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Climatic analysis of the distribution of *Fusarium graminearum*, *F. pseudograminearum* and *F. culmorum* on cereals in Australia

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Abstract. The distributions of *Fusarium graminearum* (*Gibberella zeae*), *F. pseudograminearum* (*F. graminearum* Group 1) and *F. culmorum* from cereals in Australia were determined from published survey data and accessions to culture collections. The distributions were analysed in terms of climate, using the climate matching system BIOCLIM. *Fusarium graminearum* was found mostly in warm temperate to subtropical areas with moderate to high summer rainfall, where mean temperature of the warmest quarter was greater than 18.7°C and rainfall of the warmest quarter was greater than 195 mm. This appeared to be due to the effect of climate on production of maize, the host from which most records were obtained. *Fusarium pseudograminearum* occurred throughout the main cereal growing areas and its occurrence did not appear to be limited by climate within the Australian grain belt. The distribution of *F. culmorum* on cereals was more limited than that of *F. pseudograminearum*. In the southern winter rainfall zone, *F. culmorum* was restricted to sites with mean summer temperatures less than about 22° C and annual rainfall greater than about 350 mm, while in the northern summer rainfall zone *F. culmorum* was restricted to areas with mean summer temperatures less than about 24.5° C and annual rainfall greater than about 625 mm.

Additional keywords: wheat, crown rot, foot rot, head blight

Introduction

Fusarium graminearum, *F. pseudograminearum* and *F. culmorum* are a group of closely related species, which form part of the complex of *Fusarium* species associated with diseases of cereals (Parry *et al.* 1994). *Fusarium culmorum* causes foot and crown rots and head blight on small grain cereals (Parry *et al.* 1994). *Fusarium graminearum* (teleomorph *Gibberella zeae*) causes head blight on wheat, and stalk and cob rot on maize (Francis and Burgess 1975; McMullen *et al*. 1997). *Fusarium pseudograminearum*, previously known as *F. graminearum* Group 1 (Aoki and O'Donnell 1999), causes crown rot of wheat and barley and has not been recorded from maize (Francis and Burgess 1975). *F. pseudograminearum* has been recorded as a cause of head blight only infrequently (Burgess *et al.* 1987).

The dominant species associated with *Fusarium* foot rots and head blights differ between countries and between regions within countries. The distribution of diseases caused by each species is often qualitatively related to climate. For example, Parry *et al.* (1994) stated that *Microdochium nivale* is more commonly isolated from cereals in cool, wet regions, while *F. graminearum*, *F. culmorum* and *F. avenaceum* predominate in warmer, drier regions. In the Pacific Northwest, USA, Cook (1980) reported that while *F. culmorum* was widely distributed as a cause of foot rot of wheat, *F. pseudograminearum* was restricted to the warmest, driest areas. In Europe, head blight is more likely to be caused by *F. culmorum* and *F. avenaceum* in cooler, maritime areas and by *F. graminearum* in warmer, continental areas (Schilling *et al*. 1997).

Although there is general consensus that climate affects the distribution and prevalence of *Fusarium* species pathogenic to cereals, there have been few attempts to describe this quantitatively. Sitton and Cook (1981) compared the summer temperatures of counties in Washington State where either *F. culmorum* or *F. pseudograminearum* was the dominant pathogen. They reported that the maximum July temperature averaged 31.0°C in counties where *F. pseudograminearum* predominated, and 28.7°C in counties where *F. culmorum* predominated. In a later survey in the same region Smiley and Patterson (1996) found that the relationship between prevalence of *F. pseudograminearum* and July temperatures was weak, but was nevertheless consistent with the trend identified by Sitton and Cook (1981). Pettitt and Parry (1996) and Pettitt *et al.* (1996) related the relative dominance of *M. nivale* or *F. culmorum* as foot rot pathogens over several years in England and Wales to accumulated heat sums during the growing season. *Fusarium culmorum* predominated in counties and seasons with higher heat sums. These studies examined the influence of single climate parameters over relatively small areas. To better appreciate the role of climate, there is a need to apply more comprehensive descriptions of climate to the distribution of pathogens on a continental scale.

In Australia, *Fusarium pseudograminearum* is the most common and widespread causal agent of crown rot of wheat (Burgess *et al*. 1975; Klein *et al.* 1990). The related species *F. culmorum* and *F. graminearum* have more limited distributions (Burgess *et al.* 1975; Wearing and Burgess 1977). This paper describes the application of the BIOCLIM climate matching system (Busby 1991; Backhouse and Burgess 1995) to the distribution of these species in Australia, to test the hypothesis that their relative distributions can be explained in terms of climate.

Methods

Distribution data

Location records were obtained for isolations of *F. culmorum*, *F. graminearum* and *F. pseudograminearum* from cereals, including wheat, barley and maize. Most records came from accessions to the lyophilised culture collection of the Fusarium Research Laboratory, University of Sydney, which resulted from crop and silo surveys (Burgess *et al.* 1975; Francis and Burgess 1975; Wearing and Burgess 1977; Burgess *et al.* 1987; Klein *et al.* 1990; Hollaway *et al.* 1999). Additional accessions came from unpublished annual disease surveys as well as specimens received for identification from other workers. Published records (Chambers 1972; Wearing 1979; Blaney and Dodman 1988) were used where location data were sufficiently precise. Additional records for Western Australia were obtained from diseased specimens provided by Dr G.C. MacNish, and culture collection accessions provided by Dr R.G. Shivas. Site records were treated as independent if they were more than 20 km apart.

Operation of BIOCLIM

BIOCLIM version 2.0 (Busby 1991) was used. The operation of this program has been described previously (Backhouse and Burgess 1995). Briefly, location records were supplied to BIOCLIM as latitude, longitude and altitude coordinates. For each site, BIOCLIM used an internal algorithm based on a set of climate surfaces to estimate the mean monthly maximum and minimum temperatures, and monthly rainfall. The error of estimation is generally within 10% for monthly rainfall and 0.5° C for temperatures (Busby 1991).

From these monthly data a set of 16 synthetic climate parameters (Table 1) was calculated. Most of the parameters are self-explanatory and simple to calculate. Annual temperature span is the difference between the minimum temperature of the coldest month and the maximum temperature of the warmest month at each site. Rainfall coefficient of variation is the standard deviation of the monthly rainfall divided by the mean monthly rainfall, and is an index of seasonality of rainfall. The range of each of these parameters over all the sites from which a species was recorded constituted the climate profile for that species. Results are presented in the first instance as the lowest and highest values of each parameter among all the sites for each species, and the mean of each parameter calculated from the individual values for each site for each species.

The climate profiles were compared with the calculated climate parameters for points on a grid at 0.5° intervals of latitude and longitude over Australia. If all 16 climate parameters for a point on the grid fell within the climate profile of a species, that point was predicted to be climatically suitable for the species. Climatically suitable points were then mapped to give a predicted distribution.

Further analysis for F. culmorum *and* F. pseudograminearum

Climate profiles generated by BIOCLIM are useful for predicting potential distribution but do not directly indicate which climate parameters have the greatest effect on distribution. Many of the climate parameters are correlated, so that a species will not occur over all possible combinations of values of two climate parameters. In order to more closely define the effect of climate on the relative distributions of *F. pseudograminearum* and *F. culmorum*, the climate profiles were analysed further.

Principal Component Analysis (PCA) was used to look for patterns or regularities in the climate profiles for each species (Eeley *et al*. 1999). A data set was constructed consisting of all sites from which *F. culmorum* or *F. pseudograminearum* had been recorded, and the values of each of the 16 synthetic climate parameters for each site. Sites were coded according to whether *F. pseudograminearum* only, *F. culmorum* only, or both species, were recorded for that site. A PCA was done on the correlation matrix using Minitab statistical software.

To help find a minimum number of uncorrelated parameters that could describe the differences in distribution between *F. culmorum* and *F. pseudograminearum*, product-moment correlations were calculated for all pair-wise comparisons of the 16 climate parameters. Parameters were considered to be highly correlated with each other if $r > 0.8$ or $r < -0.8$.

Climate zones and cereal cropping areas in Australia

Most of Australia is too arid for crop growth, and extensive crop production is limited to areas of moderate to high rainfall in the south and east of the continent. Within the cropping zone, two patterns of seasonal rainfall can be distinguished. In southern New South Wales, Victoria, South Australia, Western Australia and Tasmania (Fig. 1), more than half of the annual rainfall occurs in winter and summers are relatively dry. Non-irrigated cropping is limited to the winter and spring months. In northern New South Wales and Queensland (Fig. 1), the rainfall is summer dominant and crops can be grown throughout the year.

Small grain cereals, mostly spring wheat and barley, are grown in a broad arc across southern and eastern Australia known as the grain or wheat belt. The approximate location of this is indicated by the predicted distribution of *F. pseudograminearum* (Fig. 2b). Maize production areas are indicated by the recorded distribution of *F. graminearum* (Fig. 2a). These are mostly in parts of northern New South Wales and Queensland with reliable summer rainfall, with some areas at higher elevation in tropical north Queensland such as the Atherton Tablelands (Fig. 1), and some irrigated production in winter rainfall areas of inland New South Wales.

Results

Fusarium graminearum

This species was recorded from 44 sites in eastern Australia (Fig. 2a), mostly as isolations from maize, but with some records from stem bases or heads of wheat. Apart from one outlying inland site (Hay, NSW), which was irrigated, all sites were coastal or in the northern summer rainfall zone. The ranges of most temperature parameters in the climate profile were not very different from those of *F. pseudograminearum* or *F. culmorum* (Table 1). The average for mean temperature of the wettest quarter was high, and the average of mean temperature of the driest quarter was low, reflecting the preponderance of records in the summer rainfall zone. Values of rainfall parameters tended to be high, especially rainfall in the warmest quarter which, except for the irrigated site, was greater than 195 mm.

The predicted distribution of *F. graminearum* was concentrated in the higher rainfall warm temperate and subtropical areas of northern New South Wales and southern Queensland, and small areas in north Queensland (Fig. 2a). A large area outside the recorded distribution between Maryborough and Rockhampton in Queensland was predicted to be suitable. Most of the scattered locations in southern Australia were removed from the predicted distribution when the outlying irrigated site was omitted from the analysis.

Fusarium pseudograminearum

Fusarium pseudograminearum was recorded from 113 locations. These came from most parts of the mainland grain belt. Consequently the climate profile for this species (Table 1) and the predicted distribution (Fig. 2b) coincided closely with the main small grain cereal production areas. Areas predicted to be suitable for *F. pseudograminearum* but for which records were not found included the Eyre Peninsula in South Australia, the western margins of the grain belt in central New South Wales, and an area north-east of Charleville in Queensland.

Fusarium culmorum

Records of *F. culmorum* from cereals were obtained from 37 sites. These mostly came from three areas: the eastern Darling Downs, in southern Queensland; an extensive area of western Victoria and eastern South Australia; and scattered localities in Western Australia, especially near the south coast (Fig. 2c). The predicted distribution was very similar to the recorded distribution, and excluded the main cereal growing areas of New South Wales and most of Queensland. Significant areas predicted to be climatically suitable but for which no records were obtained included the Eyre Peninsula and Mid-North in South Australia, and the Goulbourn Valley area in northern Victoria.

Comparison of F. pseudograminearum *and* F. culmorum

A PCA was done on all site records of *F. pseudograminearum* and *F. culmorum*. The first two principal components accounted for 52% and 21% respectively of the variation in the data set. All sites were plotted using their scores on the first two principal components (Fig. 3). The sites formed two main clusters that were separated by their scores on principal component 1. These clusters corresponded to the summer rainfall zone (northern New South Wales and Queensland; positive values of principal component 1) and the winter rainfall zone (Victoria, South Australia and Western Australia; negative values of principal component 1), with some sites from central New South Wales bridging between them. Sites from which *F. culmorum* was recorded formed a tight group within the summer rainfall cluster. The *F. culmorum* sites were more widely scattered within the winter rainfall cluster. The PCA suggested that the effect of summer versus winter dominance of rainfall was so strong that it would be difficult to find limiting values of climate parameters for *F. culmorum* that were common to both zones. It also suggested that the distribution of *F. culmorum* was less restricted by climate in the southern, winter rainfall zone than it was in the northern summer rainfall zone.

PCAs were done separately for the southern and northern sites. When these were plotted (not shown), they gave similar relative distributions of *F. culmorum* and *F. pseudograminearum* to those within the individual clusters in the combined PCA (Fig. 3). Within each PCA, the sites from which *F. culmorum* was recorded tended to be clustered in directions associated with low values of temperature parameters and high levels of rainfall parameters.

Records of occurrence of *F. culmorum* and *F. pseudograminearum* were mapped together. Sites from which *F. pseudograminearum* had been recorded that were outside the mapped distribution of *F. culmorum* were identified. For each of the summer and winter rainfall zones, climate profiles were generated for *F. culmorum* and for the part of the distribution of *F. pseudograminearum* that was outside the distribution of *F. culmorum*. The climate profiles were inspected for the minimum number of climate parameters that were not highly correlated and that would separate the distribution of *F. culmorum* from those *F. pseudograminearum* sites outside this distribution. A combination of mean temperature of the warmest quarter and annual rainfall gave a good separation of the sites in both the northern summer rainfall zone and the southern winter rainfall zone (Fig. 4).

The limiting values of the temperature and rainfall parameters were quite different for the two zones. In the south, *F. culmorum* was found over a wide range of annual rainfall but was restricted to sites with mean summer temperatures less than about 22° C (Fig. 4a). These sites all had annual rainfall greater than about 350 mm. The range of *F. pseudograminearum* extended beyond this into hotter sites, which also all had low annual rainfall.

In the north *F. culmorum* was restricted to areas with annual rainfall greater than about 625 mm (Fig. 4b). These sites were also relatively cool, with mean summer temperatures less than about 24.5° C. There were several records of *F. pseudograminearum* from sites in the north with summer temperatures below 24° C and rainfall above 600 mm (Fig. 4b), that were outside the recorded distribution of *F. culmorum*. These sites were in the Gulgong-Coolah area of New South Wales, at altitudes above 400 m. They were excluded from the predicted distribution of *F. culmorum* (Fig. 2c) mostly by low mean temperatures of the driest quarter (winter). This area may be suitable for the occurrence of *F. culmorum*, with the fungus not having been detected because of lack of surveys.

Discussion

Mapping of the known distributions of *F. graminearum*, *F. pseudograminearum* and *F. culmorum* over a whole continent, and analysis of these distributions by the climate matching system BIOCLIM, supported the hypothesis that their relative distributions can be described in terms of climatic factors.

A limitation of BIOCLIM is that criteria for defining climatically suitable areas are based on recorded distributions only, so the climate profiles and predicted distributions are only as good as the distribution information available. Survey data and other records gave a good coverage of the main wheat and maize growing areas of eastern Australia. Records from the margins of the grain belt, such as the higher slopes of eastern Australia, and from Western Australia were less comprehensive. Additional surveys in these areas may change some of the finer details of climate profiles and predicted distributions. However, the large-scale patterns of the association between distribution and climate would be unlikely to change if additional data were included.

In Australia, *F. graminearum* appears to be restricted to warm temperate and subtropical areas with moderate to high rainfall in summer. It is possible that these areas provide conditions best suited to dispersal and infection by ascospores of the teleomorph, *Gibberella zeae*. However, most records were from maize. The climate profile may therefore reflect the range of climates suitable for rain-fed production of maize. The epidemiology of diseases caused by *F. graminearum* in Australia is poorly understood. Further experimental work is needed to assess the relative contributions of climate effects on the fungus, and the availability of particular host species, to control of the distribution of *F. graminearum.*

Fusarium graminearum has been isolated from greenhouse-grown carnations in Victoria (Kalc Wright *et al*. 1997) outside the predicted range of the species, showing that distributions may also be extended where suitable microclimates and hosts exist.

Records of crown rot caused by *F. pseudograminearum* were obtained from throughout the main cereal growing areas, and BIOCLIM predicted that most of the grain belt was climatically suitable for occurrence of this fungus. However the data that were used only indicated the presence of the species at particular locations, and could not be used to determine any effect of climate on incidence of *F. pseudograminearum* relative to other species that occurred at the same site. In the Pacific Northwest, USA, Smiley and Patterson (1996) found that prevalence of *F. pseudograminearum* became less as both elevation and precipitation increased. Mean temperatures in the area where they worked were lower than in Australian wheat-growing areas. *Fusarium pseudograminearum* was reported to be less prevalent than *F. culmorum* on cereal stem bases from some sites in southern Victoria with high winter rainfall (Holloway *et al*. 1999). This area is also relatively cool. It is possible that more detailed surveys of the cooler, wetter margins of cereal production may identify limits to the distribution of *F. pseudograminearum*.

The reported greater prevalence of crown rot due to *F. pseudograminearum* in northern New South Wales and Queensland compared with southern Australia (Murray and Brown 1987) is probably due to factors other than climate. The crown rot fungus survives between seasons in infested stubble (Wearing and Burgess 1977) and the disease is favoured by continuous cereal cropping and stubble retention, practices which have been more common in the north (Martin *et al*. 1988). There is evidence of crown rot increasing in prevalence in the southern region as reduced tillage and stubble retention become more widely practised (Hollaway *et al*. 1999).

The recorded and predicted ranges of *F. culmorum* overlapped considerably with the cooler and wetter part of the range of *F. pseudograminearum*. This is consistent with reports from other countries where both species are known to occur, such as South Africa (Klaasen *et al*. 1991) and the Pacific Northwest, USA (Smiley and Patterson 1996). It is unlikely that the climate profile calculated for *F. culmorum* on cereals extends to the coldest part of its potential range, since all areas where wheat is grown on a large scale in Australia, and from which records were obtained, are relatively warm. This may be why the average maximum temperature of the warmest month for sites from which *F. culmorum* was recorded was higher than that reported by Sitton and Cook (1981) from the Pacific Northwest, being 29.8°C compared with 28.7°C.

There was strong evidence for the exclusion of *F. culmorum* from areas with high summer temperatures and low rainfall. However, the large differences in the limiting values of these parameters between northern and southern regions suggest that they are only indirect indicators of the true climatic constraints. It is possible that high summer temperatures have an adverse effect on survival of the fungus in soil or residues. An alternative hypothesis is that the activity of the fungus is more strongly controlled by temperature and moisture conditions in spring, when infection presumably occurs. Unfortunately BIOCLIM does not generate rainfall and temperature parameters specific to spring. Very little is known of the epidemiology of *F. culmorum* in Australia. A study of the time course of infection by this species would identify critical stages during the disease cycle for which alternative climate parameters could be constructed and tested.

The restriction of records of *F. culmorum* in Queensland to a small area at the higher, cooler edge of the cereal cropping zone indicates that this area is very marginal for the occurrence of the species. Most records used in this study were obtained from unpublished surveys of cereal crops in the region by R.L. Dodman and L.W. Burgess in the years 1976 to 1981, when the species was apparently reasonably common. In contrast, *F. culmorum* was isolated from only 3 of 1285 plants with crown or foot rot symptoms from 52 crops in this area in surveys in 1996 and 1997 (G.B. Wildermuth, L.W. Burgess, D. Backhouse and A. Abubakar, unpublished). If the distribution is limited by high temperature, then an increase in temperatures could account for a decline in abundance of *F. culmorum*. Temperatures in Queensland have risen from below or close to the long-term average in the late 1970s to consistently above average in the 1990s (Lough 1997). Changes in prevalence of *F. culmorum* in southern Queensland over this period could provide a useful model for studying the effects of climate change on soilborne plant diseases.

The relationship between climate and the distribution across the Australian continent of these three species of *Fusarium* was consistent with expectations based on observations from more limited areas in Europe, North America and South Africa. BIOCLIM provided a set of climate parameters that could be used to describe the distributions quantitatively. However the relationships suggested are only empirical correlations. Further experimental work is required to more precisely define the effects of temperature and water availability on the activity of each species, and especially on competition between species. This study was based on historical records of presence or absence only, and more detailed surveys are required of the relative prevalence of *Fusarium* species in agroclimatic zones where their distributions overlap.

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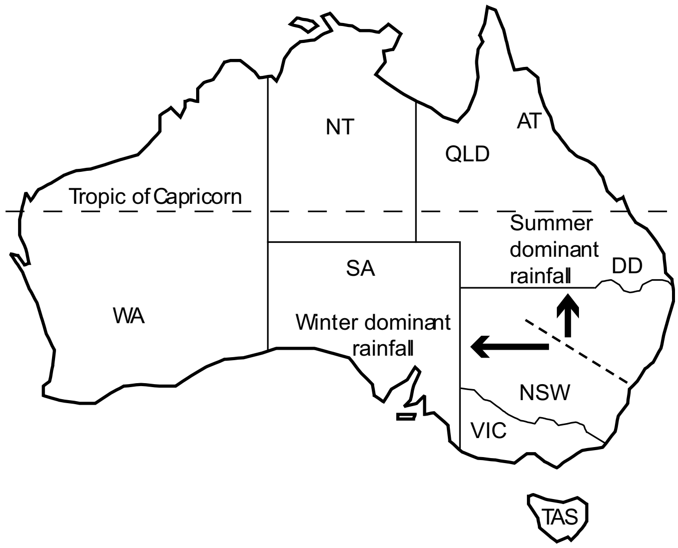

Fig. 1. Map of Australia showing state boundaries, location of geographical areas referred to in the text, and areas of summer-dominant rainfall north of a line through central New South Wales and areas of winter-dominant rainfall south and west of this line. AT, Atherton Tableland; DD, Darling Downs; NSW, New South Wales; NT, Northern Territory; QLD, Queensland; SA, South Australia; TAS, Tasmania; VIC, Victoria; WA, Western Australia.

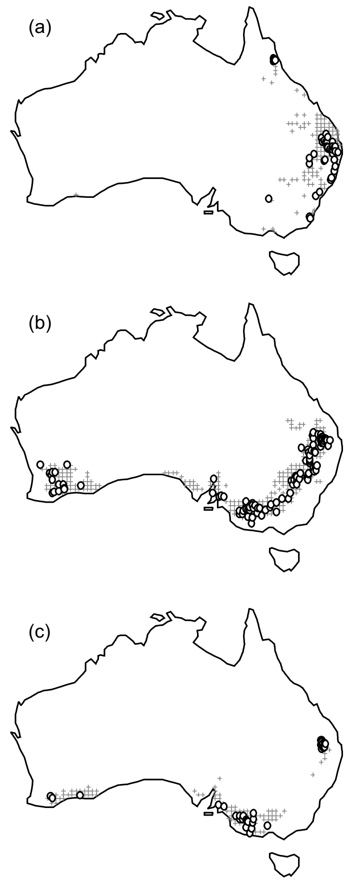

Fig. 2. Distributions within Australia of site records (○) and points on a 0.5° by 0.5° grid predicted to be climatically suitable (+) for (a) *Fusarium graminearum*, (b) *F. pseudograminearum* and (c) *F. culmorum*.

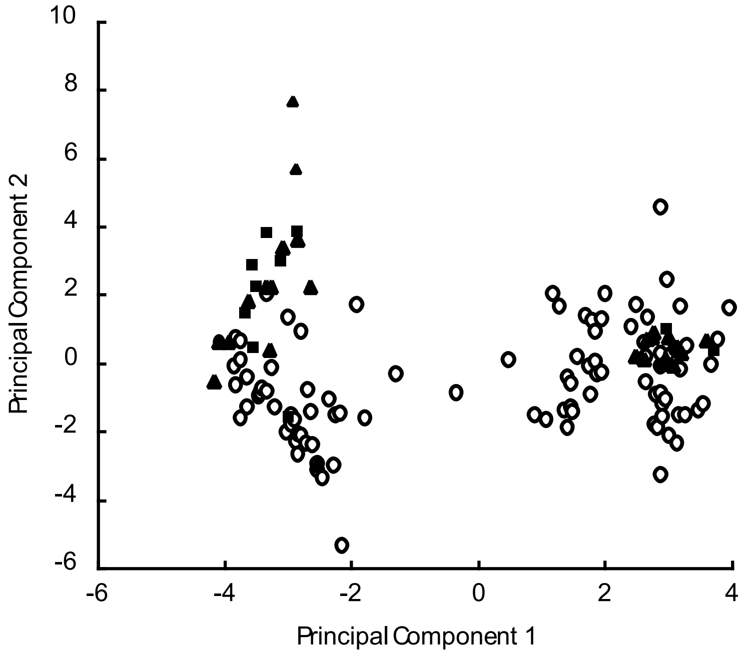

Fig. 3. Principal components analysis of 16 climate parameters for all sites from which *Fusarium pseudograminearum* (O), *F. culmorum* (σ) or both species (ν) were recorded. Sites are plotted against the first two principal components, which accounted for 52% and 21% of the variation in the data set respectively.

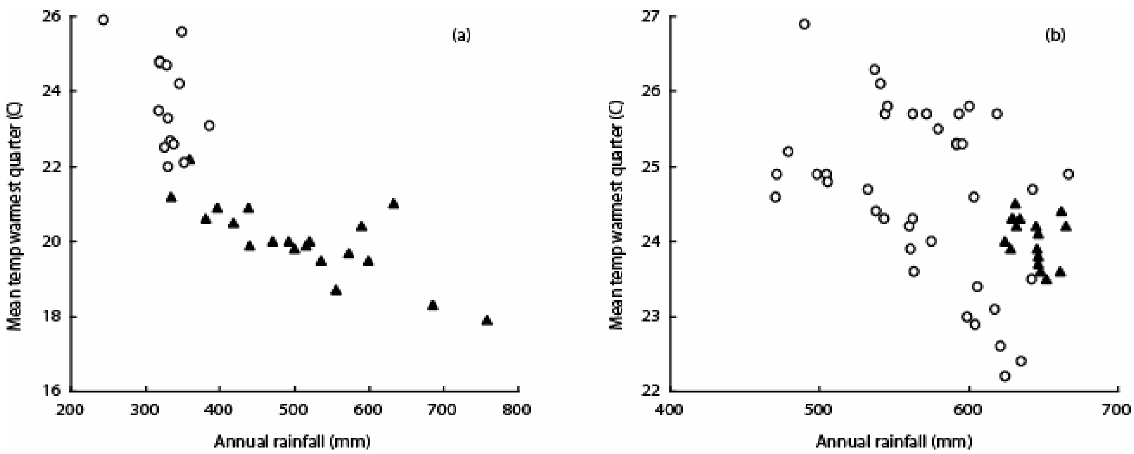

Fig. 4. Annual rainfall and mean temperature of the warmest quarter for sites from which *F. culmorum* was recorded (σ) and sites from which *F. pseudograminearum* was recorded that were outside the mapped distribution of *F. culmorum* (O), for (a) the southern grain belt (Vic, SA, WA) and (b) the northern grain belt (NSW, Qld).

Table 1. Range and mean (in parentheses) of 16 climate parameters calculated for all sites from which *Fusarium graminearum*, *F. pseudograminearum* and *F. culmorum* have been recorded from cereals in Australia

	Range of parameter for each species		
Climate parameter	*F. graminearum*	*F. pseudograminearum*	*F. culmorum*
Temperature			
Average annual (°C)	13.1-(18.2)-21.9	13.6-(17.0)-19.9	13.3-(16.3)-18.7
Min. of coldest month (°C)	-0.6-(4.8)-10.9	0.1-(3.2)-6.2	1.3-(3.4)-6.2
Max. of warmest month (°C)	23.9-(29.2)-33.5	26.6-(31.4)-34.8	24.1-(29.8)-31.9
Annual span (°C)	18.8-(24.4)-30.9	22.6-(28.2)-31.5	18.6-(26.4)-29.6
Mean of coldest quarter (°C)	7.1-(12.6)-18.1	8.1-(10.5)-13.7	8.1-(10.4)-12.0
Mean of warmest quarter (°C)	18.7-(23.0)-25.7	18.7-(23.3)-26.9	17.9-(22.0)-24.5
Mean of wettest quarter (°C)	10.4-(22.4)-25.7	8.1-(18.2)-26.9	8.6-(16.1)-24.4
Mean of driest quarter (°C)	10.2-(14.4)-22.5	8.9-(16.9)-24.0	10.4-(17.1)-21.2
Rainfall			
Annual (mm)	343-(941)-1881	243-(510)-828	335-(564)-759
Wettest month (mm)	35-(147)-389	31-(65)-124	35-(76)-103
Driest month (mm)	9-(36)-66	8-(26)-42	12-(25)-35
Coefficient of variation (%)	13.1-(47.1)-110.2	7.4-(31.8)-71.3	14.3-(39.1)-50.6
Wettest quarter (mm)	95-(409)-1081	88-(181)-339	103-(211)-276
Driest quarter (mm)	34-(121)-213	30-(87)-135	44-(83)-117
Coldest quarter (mm)	51-(143)-263	84-(123)-204	95-(142)-255
Warmest quarter (mm)	77-(372)-843	35-(149)-339	44-(155)-276
Number of site records	44	113	37

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