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Event frequency and severity of sorghum ergot in Australia

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Abstract. The temporal and regional distribution of the severity and potential number of events of sorghum ergot on grain sorghum in Australia were analysed using daily climatic data from 1957 to 1998. This analysis was conducted using both a rule-based method and a regression model. Between December and March, the main flowering period for most commercial grain sorghum crops, we found a likely increase of ergot events in eastern Australia from south to north as well as from west to east. When crops flowered in April or May the number of potential monthly events increased, particularly in the southern areas. The smallest number of events occurred when flowering occurred between September and December. The temporal and geographic distribution of the number of events and severity of sorghum ergot is closely related to relative humidity during the flowering period. The analysis indicates that grain sorghum crops flowering between early December and February are unlikely to be severely infected with sorghum ergot. Late flowering sorghum has increased risk to severe infection, especially in the coastal regions.

Introduction

Sorghum ergot, caused by the fungus *Claviceps africana* Frederickson, Mantle & De Milliano, has had significant impact on the Australian sorghum industry since it was first reported in April 1996 (Ryley *et al.* 1996). At present no commercial variety is resistant to sorghum ergot. Management options, such as variation in planting dates to avoid weather conditions favouring infection and the use of agronomic practices that ensure even flowering, can minimise the disease's impact (Ryley 1997). It is particularly important to quantify the relationships between ergot infection and environmental factors to develop effective management strategies and to ensure that the planting windows recommended for minimising the impact of the disease are accurate.

Sorghum ergot has been reported to be favoured by temperatures of approximately 20°C and relative humidities of 90% and above (Bandyopadhyay *et al*. 1998). Recently McLaren and others (McLaren and Wehner 1990, 1992; McLaren 1997; McLaren and Flett 1998) have attempted to quantify the relationships between ergot severity and weather factors. McLaren and Flett (1998) found that mean minimum temperature 23–27 days before flowering, and mean maximum temperature and mean daily maximum relative humidity 1–5 days after flowering (±10% pollen shed) had the highest correlations with ergot severity (= incidence *sensu* McLaren and Flett 1998). Earlier, McLaren and Wehner (1992) had demonstrated that mean night temperatures of <12°C 3–4 weeks before flowering significantly reduced pollen viability and increased susceptibility to ergot. The date of flowering had a profound effect on ergot severity, mainly due to the environmental effects on pollen viability (McLaren 1997). However, these relationships may not be applicable to geographical regions other than those in which these studies were conducted, because a fixed number of days was used to characterise the sensitive stages, e.g. the start and duration of both the flag leaf stage and the flowering stage. The starting dates and the lengths of these stages are known to vary with weather conditions, such as daily temperatures (Hammer *et al.* 1989).

In a previous paper (Wang *et al.* 2000*a*) we reported on the physiologically based relations between sorghum growth and development, and between ergot infection and weather conditions. An infection factor based on hourly temperature during the flowering period was developed. This infection factor and the mean relative humidity at 0900 hours during the flowering period were the main factors influencing ergot infection. Mean daily minimum temperature during flag leaf stage also had a significant effect on ergot severity, although no relation was found between this mean daily minimum

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temperature and pollen viability. It was found that an infection was likely to occur if the infection factor in the flowering period was above 0.3 and the mean relative humidity at 09 00 hours was above 70%. These findings had been incorporated into a simple regression model that could account for 94% of the environmentally caused variation in ergot severity observed in a genotype test. In the model both the start and duration of flag leaf stage and flowering period were simulated using thermal time.

In this paper we report on the temporal and regional distribution of the relative severity and frequency of potential events of sorghum ergot, based on long-term weather data from 1957 to 1998. Meinke and Ryley (1997) conducted a similar preliminary climatic risk analysis for sorghum ergot using a set of rules, formulated from research published by McLaren and others, to interrogate a database of long-term daily weather records. This study uses the findings reported in Wang *et al.* (2000*a*), and provides a more detailed regional analysis than that of Meinke and Ryley (1997).

Materials and methods

Historical weather data

Localities throughout the sorghum-growing areas of Australia, including the seed production areas of southern Australia and the Ord River, in the north-east of Western Australia, were selected (Table 1). The SILO patched climate data from 1957 to 1998 for each locality were used in the analysis (data courtesy of the Bureau of Meteorology and the Data Drill, Queensland Centre for Climate Applications, 1998; WWW: http://www.dnr.qld.gov.au/resourcenet/silo/datadril.html). The SILO climate data include daily maximum and minimum temperature, but vapour pressure instead of the relative humidity at 09 00 hours. In order to calculate the relative humidity, the temperature at 09 00 hours (T_{0900}) was estimated using the daily maximum and minimum temperature based on the method proposed by Goudriaan and van Laar (1994) (see also Parton and Logan 1981). This method can estimate temperatures at any time of the day and has been tested by Wang *et al.* (2000*b*) using hourly weather data from Gatton, Queensland. The saturated vapour pressure (hPa) at 09 00 hours ($e_{s,0900}$) was then calculated according to Goodriaan and van Laar (1994):

$$e_{s,0900} = 6.107 \exp[17.4\, T_{0900} / (239 + T_{0900})]$$

Then the relative humidity (%) at 09 00 hours was calculated using $e_{s,0900}$ and the SILO vapour pressure ($e_{a,0900}$):

$$RH_{0900} = 100\, e_{a,0900} / e_{s,0900}$$

Critical growth stages and the infection factor

As described later in this paper we used a set of rules to predict ergot events, and an equation to predict ergot severity on sorghum which had started to flower, for every day of the year. According to Wang *et al* (2000*a*) weather factors during the flag leaf and flowering stages have a significant influence on ergot severity. The start and end date, and the length of the flag leaf period for each flowering day was simulated using the APSIM sorghum model (Hammer and Muchow 1994; McCown *et al.* 1996). The starting date of flag leaf stage was simulated by assuming that the flag leaf begins to emerge when the third leaf prior

Table 1. Weather stations where climatic data were used in the simulation

St. No.	Station name	Latitude	Longitude
033002	Ayr DPI Research Stn	–19.62	147.38
039006	Biloela DPI	–24.38	150.52
033257	Bowen Airport	–20.02	148.22
033007	Bowen Post Office	–20.02	148.25
033094	Bowen Qld Salt	–20.01	148.23
035019	Clermont Post Office	–22.83	147.64
041522	Dalby Airport	–27.17	151.27
041023	Dalby Post Office	–27.18	151.26
065012	Dubbo (Cooreena Rd)	–32.21	148.57
065037	Dubbo State Forest	–32.27	148.62
035264	Emerald Airport	–23.57	148.17
035027	Emerald Post Office	–23.53	148.16
040082	Gatton Lawes College	–27.55	152.34
040436	Gatton QDPI Research Stn	–27.55	152.33
041521	Goondiwindi Airport	–28.52	150.33
041038	Goondiwindi Post Office	–28.55	150.31
075041	Griffith Aero	–34.26	146.06
075028	Griffith CSIRO	–34.32	146.07
073128	Gundagai Ridge Street	–35.08	148.1
055023	Gunnedah Pool	–30.99	150.25
055024	Gunnedah SCS	–31.03	150.27
075018	Hay Corrong	–34.22	144.46
075134	Hay Epsom Downs	–34.88	145.29
075031	Hay Miller Street	–34.52	144.85
040112	Kingaroy Prince St	–26.55	151.85
002038	Kununurra	–15.78	128.74
002056	Kununurra Aero	–15.78	128.71
040083	Gatton Post Office	–27.56	152.28
033045	Mackay Aero	–21.17	149.18
031066	Mareeba QWRC	–17.00	145.43
042023	Miles Post Office	–26.66	150.18
039104	Monto Post Office	–24.87	151.12
012056	Moree	–31.6	119.14
053048	Moree Comparison	–29.48	149.84
053027	Moree Post Office	–29.5	149.9
054120	Narrabri Bowling Club	–30.32	149.79
053030	Narrabri West Post Office	–30.34	149.75
051115	Narromine Airport	–32.22	148.23
051037	Narromine Post Office	–32.23	148.24
002041	Ord River Regeneration St	–17.39	128.92
041082	Pittsworth Post Office	–27.71	151.63
039083	Rockhampton Aero	–23.38	150.48
043091	Roma Airport	–26.55	148.78
043030	Roma Post Office	–26.57	148.79
035065	Springsure Post Office	–24.12	148.09
043034	St George Post Office	–28.04	148.58
041103	Toowoomba	–27.58	151.93
072150	Wagga Wagga AMO	–35.16	147.46
074114	Wagga Wagga SCS	–35.13	147.31
052026	Walgett	–30.04	148.12
054029	Warialda Post Office	–29.54	150.58
041176	Warwick Dragon St	–28.22	152.03
041111	Warwick Post Office	–28.22	152.03

to flag leaf is fully expanded (G. A. Hammer, pers. comm.), and that each of the last 3 leaves needs 20 degree-days to fully expand. Start of anthesis was defined as 100 degree-days after the flag leaf has fully expanded. It was assumed that these values are genotype-independent. The length of the flowering period was calculated using a thermal time value of 128 degree-days with a base temperature of 3.2°C based on the original observation data of Hammer *et al.* (1989). This was a mean value across genotypes.

In order to increase the accuracy of thermal time calculation, estimated hourly temperature was used in calculating the thermal time for predicting the flowering period and flag leaf stage. The estimation of hourly temperatures from daily maximum and minimum temperatures was based on the method proposed by Goudriaan and van Laar (1994). Every hour a thermal time value was calculated, and the mean of the 24 values on each day was used as the daily thermal time. Estimated hourly temperatures were also used for each day during flowering period to identify the part of the day with temperatures favourable to infection, and to calculate the value of the infection factor (*f*) every hour using Eqn 1. A daily mean infection factor value was used:

$$f = \exp(-0.026T^2+1.014T-9.8865) \quad (1)$$

where *T* is the hourly temperature (°C).

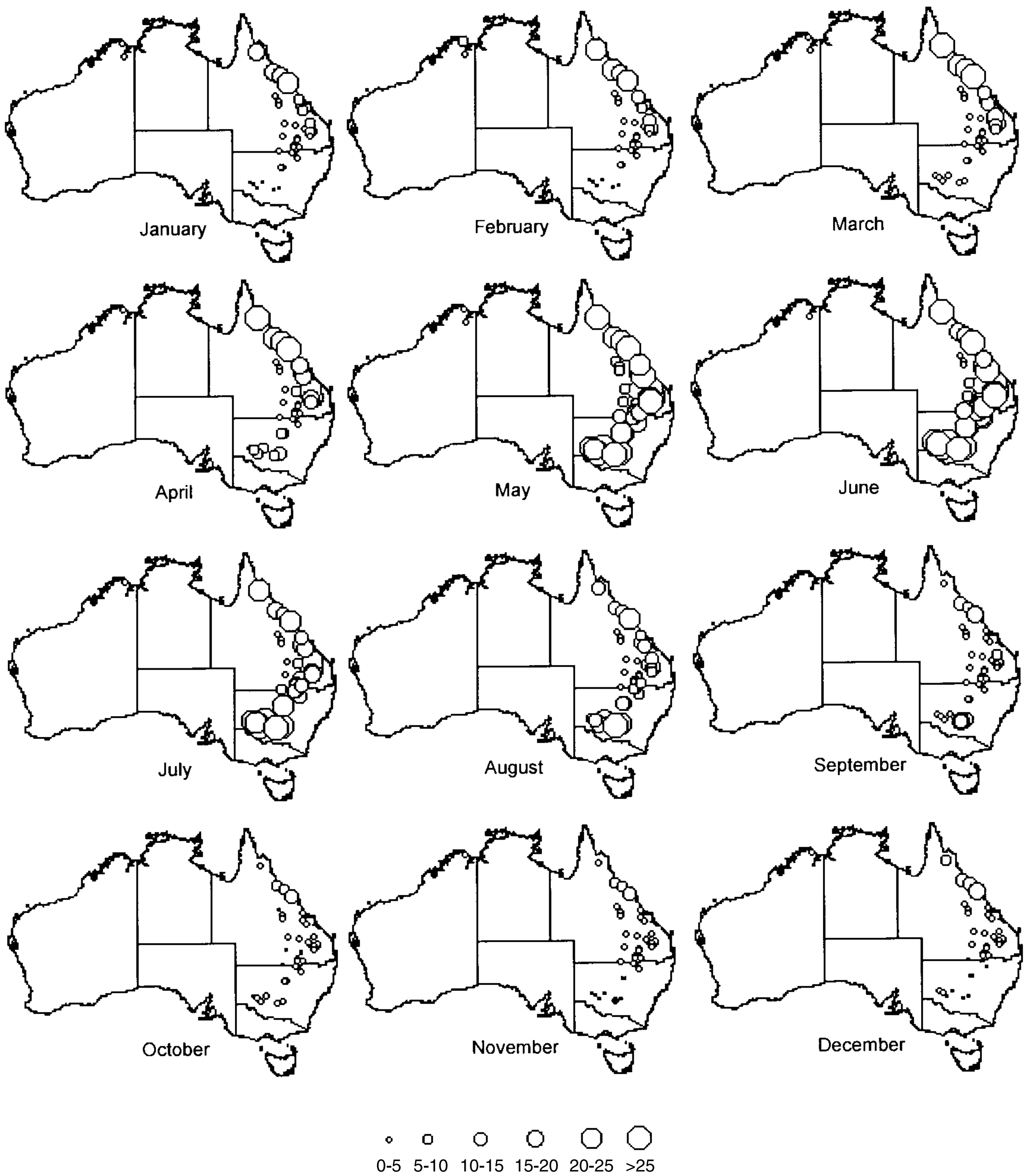

Fig. 1. Mean number of monthly events of sorghum ergot (simulated using the SILO climate data 1957–1998). A dot represents zero events.

Prediction of ergot events—a rule based approach

The above method was applied for every day of the year. Means of the daily minimum temperature during the flag leaf period, the daily infection factor based on hourly temperatures during the flowering period, and relative humidity at 09 00 hours during the flowering period were calculated. The following conditions had to be met before it was assumed likely that ergot outbreak could occur:

(*i*) The mean relative humidity at 09 00 hours during the whole flowering period was >70%.

(*ii*) If mean daily minimum temperature during the flag leaf stage was <13°C, male sterility in hybrid grain sorghum was assumed to occur. In these cases, the mean infection factor (f) based on the hourly temperature during the whole flowering period had to be >0.05. If that temperature was ≥13°C, the mean infection factor had to be >0.30.

If on a given day both the above conditions were met, it was assumed that sorghum starting flowering on this day could be subject to infection. This day was then counted as one 'event'. The mean number of monthly events that would have been conducive to infection was calculated from January 1957 to May 1998.

Prediction of ergot severity

The following regression equation (Wang *et al.* 2000*a*) was used to predict the ergot severity on sorghum which had started to flower on any particular day of the year, at each selected locality:

$$Y = 9.9953 f + 0.379 R_H - 0.7532 T_{flm} - 23.799$$

Where f is the mean infection factor during the flowering period, R_H is mean relative humidity at 09 00 hours during the flowering period, and T_{flm} is mean daily minimum temperature during the flag leaf stage.

This information was used to calculate the mean monthly ergot severity. In order to account for the difference of genotypes in their response to environmental factors and their resistance to ergot, a standardised scale value of predicted severity was used with a severity range between 1.0 (maximum) and 0.0 (minimum).

Results and discussion

Figure 1 shows the mean number of monthly events that would have been conducive to an outbreak of sorghum ergot. The analysis indicates that sorghum ergot could occur at least once a month at most locations in the sorghum-growing areas, with the exception of southern New South Wales remaining incident-free from November to February (Fig. 1). At most locations, the least number of events occurred in October and November while May and June had the highest number of potential monthly events. During the major flowering period of commercial sorghum in Australia (between December and March) the number of events gradually increased, and there was a distinct gradient of increasing events from south to north and west to east, respectively. The highest number of monthly events occurred along the north-east coast of Queensland from March to April. From this period onwards, to June, the number of events in coastal southern Queensland and southern New South Wales increased, reaching similar levels to those in northern Queensland. At Kununurra, the model predicted that

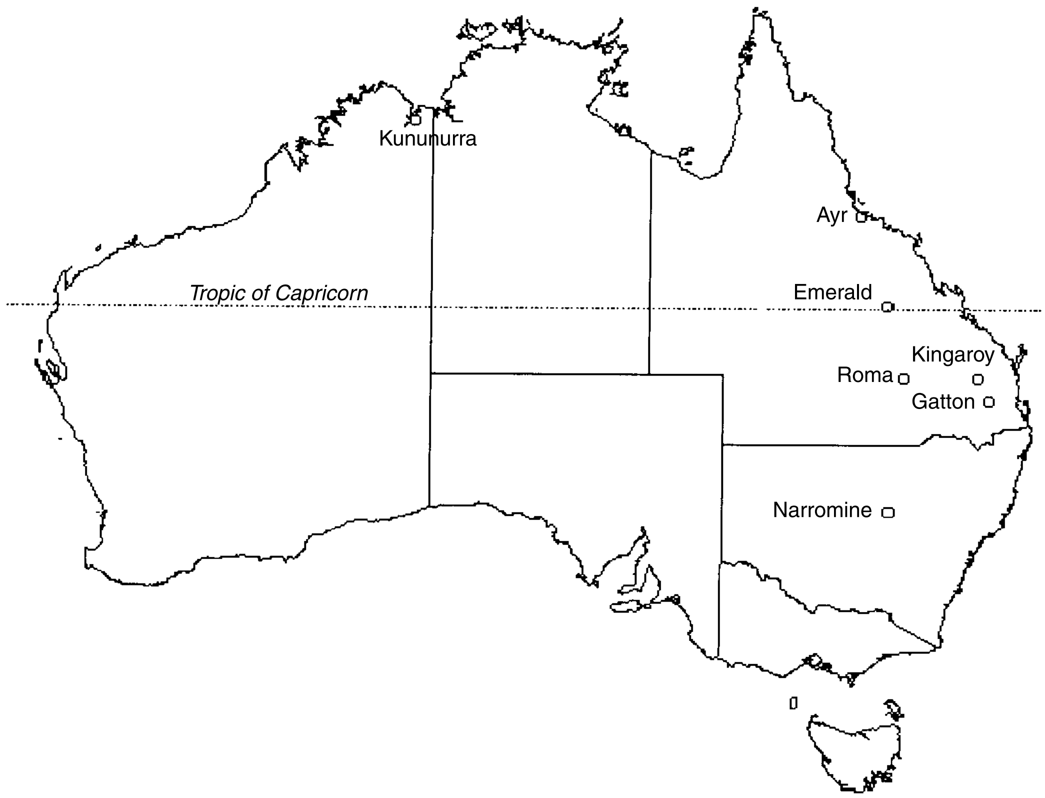

Fig. 2. Geographic positions of the locations: Kununurra, Ayr, Emerald, Kingaroy, Roma, Gatton, and Narromine.

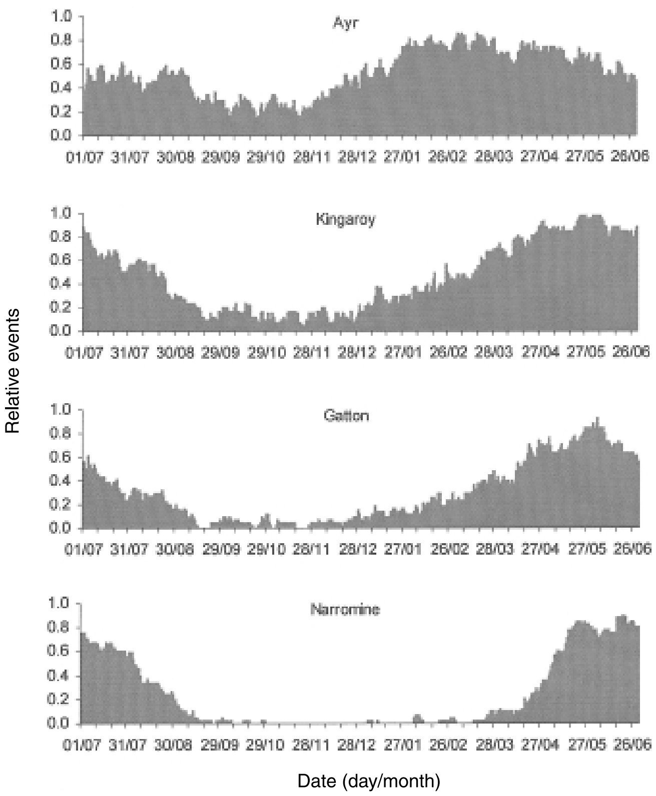

Fig. 3. Relative ergot events in the period 1957–1988 for Ayr, Kingaroy, Gatton, and Narromine, simulated based on the SILO climatic data. In the simulation each day was taken as the starting day of flowering. A relative event value of 0 means no infection could have occurred during this period; 1 means infection could have occurred on that day in all years.

sorghum ergot events are possible between November and July, but fewer than 5 events were predicted.

Meinke and Ryley (1997) also found a similar geographical trend in the number of ergot events. However, their use of a condition that there must be a minimum daily temperature of <14°C for at least 3 consecutive days, 2–3 weeks before anthesis, precluded the prediction of ergot events in northern Queensland where minimum temperatures during this stage are often >14°C. Our data (Wang *et al.* 2000*a*) indicated that ergot infection could occur even when night temperatures during the flag leaf stage were higher than 14°C.

A yearly cycle in the potential number of events is evident at each location. Cycles for 7 selected localities (Fig. 2) are presented in Figs 3 and 4. At each of these locations except Kununurra and Ayr, the relative number of potential events (proportion of years in which events could occur) was lowest during spring and summer (September to February), then gradually increased to a maximum in late April to June. At Kununurra and Ayr (where hybrid sorghum seed is produced during winter), the highest relative number of events occurred in late January–early March. The onset of a rapid increase in ergot events at all the selected locations was late

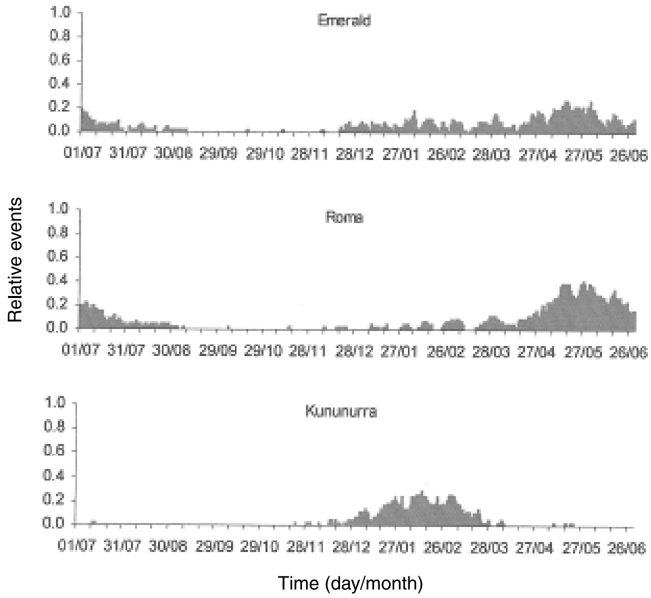

Fig. 4. Relative ergot events in the period from 1957 to 1988 for Emerald, Roma, and Kununurra based on the SILO climatic data. In the simulation each day was taken as the starting day of flowering. A relative event value of 0 means no infection could have occurred during this period; 1 means infection could have occurred on that day in all years.

December except at Narromine (where it was in late March) and Ayr (late November). The analysis indicated that ergot is likely to occur during this period in >80% of years at Ayr, Kingaroy, Gatton, and Narromine, but in <40% years at Emerald, Roma, and Kununurra. In addition, ergot events could occur throughout the year at Ayr, Kingaroy, and Gatton. This has particular significance for some breeders' nurseries that are grown during winter at Ayr.

The geographical and temporal trends in mean relative ergot severity (Fig. 5) were similar to those of the mean number of events. Between October and February, the relative severity was lowest for most locations, then increased particularly along the north coast of Queensland and southern New South Wales. Maximum values occurred in north Queensland during April and May, in southern Queensland, in August, and in southern New South Wales between May and September. The potential relative severity of sorghum ergot during the flowering period (December–March) of most grain sorghum crops was generally <0.4%.

The temporal and geographic trends in both predicted ergot events and predicted ergot severity reported in this paper correspond closely with field observations since ergot was first recorded in Australia in April 1996 (Ryley *et al.* 1996). The vast majority (>95%) of sorghum crops flowering between December and March have had very low ergot severity (<1%) irrespective of the locality, with the worst outbreaks occurring in late-sown crops flowering from April onwards. Both the number and severity of ergot events during the summer months has been higher in eastern locali-

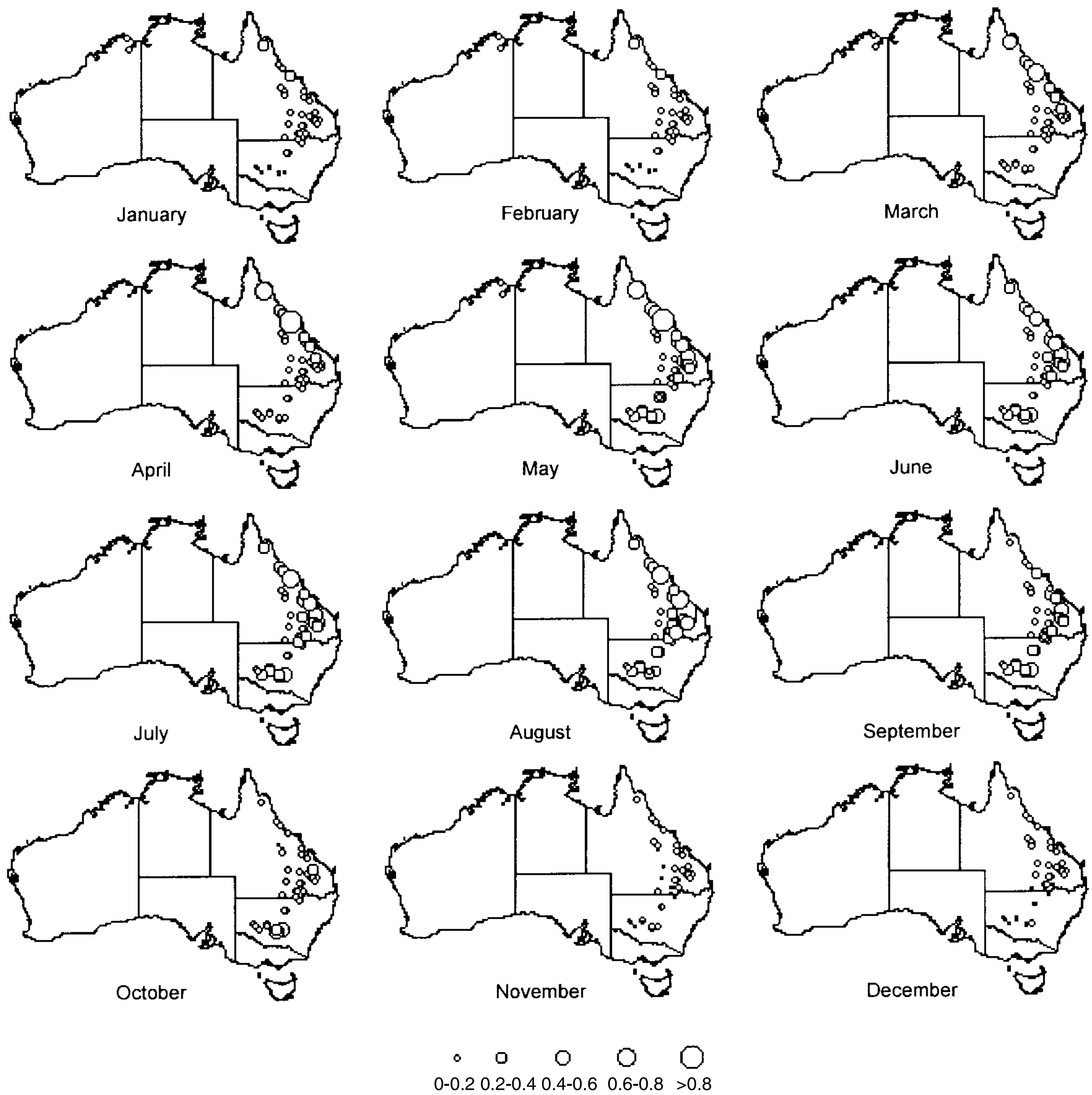

Fig. 5. Monthly mean of predicted relative sorghum ergot severity (simulated using the SILO climate data 1957–1998). A standardised scale is used with a severity range between 0.0 (minimum) and 1.0 (maximum). A dot represents zero severity.

ties (Kingaroy and Gatton) than those further West (Emerald and Roma). However, the analysis did not predict an ergot outbreak that occurred in Kununurra in October 1998. Because the analysis was based on 32 years of weather data from each locality, it would be expected that weather conditions that are conducive to ergot would occur in some other years.

The temporal and regional distributions of both ergot severity and potential number of monthly events are related to relative humidity (Fig. 6), which reflects the combination effect of rainfall (Fig. 7) and temperature (Fig. 8). From November to March there is an increasing gradient in the mean monthly relative humidity (Fig. 6) from south to north and from west to east, respectively. The rainfall distribution during this period (Fig. 7) appears to strongly influence the relative humidity patterns (Fig. 6). From March onwards the mean monthly rainfall and mean monthly temperature gradually decreases for most locations (Figs 7 and 8). The

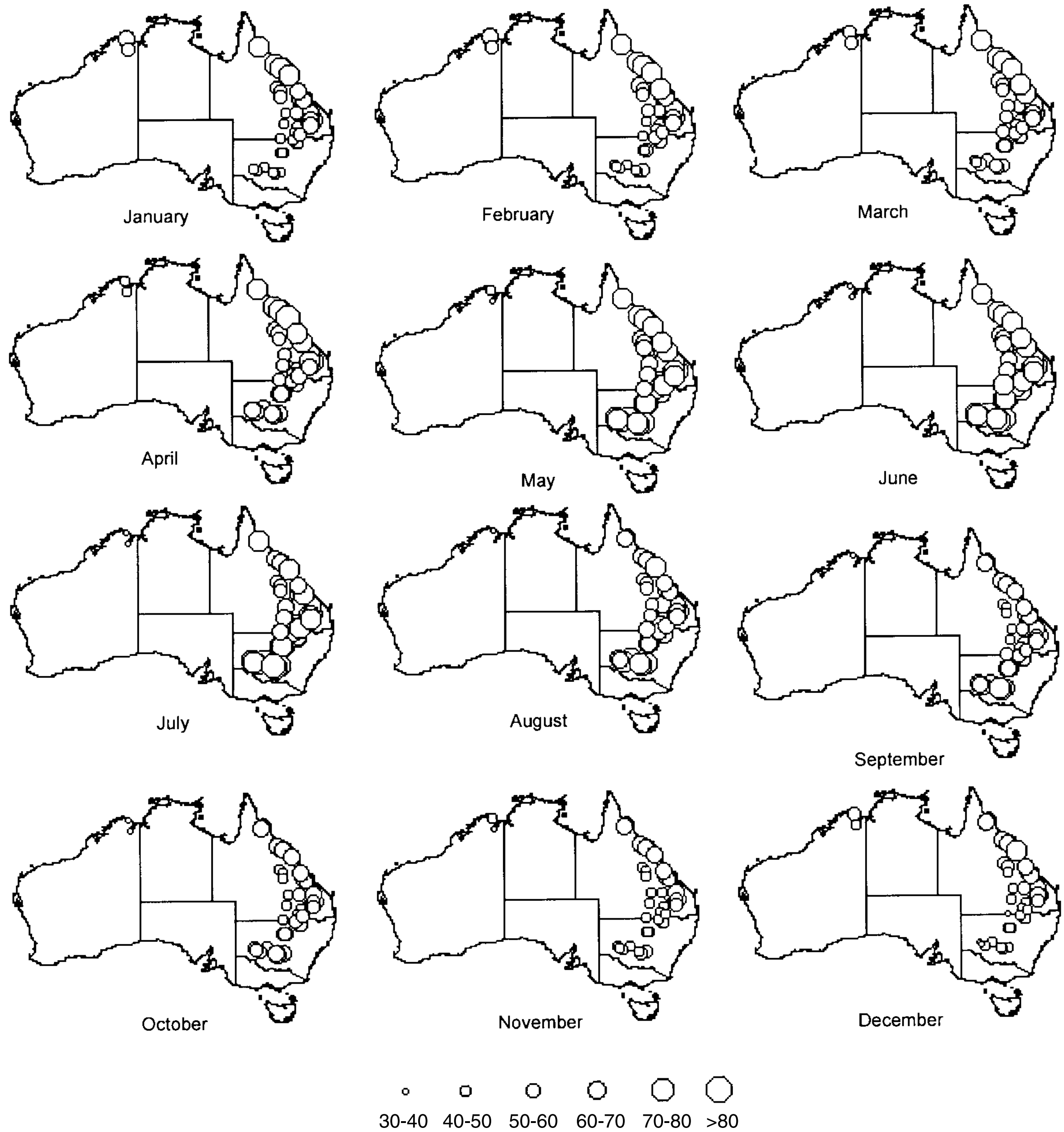

Fig. 6. Monthly mean of relative humidity (%) at 0 900 hours (calculated using the SILO climate data 1957–1998).

decreasing temperature results in high relative humidity. According to the model, temperature is not a constraint in most regions, with humidity appearing to be the major factor controlling sorghum ergot outbreaks in Australia.

In cooler regions, low night temperatures during flag leaf stage can cause male sterility and may have a large effect on ergot infection, as indicated by McLaren and Wehner (1992), McLaren (1997), and McLaren and Flett (1998). In the main sorghum-growing regions in Australia, when most commercial grain sorghum crops are flowering (between December and March), temperatures are usually high (Fig. 8). Sterility may only occur for very early- and late-planted sorghum.

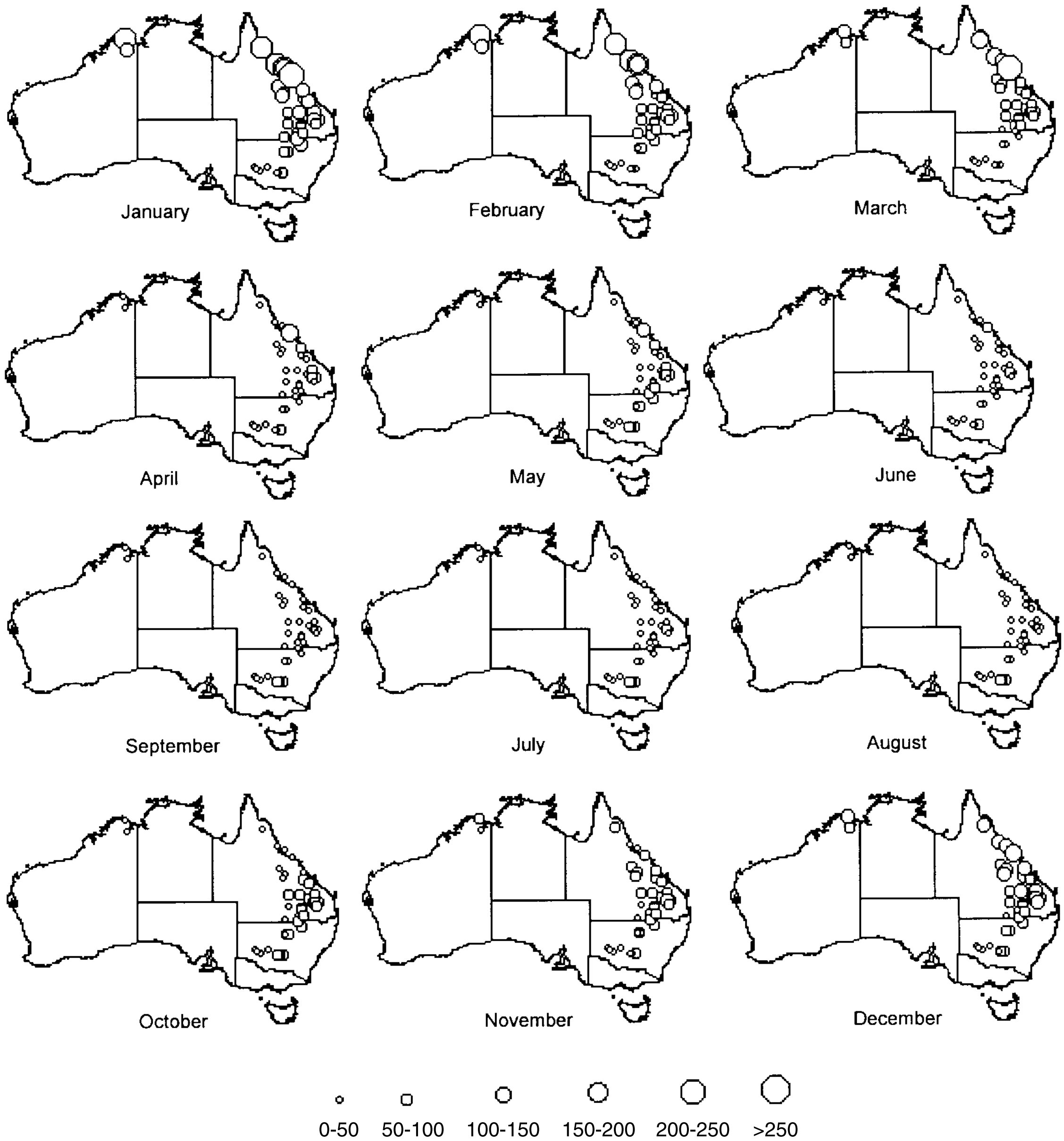

Fig. 7. Monthly mean of total rainfall (mm) (calculated using the SILO climate data 1957–1998).

During the flowering period temperatures are generally within the infection range, and once humidity is high, infection can occur.

Models such as those of McLaren and Flett (1998) and the one developed in this study have applications beyond the qualification of temporal and spatial distribution of ergot outbreaks. Fungicides are commonly applied to male sterile lines in seed production blocks and nurseries to protect them from sorghum ergot, and these models can be used to predict chances of outbreaks, thereby optimising the timing of fungicide sprays. In field trials that aim to assess the resistances of genotypes to sorghum ergot, flowering may occur over a number of weeks, during which genotypes are exposed to a range of weather conditions when they flower. Further, the approach could be used to adjust ergot severity data for different genotypes. However, there is evidence that relation-

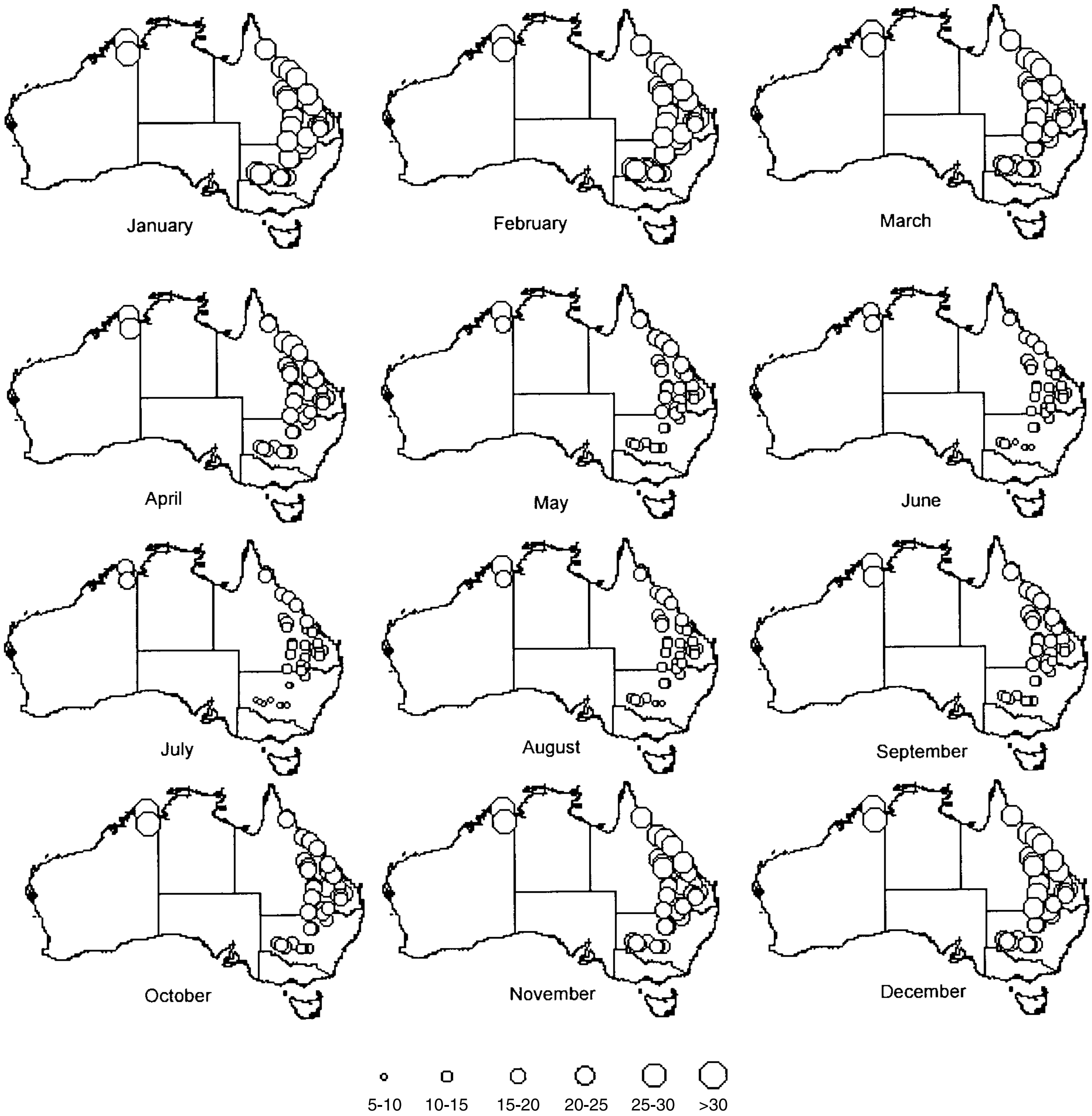

Fig. 8. Monthly mean of daily average temperature (°C) (calculated using the SILO climate data 1957–1998).

ships between ergot severity and critical environmental parameters differ for different genotypes (McLaren and Wehner 1992), which complicates any adjustments. In addition, the model developed in this paper cannot be used to predict ergot severity for a particular genotype. However, the model can be used in the relative comparison of ergot infection in different geographical regions.

This study used daily mean weather data to investigate ergot disease outbreaks. Further studies are required to improve our understanding of the influences of various climatic parameters on host factors such as pollen production, viability, stigma receptivity, and on pathogen characteristics such as secondary sporulation, spore dispersal and infection, and the interactions between them. In particular, hourly measurements of temperature, relative humidity, and rainfall will help to explain some of these interactions. Climatic analyses such as the current study can be further refined as addition of information is gathered.

It should be emphasised that the current analysis was based on the average events and severity in the period from 1957 to 1998. The number of events in any particular year differed strongly depending on the season type. In some wet years the starting date for infection is likely to occur earlier and with higher severity. These seasonal variations are associated with ENSO patterns, which might offer some predictability and hence the opportunity for producers to integrate such probabilistic forecasts into their overall crop management. For this it is necessary to analyse the distribution of events and severity in years with different SOI (Southern Oscillation Index) phases (Stone *et al.* 1996; Meinke and Hochman 2000). However, this requires measured daily weather data for a minimum of 50 years, which are still difficult to obtain.

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