm)
2050Hi rainfall
30yr mean temp
2050Hi temp

Figure3

Figure4

Click here to download high resolution image

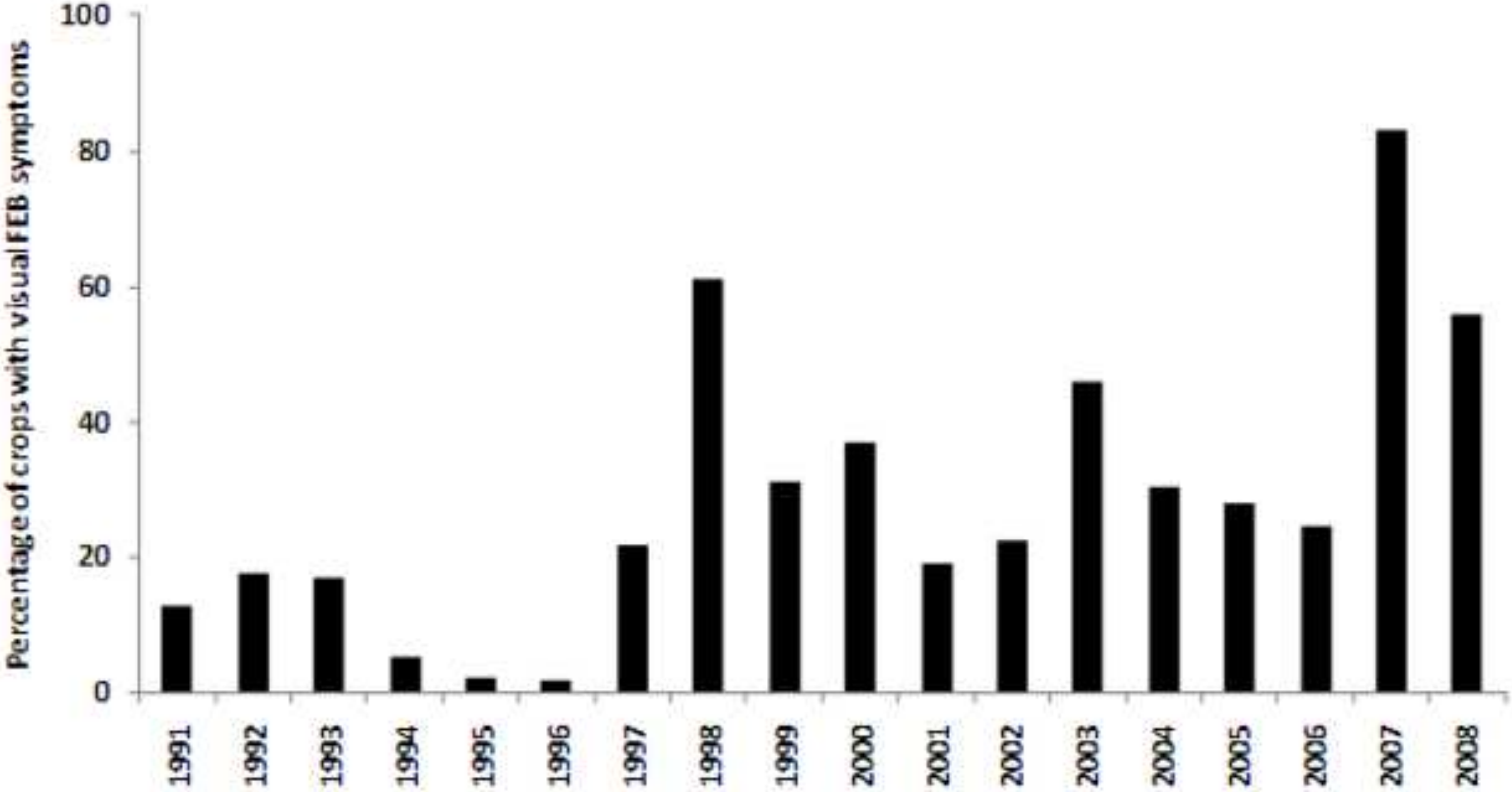


Figure5

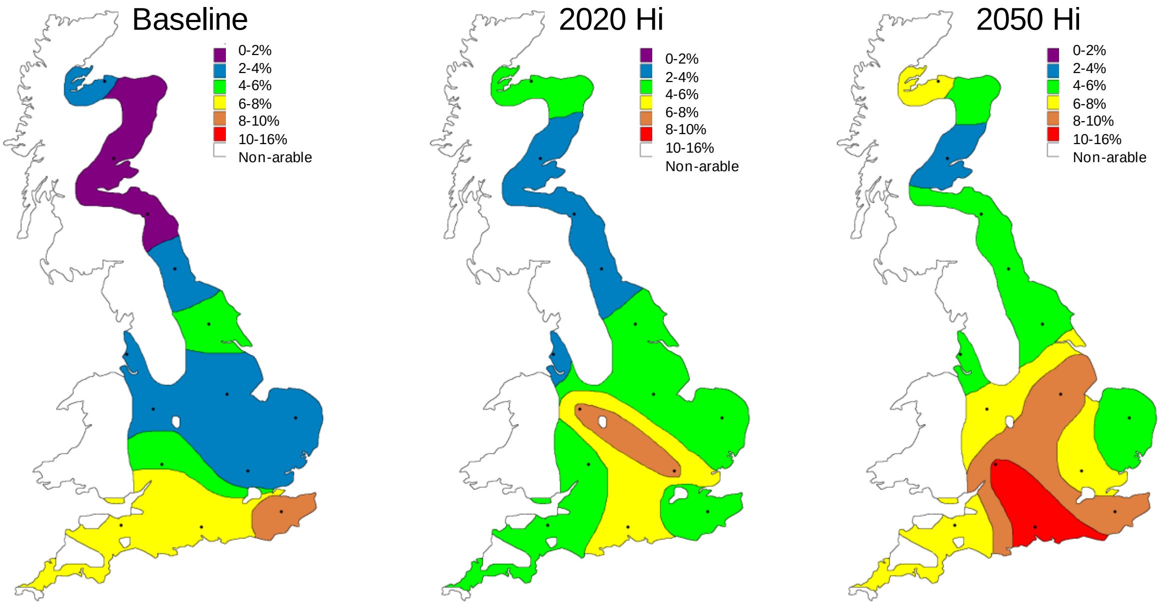
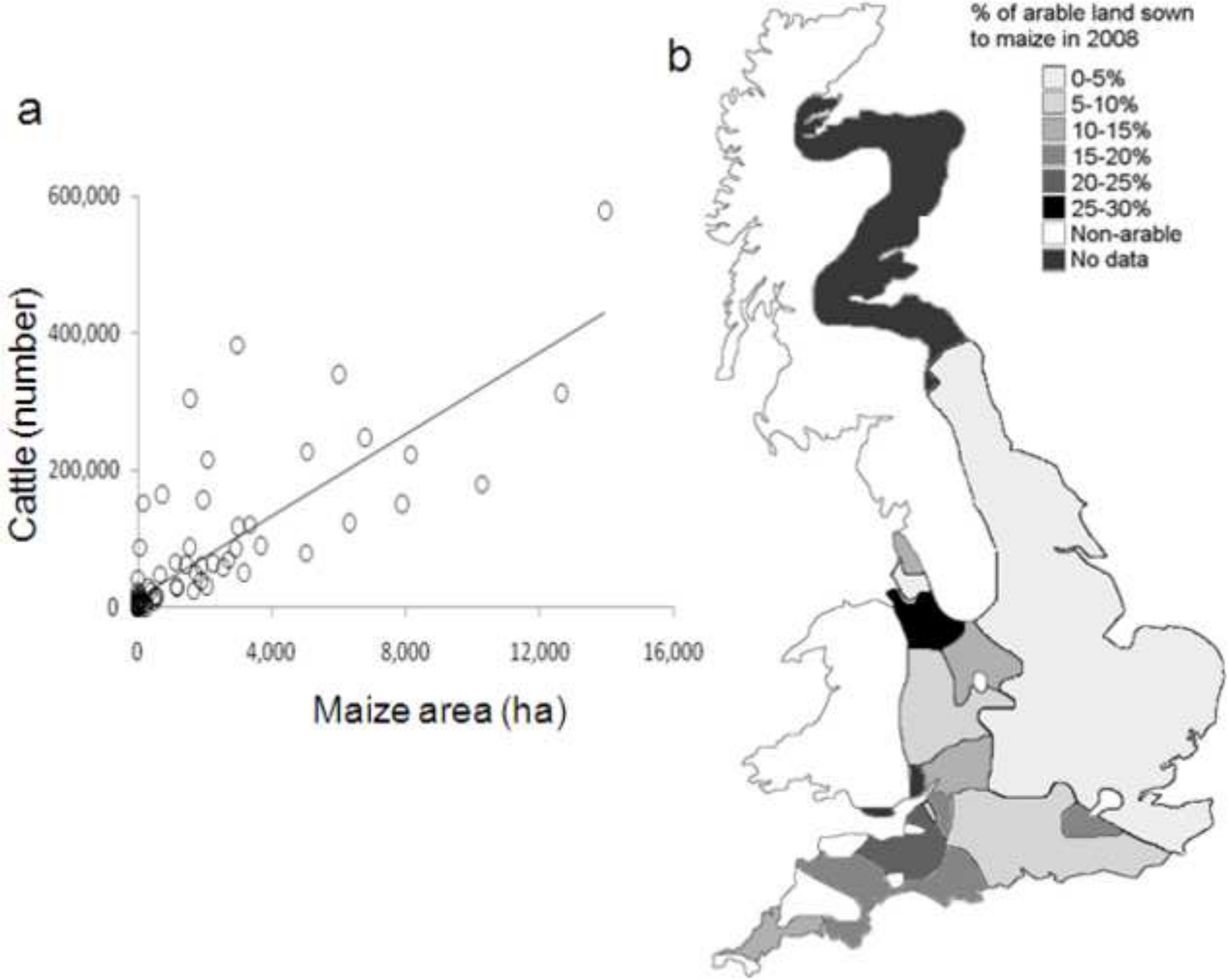

Baseline
0-2%
2-4%
4-6%
6-8%
8-10%
10-16%
Non-arable
2020 Hi
0-2%
2-4%
4-6%
6-8%
8-10%
10-16%
Non-arable
2050 Hi
0-2%
2-4%
4-6%
6-8%
8-10%
10-16%
Non-arable

Figure6


a
Cattle (number)
600,000
400,000
200,000
0
0
4,000
8,000
12,000
16,000
Maize area (ha)
b
% of arable land sown to maize in 2008
0-5%
5-10%
10-15%
15-20%
20-25%
25-30%
Non-arable
No data