The flood bug, Australiodillo bifrons (Isopoda: Armadillidae): A potential pest of cereals in Australia?

M.G. Paoletti a,⁎, A. Tsitsilas b, L.J. Thomson b, S. Tait c, P.A. Umina b

a Department of Biology, University of Padova, Padova 35100, Italy
b Centre for Environmental Stress and Adaptation Research, Department of Zoology, The University of Melbourne, Parkville, Victoria 3010, Australia
c Istituto per lo Studio degli Ecosistemi, CNR, 50019 Sesto Fiorentino (Firenze), Italy

ABSTRACT

Agricultural invertebrate pests cause substantial losses through reduced productivity and increases in pesticide application. Understanding the basic biology of pest species and how they interact with other invertebrates within specific industries is important for developing targeted control strategies. In 2006, feeding damage to emerging cereal crops in parts of New South Wales, Australia, was caused by Australiodillo bifrons (Budde-Lund, 1885), an endemic slater species. This appears to be a new phenomenon as slaters are not widely known to be a pest of cultivated plants, but rather feed on decaying organic matter. Samples were collected from these areas and affected farmers interviewed. We observed and report on the swarming of A. bifrons populations in the field, a characteristic behaviour that may contribute to the pest status of this species. We also examined the feeding characteristics of A. bifrons and another slater species, Porcellio scaber (Latreille), to wheat seedlings under laboratory conditions. Our results suggest A. bifrons can cause significant feeding damage to wheat seedlings and reaches very high densities in the field. The presence of shelterbelts along crop margins could be harbouring large populations of A. bifrons, although they also provide a refuge for many beneficial invertebrates that could control pest populations. We propose that the pest status of A. bifrons in parts of New South Wales may be increasing due to changes in farming practices and/or in response to climate change.

Crown Copyright © 2007 Published by Elsevier B.V. All rights reserved.

1. Introduction

Invertebrate pests represent a significant challenge to broad-acre agriculture in Australia and throughout the world. The use of pesticides has been and continues to be the most common management option for the control of these pests (Beaulieu and Weeks, 2007). Continued application of pesticides to control agricultural pests leads to problems in pest resurgence, secondary pests and the development of pesticide resistance (Jutsum et al., 1998; Hopper, 2003). The intensification of agriculture and projected increase in the use of agrochemicals, combined with public concern about health and environmental impacts of pesticides, means it is increasingly important to develop alternative methods of crop protection (Al-Assiuty and Khalil, 1995; Isman, 2006). The most effective means of control should not rely solely on chemicals, but combine several methods together to provide an integrated and targeted approach (McRoberts et al., 2003). Devising such strategies requires accurate identification and an
understanding of the biology of pest species (Kogan, 1998; Umina et al., 2004).

In July 2006, a number of reports were made of feeding damage to emerging cereal crops around Moree, in the North West Slopes and Plains district of New South Wales, Australia. The pest in question was identified as Australiodillo bifrons (Budde-Lund, 1885), an endemic Slater species. Reports indicated that the number of slaters per cereal plant was staggering and that individuals could be seen crawling up the plant and feeding mainly on the tips of the leaves. In many situations, crops needed to be re-sown due to the extent of feeding damage sustained. This insight into slaters gives cause to question the effects of other formerly innocuous invertebrates in broad acre cropping. We may be observing a shift in perspectives and represents an undisturbed natural habitat. Interviews with farmers were performed to gain an insight into previous experiences with slaters and to obtain information on paddock history. Slaters were collected directly from the soil surface from cereal paddocks and under logs and litter in shelterbelts. Samples were stored in 80% ethanol, and later sorted and examined under a stereomicroscope. Brief descriptions of specimens were made and observations in the field recorded. Slaters were independently identified by two specialists (Dr George Wilson from Australia Museum, Sydney, Australia and Dr Stefano Taiti, CNR, Florence, Italy) as A. bifrons (Budde-Lund, 1885).

Samples were also collected using pitfall traps, which were used to compare Slater numbers across different landscapes. Six pitfall traps (Genfac Plastics, Melbourne, Australia) (7 cm diameter × 12 cm deep; 1/3 filled with ethylene glycol) were placed in a single wheat crop and another six in the adjacent shelterbelt at one farm (Glenco). Five pitfall traps were also placed in each of two forested areas of Mount Kaputar National Park to obtain a clearer understanding of the slaters and other invertebrates present in an undisturbed forested habitat. Pitfall traps were used to document A. bifrons and other ground-dwelling invertebrates in natural and agricultural systems. It should be noted that pitfall traps reflect invertebrate foraging behaviour and population dynamics (Neville and Yen, 2007).

2. Materials and methods

2.1. Field surveys and collections

Field surveys and collections were conducted in the Moree area in late spring 2006 (October–November). Five separate farms (Bullarah—29°17′47″S 149°24′21″E, Glenco—29°19′04″S 149°09′24″E, Gundare—29°31′57″S 149°18′45″E, Greer—29°24′28″S 149°14′49″E and Ponjola—29°08′19″S 150°03′07″E) that experienced feeding damage in the previous autumn (June–July 2006) were sampled on multiple occasions. Shelterbelts adjacent to the fields and one area of a National Park (Mount Kaputar National Park—30°17′08″S 150°08′11″E) were also surveyed together with gardens inside the town of Moree. Mount Kaputar was chosen because it is nearby the affected properties and represents an undisturbed natural habitat. Interviews with farmers were performed to gain an insight into previous experiences with slaters and to obtain information on paddock history. Slaters were collected directly from the soil surface from cereal paddocks and under logs and litter in shelterbelts. Samples were stored in 80% ethanol, and later sorted and examined under a stereomicroscope. Brief descriptions of specimens were made and observations in the field recorded. Slaters were independently identified by two specialists (Dr George Wilson from Australia Museum, Sydney, Australia and Dr Stefano Taiti, CNR, Florence, Italy) as A. bifrons (Budde-Lund, 1885).

Samples were also collected using pitfall traps, which were used to compare slater numbers across different landscapes. Six pitfall traps (Genfac Plastics, Melbourne, Australia) (7 cm diameter × 12 cm deep; 1/3 filled with ethylene glycol) were placed in a single wheat crop and another six in the adjacent shelterbelt at one farm (Glenco). Five pitfall traps were also placed in each of two forested areas of Mount Kaputar National Park to obtain a clearer understanding of the slaters and other invertebrates present in an undisturbed forested habitat. Pitfall traps were used to document A. bifrons and other ground-dwelling invertebrates in natural and agricultural systems. It should be noted that pitfall traps reflect invertebrate foraging behaviour and population dynamics (Neville and Yen, 2007).

2.2. Other soil invertebrates

Soil samples (10 cm wide × 10 cm long × 6 cm deep) were collected from four farms (Glenco, Gundare, Greer and Ponjola) and Mount Kaputar National Park. Samples were brought back to the laboratory and placed into modified Berlese-Tullgren funnels (25 W light bulbs), which uses a humidity and light gradient to force soil invertebrates to escape the drying substrate and move into a collection vial containing monophenol drops. Berlese-Tullgren funnels are the most common method for separating small invertebrates from soil and litter (Behan-Pelletier, 1999). Samples remained in the Berlese-Tullgren funnels for 1 week. Invertebrates were then identified and counted.

2.3. Plant damage evaluation

A laboratory trial was performed to determine the feeding damage of A. bifrons on wheat seedlings when presented with different leaf litters. In October 2006, 12 wheat (Triticum aestivum cv. Bobwhite) seeds were sown into 16 clear plastic containers (Décor, Melbourne, Australia) (15 cm long × 10 cm wide × 21 cm deep) using cotton wool. The containers had two ventilation holes of approximately 6 cm in diameter covered by gauze to prevent the movement of slaters. Seeds were sown...
in only one half of each container. The containers were watered to germinate seedlings and placed in a randomized block arrangement. After 4 weeks the seeds had germinated and were an average 33 mm (±18 mm) long. Some seedlings (1–2 per container) were removed to ensure all containers had 10 seedlings before introducing slaters. In the other half of the each container approximately 10 g (±0.08 g) leaf litter was placed onto the cotton wool. In nine containers, the litter added (herein referred to as ‘litter A’) was collected from a shelterbelt at Ponjola, containing predominately Casuarina cristata. In another seven containers, the litter added (herein referred to as ‘litter B’) was collected from a shelterbelt at Gundare, containing predominately Eucalyptus spp.

Live slaters were collected from Moree, placed in small containers with leaf litter and moist paper-toweling and transported to the laboratory. Ten adult A. bifrons were placed into four containers with litter A and four containers with litter B. This density of slaters roughly corresponded to densities reported and directly observed in field crops. To compare the feeding behaviour and plant damage with another slater species, Porcellio scaber were collected from a domestic garden in Diamond Creek, Victoria (37°40’33S, 145°07’45E) and examined. Ten adult P. scaber were added to three containers with litter A and three containers with litter B. Two containers, which had litter A, lacked slaters and acted as controls. All containers were placed in a temperature cabinet at 17 °C with a L14:D10 cycle.

The number of slaters in each container was counted weekly for 5 weeks, after which time the majority of wheat seedlings were dead. The number of seedlings alive in each container was counted each week. Feeding damage to seedlings (which appears as irregular patches removed from the leaves) was rated based on a 0–10 scale, where 0 indicates no visible damage, 5 indicates 50% of the leaves damaged and 10 indicates all plants dead or dying. This method of assessing plant damage has been validated by numerous authors working on crop invertebrate pests (Gillespie, 1993; Liu and Ridsdill-Smith, 2000; Umina and Hoffmann, 2004). After week 4, two containers with A. bifrons and litter B became infected with fungal mycelium. Because this was detrimental to wheat seedlings, these containers were excluded from the analyses at week 4 and week 5. Differences between treatments were tested by analysis of variance (ANOVA), and if significant, a Tukey’s b-test was performed for a posteriori comparisons. Repeated measure ANOVAs were also performed on the two plant damage indices to determine if there were any differences between treatments when averaged across the sampling period. All analyses were performed using SPSS 14.0.

### 2.4. Climatic data at Moree

The relatively recent emergence as A. bifrons, a native species to Australia, as a pest of broad-acre crops could be explained by environmental changes influencing survival and population expansions. Climatic data, including temperature, humidity and rainfall, from Moree was obtained from the Australian Bureau of Meteorology (www.bom.gov.au) from 1984 to 2005. Significant changes in climatic variables over time were determined using linear regression.

3. Results and discussion

#### 3.1. Field surveys and observations

Very little is known about the ecology of A. bifrons. Goodyer (1979) first reported this species occasionally damaging wheat and oat crops in the north west of New South Wales, Australia, but it is unclear why A. bifrons has recently become an important pest in the Moree district. A. bifrons occurs in many parts of eastern Australia, including New South Wales (Murray-Darling basin), Northern Territory, Queensland (Lake Eyre Basin, N Gulf, NE coastal) and Victoria (Murray-Darling basin) (Green et al., 2002). Gaining a basic understanding of the ecology of this species and investigating the potential feeding damage to cereals will assist in dealing with this pest in the future.

Interviews with five farmers were undertaken to gain an insight into the previous sightings and problems caused by A. bifrons. All five growers observed dense populations during the day. In four cases, slaters were directly observed crawling up wheat and/or oat seedlings in June–July 2006 and feeding primarily from the tips of the young plants. Although the damage did not exceed more than 10–15% of the total number of seedlings that emerged, each farmer decided to spray insecticides to control the slater populations. Two of the fields were subsequently reseeded (in the damaged sections), and two other fields were abandoned for grazing by cattle. Only one farmer (of the five) observed large numbers of slaters in June–July 2006 and did not experience any feeding damage to emerging crop seedlings. However, this paddock was planted with chick peas (not cereals) and was part of a 5 year legume-cereal rotation with a no-tillage regime. It is still unclear where A. bifrons spend most of their time and precisely why they move into wheat crops, which contain a reduced litter layer. Although high numbers were detected in shelterbelts adjacent to the affected paddocks, this does not account for the extremely high densities observed in the ‘swarms’ (discussed below).

Of the five farms in Moree that reported slaters causing damage to cereals in autumn 2006, A. bifrons was collected from three properties (Glenclo, Gundare and Ponjola). During the collection period in October–November, conditions were relatively hot and dry. This also followed an extended dry period through winter–early spring. The extent to which these conditions affected our collections and observations is unknown. It is likely that soil (and litter) moisture levels influenced the efficiency of pitfall trap catches. Nonetheless, numbers were large enough to assess sex ratio, the presence of ovigerous females and pulli, and to examine the morphology in detail (Table 1). This species has an oval shaped and flattened body, light brown colour with darker irregular spots and a longitudinal dark brown stripe in the middle of the back (Fig. 1). There is a characteristic split on the frontal plate of both males and females. Males are larger than females: the maximum dimensions observed in the specimens examined were 9.2 mm long × 6.6 mm wide for males and 8.5 mm long × 4.5 mm wide for ovigerous females. Larger males have more of a broad-oval shape than the females, which are clearly more slender and sub-parallel (Fig. 1). The sex ratios of A. bifrons varied between properties, however these were not
significantly skewed (Table 1). Juveniles were collected from only two samples, and these samples also contained ovigerous females (females bearing large eggs or pulli). The number of pulli per female from these sites varied between 3 and 12.

Pitfall traps were placed in a wheat paddock and adjacent shelterbelt at one farm (Glenco). Despite not being able to directly collect living *A. bifrons* from this property on two separate visits, a large number of individuals were collected in the pitfall traps that were placed in the wheat crop for 3 days. An average of 65.83 (s.e. = 17.94) slaters were found per trap. A number of other invertebrates were collected, primarily ants, mites and beetles. The pitfall traps placed in the shelterbelt adjacent to the wheat did not contain *A. bifrons*. The most abundant invertebrates collected were beetles, ants and spiders. Ants were examined more closely as many species are predatory and could play an important role in controlling *A. bifrons* under some circumstances. There were many species of ants identified, primarily belonging to the *Iridomyrmex*, *Polyrhachis*, *Rhytidoponera*, *Pheidole* and *Melophorus* genera. Most species were found in pitfall traps placed in both the wheat crop and shelterbelt, however, individuals belonging to the *Melophorus* and *Pheidole* genera were only collected from the wheat crop. Mount Kaputar contained no *A. bifrons*, however other isopods were collected directly and found in the pitfall traps (Table 2). The majority of the invertebrate fauna at Mount Kaputar were ants, beetles, spiders and flies. The ant fauna at Mount Kaputar was considerably different compared with those collected at Glenco. The genera were

<table>
<thead>
<tr>
<th>Farm</th>
<th>Collection</th>
<th>Date and time</th>
<th>Males</th>
<th>Females</th>
<th>Juveniles and pulli</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gundare</td>
<td>Small swarm</td>
<td>01 Nov 06 am</td>
<td>39</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Medium swarm</td>
<td>03 Nov 06 am</td>
<td>14</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Large swarm</td>
<td>03 Nov 06 am</td>
<td>86</td>
<td>84</td>
<td>Many</td>
</tr>
<tr>
<td>Ponjola</td>
<td>Large swarm (juvenile abundant section)</td>
<td>02 Nov 06 am</td>
<td>9</td>
<td>22</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>Large swarm (adult abundant section)</td>
<td>02 Nov 06 am</td>
<td>52</td>
<td>87</td>
<td>Some</td>
</tr>
<tr>
<td>Glenco</td>
<td>Shelterbelt (dead specimens)</td>
<td>31 Oct 06 am</td>
<td>13</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pitfall traps in wheat</td>
<td>03 Nov 06 am</td>
<td>8</td>
<td>36</td>
<td>Rare</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td>221</td>
<td>298</td>
<td>68</td>
</tr>
</tbody>
</table>

Fig. 1 – Dorsal and ventral views of male and female *Australiodillo bifrons* collected from Moree. Arrow indicates characteristic split in the frontal plate.
A total of eight species of terrestrial isopods were collected in the study (Table 2). Only *A. bifrons* is associated with crop damage in the Moree district. *A. bifrons* was also the only species observed and reported to display an unusual behaviour of forming large aggregations and moving in swarms. Four additional species are endemic to Australia and likely to be new/undescribed species. Only one of these was collected from farms near Moree; the others were collected at Mount Kaputar and found in very small numbers. One species, *Porcellionides pruinosus* (Brandt), is an introduced species and was only found in the shelterbelt at Glenco. *Porcellio laevis* (Latreille) was only found in highly watered gardens inside the town of Moree.

The swarming behavior of *A. bifrons* was observed during October–November 2006. We define ‘swarming’ as a consistent mass of individuals moving along the soil surface (sometimes ascending–descending living or dead trees) or moving along logs/posts on the soil (Fig. 2). This was seen across two sites on five occasions. The size and make-up of each swarm varied and may have been influenced by several factors, including time of day, weather conditions, surrounding vegetation, etc. We attempted to estimate the number of slaters within each swarm. This was done by first measuring the dimensions of each swarm. The number of slaters within 10 cm² was then counted and extrapolated to provide an estimate of the total number of individuals. At Gundare, three swarms were observed, ranging in size from approximately 30 m² to 150 m long × 40 m wide. All three swarms contained individuals of both sexes and juveniles. The two larger swarms also contained pulli (newly-hatched juveniles). The swarms were conservatively estimated to contain approximately 8000 (1st swarm), 500,000–800,000 (2nd swarm) and 1 million (3rd swarm) *A. bifrons*. The swarms were observed on a gravel road, in roadside vegetation and in pastures. Individuals tended to move in one main direction. In the Ponjola farm, two large swarms of *A. bifrons* were observed on a gravel road and a shelterbelt dominated by Casuarina cristata. The area covered by the first swarm was 150 m long × 10 m wide, and contained approximately 250,000–400,000 individuals. The second swarm contained several million *A. bifrons* and covered an area approximately 450 m long × 10 m wide. Adults, juveniles and pulli were abundant in both of these swarms. We observed aggregations that were cannibalistic on injured or dead *A. bifrons*. Within this swarm, one species of ants, *Iridomyrmex purpureus* (Smith), were observed actively preying on medium and small sized *A. bifrons*.

### 3.2. Laboratory plant damage experiment

Except in three cases, which had nine slaters each, ten individuals were collected from all containers (except the controls) at the conclusion of the plant damage study. This indicates that both *A. bifrons* and *P. scaber* were unlikely to be adversely affected by the experimental conditions. This is further supported by the fact the *A. bifrons* persisted and reproduced in other containers that were established prior to this study and contained only cotton wool, leaf litter and wheat seedlings (data not shown).

Throughout the experiment *A. bifrons* and *P. scaber* were observed occasionally feeding on wheat seedlings, although the majority of time was spent on or underneath the leaf litter. This supports farmers’ claims that slaters can cause feeding damage to emerging crop plants. The number of seedlings that were alive over the duration of the experiment was not significantly different between treatments (Fig. 3), except at week 5. At week 5 there were significantly more seedlings in the control compared to containers with *P. scaber* (regardless of litter type). Containers with *A. bifrons* and *P. scaber* did not differ significantly in the number of seedlings that were killed as a result of feeding at each sampling point. There was also no significant difference in litter treatments. The repeated

---

**Table 2 – Terrestrial isopods collected in the Moree district in 2006**

<table>
<thead>
<tr>
<th>Species</th>
<th>Origin/Locality</th>
<th>Location</th>
<th>Collection details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australiodillo bifrons</td>
<td>Australia, endemic</td>
<td>Glenco, Gundare &amp; Ponjola</td>
<td>In paddocks, shelterbelts and natural vegetation, abundant</td>
</tr>
<tr>
<td><em>Buddelundia</em> sp. (Armadillidae)</td>
<td>Australia, endemic</td>
<td>Glenco &amp; Gundare</td>
<td>Under dead logs, rare</td>
</tr>
<tr>
<td><em>Armadillidae gen. sp.</em></td>
<td>Australia, endemic</td>
<td>Mt. Kaputar NP</td>
<td>Under dead logs, rare</td>
</tr>
<tr>
<td><em>Schismadiella</em> sp. (Armadillidae)</td>
<td>Australia, endemic</td>
<td>Mt. Kaputar NP</td>
<td>Under dead logs, rare</td>
</tr>
<tr>
<td><em>Laevophiloscia</em> sp. (Philosciidae)</td>
<td>Australia, endemic</td>
<td>Mt. Kaputar NP</td>
<td>Forest litter collected by pitfall traps, rare</td>
</tr>
<tr>
<td>Porcellio laevis</td>
<td>Introduced</td>
<td>Moree</td>
<td>Town garden under mulch, abundant</td>
</tr>
<tr>
<td><em>Porcellionides pruinosus</em> (Porcellionidae)</td>
<td>Introduced</td>
<td>Glenco</td>
<td>In garden and under dead logs, rare</td>
</tr>
</tbody>
</table>

* Probable new ‘undescribed’ species.

---

![Fig. 2 – Photo showing typical swarming behaviour of Australiodillo bifrons moving across a Casuarina cristata shelterbelt at the Ponjola farm (Photo: A. Tsitsilas; 02 Nov 2006).](image-url)

---

Author’s personal copy
measure ANOVA showed no difference between the two litter types and the number of seedlings alive when averaged across weeks ($F = 0.984$, df = 1, $P = 0.350$). However, there was a significant difference between the number of seedlings alive and species when averaged across weeks ($F = 5.652$, df = 1, $P = 0.045$). This suggests that $P. \text{scaber}$ had greater impact on seedling survival than $A. \text{bifrons}$. There was no interaction evident among treatment and time in the repeated measures ANOVA for plant damage ($F = 1.823$, df = 4, $P = 0.149$).

Scoring seedling mortality could be seen as a rudimentary approach for assessing feeding damage. A more widely accepted method is to score damage as a percentage of plant injury. Fig. 4 shows the plant damage scores over the duration of the experiment. For treatments containing both $A. \text{bifrons}$ and $P. \text{scaber}$ there was an increase in plant damage over time. After 5 weeks there was significant damage to wheat seedlings caused by both species when presented with both litter types. After week 2, there were significant differences between the treatments and the control containers. This persisted for the remaining period of study. There were no differences in plant damage scores between litter types at any sampling point. There were also no differences between species at any sampling point, except at week 5. On average, $P. \text{scaber}$ (litter B) caused significantly more plant damage than $A. \text{bifrons}$ (litter A) at week 5. However, the results from the repeated measures ANOVA indicated no difference in plant damage and species when averaged across weeks ($F = 2.898$, df = 1, $P = 0.127$). This suggests that wheat seedlings did not suffer more damage from $P. \text{scaber}$ feeding compared with $A. \text{bifrons}$. There was also no difference between the two litter types and plant damage when averaged across weeks ($F = 0.002$, df = 1, $P = 0.966$), indicating feeding damage is no different when slaters are presented with either litter. There was no significant interaction among treatment and time in the repeated measures ANOVA for number of seedlings ($F = 0.604$, df = 4, $P = 0.663$).

Litter A was collected from a shelterbelt containing predominately $Eucalyptus \text{coolabah}$, at Gundare, which suffered significant feeding damage to emerging cereal plants. This could indicate $A. \text{bifrons}$ do not attack chick peas and may have a relatively narrow plant host range. However, the lack of damage to the chick peas may instead reflect the adequate nutritional requirements within the rich and well fragmented soil litter in the shelterbelt at the Ponjola farm. We found no difference between the damage caused to wheat seedlings by $A. \text{bifrons}$ when presented with either litter A or litter B. This suggests litter type is not the primary factor influencing slater attacks to crop seedlings. Chick peas may therefore not be a suitable host for $A. \text{bifrons}$, and could play a role in any cultural control strategies aimed at avoiding losses caused by this pest.

The plant damage experiment shows that $A. \text{bifrons}$ can cause significant feeding damage to wheat seedlings and supports the notion that this species is an important pest of cereals. It is hard to make direct comparisons to the impact of this damage in the field, however, given the very large densities we observed and those reported by farmers, it is not surprising yield losses were experienced in the Moree district in 2006. Interestingly, $P. \text{scaber}$, an introduced isopod that is a cosmopolitan garden species (Paoletti et al., 2007), also caused feeding damage in the plant damage experiment. $P. \text{scaber}$ is not known to be a pest of cultivated plants, but thought to feed primarily on decaying organic matter (Paoletti and Hassall, 1999). This raises several questions. Since $P. \text{scaber}$ is widely distributed in Australia, what is the reason/s this species is not a pest of cereals and other crops? Perhaps this reflects abiotic factors (e.g. humidity) that restrict this species surviving away from urbanized environments. Alternatively, juvenile $P. \text{scaber}$ may require a rich soil litter to survive. They may not be capable of penetrating the outer plant cuticle and/or obtaining sufficient nutrients from crop plants. Do other isopods besides $A. \text{bifrons}$ have the potential to become pests of broad-ace crops? We identified several species of isopods, including many native species, both in the farms at Moree and a nearby National Park. However, there is no evidence that any of these species are pests of broad-ace crops. The swarming behaviour and high densities of $A. \text{bifrons}$ are likely to be
important factors contributing to the pest status of this species. As far as we know, these characteristics do not occur in other isopod species within Australia.

3.3. Climatic data

The relatively recent emergence as *A. bifrons* as a pest of broad- acre crops could be explained by environmental changes influencing survival and population expansions. We compared numerous climatic variables from 1984 to 2005 at Moree using all data available. There were significant changes in several of these, indicating temperatures have become warmer and conditions less humid in the past 22 years. Mean daily maximum temperature has increased significantly since 1984 ($t = 13.314$, $P < 0.01$) (Fig. 5). Mean relative humidity at 9am ($R^2 = 0.287$, $t = 8.044$, $P < 0.05$), noon ($R^2 = 0.338$, $t = 9.506$, $P < 0.01$), 3pm ($R^2 = 0.268$, $t = 6.955$, $P < 0.05$), 6pm ($R^2 = 0.223$, $t = 5.448$, $P < 0.05$) and 9pm ($R^2 = 0.195$, $t = 4.606$, $P < 0.05$) have all decreased since 1984. All other variables tested (mean daily minimum temperature, total monthly rainfall and mean relative humidity at 6am) have not significantly changed in the past 22 years (data not shown).

A rise in temperature since 1984 at Moree could be partly responsible for an increase in the abundance of *A. bifrons* and relative importance as a pest species. *A. bifrons* is a low-land swampy soil species adapted to marshy environments. The swarming phenomenon is well described by the folk name given to this species (*flood bugs*). In Moree, *A. bifrons* appear constrained by a high moisture requirement and avoidance from inundation. The areas worse affected by *A. bifrons* in the past are generally prone to flooding. For example, in 1988 and 2000, many of the farmers interviewed could not enter their paddocks for weeks due to local inundations. Rising temperatures over the past 22 years coupled with the recent outbreak of *A. bifrons* could represent another example of an adaptive evolutionary response of a species to climate change, as has recently been found in other invertebrate species (Bradshaw and Holzapfel, 2001; Umina et al., 2005). Other factors that could explain the relatively recent emergence of this species as an important pest is alterations to farming practices and other landscape uses. Despite the benefits of minimal or no-tillage and stubble retention (e.g. weed control, moisture retention, maintaining soil structure), these changes over the last 10–20 years can have a number of drawbacks in regards to pest species, including isopods (see Paoletti, 1987; Stinner and House, 1990; Paoletti and Cantarino, 2001). For example, damage caused by slugs has become a more serious problem with the wider use of stubble retention and direct drilling in many parts of southern Australia (Norton, 1992; Barker, 2002; Nash et al., 2007). This is presumably due to a more favorable microhabitat being produced.

3.4. Conclusion

Clearly, there is much to learn about *A. bifrons* and its potential to become a widespread agricultural pest in Australia. Our results show this species can cause significant feeding damage to wheat seedlings and reaches very high densities in the field. We also report on the swarming of *A. bifrons*, a characteristic behaviour that may contribute to the pest status of this species. Further research of this “emerging pest” is required to prevent the reliance on a sole control-strategy based on pesticide use. Research should focus on better understanding the life-cycle, plant hosts, nesting behaviours and mapping the distribution of this species. Knowledge of the role aggregation pheromones have in the swarming behaviour of *A. bifrons* could also provide potential avenues for devising integrated control strategies (e.g. Takeda, 1984; Warburg, 1993). Finally, the deficiency of minerals like calcium or magnesium in the soil/litter could stimulate *A. bifrons* to seek food sources which contain these minerals. Understanding the importance of this could enable landscape management strategies to be devised for controlling this pest. Severe drought years can exacerbate the shift of behavior of our isopod and the climatic trend appear in this direction.

Acknowledgements

We thank all the farmers and agronomists who shared their observations and assisted in locating affected paddocks. Thanks to Gareth Holmes for assistance with plant identifications and Lisa Lobry de Bruyn and Chee Seng Chong for identifying ants. George Wilson is thanked for taxonomical insight into *A. bifrons*. Renzo Mazzaro has helped with Fig. 1. We also thank Ary Hoffmann for comments on this manuscript. Anonymous referee helped to improve our manuscript. This work was supported by the Grains Research and Development Corporation through the National Invertebrate Pest Initiative.

References


