Author: R. Thapa, D.R. Kemp and M.L. Mitchell

Title: Climatic conditions for seedling recruitment within perennial grass swards in south-eastern Australia

Journal Title: Crop and Pasture Science

ISSN: 1836-0947

Year: 2012

Volume: 63

Issue: 4

Pages: 389-398

URLs:http://researchoutput.csu.edu.au/R/-?func=dbin-jump-full&object_id=36806&local_base=GEN01-CSU01

http://dx.doi.org/10.1071/CP12162

Author Address: rthapa@csu.edu.au

Climatic conditions for seedling recruitment within perennial grass swards in south-eastern Australia

R. Thapa[A,C]*, D. R. Kemp*[A] *and M. L. Mitchell*[B]

[A]Charles Sturt University, E H Graham Centre for Agricultural Innovation, School of Agricultural and Wine Sciences, Leeds Parade, Orange NSW 2800, Australia

[B]Department of Primary Industries, Future Farming Systems Research Division, Chiltern Valley Road, Rutherglen VIC 3685, Australia

[C]Corresponding author. Email: rthapa@csu.edu.au

Short title: Climatic conditions for seedling recruitment

Abstract. Recruitment of new perennial grass plants within existing grassland ecosystems is determined by seed availability, suitable microsites, nutrients and climatic conditions, water and temperatures. This paper reports on the development of criteria to predict recruitment events using modelled soil moisture conditions associated with recruitment of certain species in five field experiments at Orange (*Phalaris aquatica*), Trunkey Creek (*Austrodanthonia*) and Wellington (*Bothriochloa macra*) in Central New South Wales, Australia, and the frequency of those conditions during the past 30 years. Recruitment events were recorded when a rainfall event (median 68 mm across the three sites) kept the surface volumetric soil moisture (0-50 mm) above the permanent wilting point for at least 15 continuous days, allowing for at most two 'dry days' in between. A key finding from our study is that rainfall events creating favourable soil moisture conditions for seedling emergence typically occurred in the second half of February, sometimes extending to early March. Previously it had been thought that recruitment would more likely occur through autumn, winter and spring when rainfall in southern Australia is more reliable. The 30 years data from 1975-2004 showed the *P. aquatica* site had a median of 20 continuous moist days each year in February-March period, whereas, there were 16 and 10 days for the *Austrodanthonia* and *B. macra* sites, respectively. The probabilities of exceeding 7 or 15 continuous days of moist surface soil were 98% and 78% at the *P. aquatica* site, 91% and 49% at the *Austrodanthonia* site, and 73% and 30% at the *B. macra* site, and indicated some recruitment is possible in most years. These analyses were extended to a number of sites across NSW, Victoria and Tasmania to estimate the frequency that recruitment could occur within natural swards. Across these sites, the probabilities of exceeding 7 continuous days of soil moisture were >55% and of exceeding 15 continuous days were lower, which showed suitable climatic conditions exist during late summer, early autumn across south-eastern Australia for a recruitment event to occur. Future research may show that the criteria developed in this paper could have wider regional application.

Additional keywords: perennial grasses, soil moisture modelling, recruitment, rainfall, irrigation

Introduction

The loss of perennial grasses from the grasslands of southern Australia and replacement by annual species (Kemp and Dowling 1991) has had severe implications for the productivity of livestock enterprises through weed invasion, the increasing incidence of erosion, salinity, acidity and the loss of biodiversity (Kemp *et al.* 2000; Michalk *et al.* 2003). Sustainability of these grasslands is of major concern to landholders, researchers and the community at large. Previous research has demonstrated that pastures based on perennial grasses are more environmentally sustainable (Kemp and Dowling 2000; Mason and Kay 2000). However, the current content of perennial grasses in many pasture systems is low, often accounting for ≤20% of pasture composition (Kemp and Dowling 1991; Schroder *et al.* 1992), well below the level (≥60%) that is desirable for sustainability (Kemp and Dowling 2000).

Seedling recruitment of perennial grasses is needed to maintain grassland productivity. The limited research to date has shown that there is often low or nil survival of desirable grass seedlings in existing pasture swards (Lodge 2004) which may be largely due to the fact that perennial grasses place less reliance on seed as the mechanism for survival but aim to survive as existing plants and put less effort into seed production. Recruitment from seed, a natural event that occurs within ecosystems, is determined by the availability of seed, suitable microsites, nutrients and climatic conditions. By definition, all mature seeds are capable of germinating when water, light and temperature conditions are sufficiently favourable (Moore *et al.* 1997). Seed availability and soil disturbance, either occurring naturally by self-mulching processes in soil or through management interventions such as soil scarifying or grazing to create suitable microsites are important to maximise recruitment (Thapa *et al.* 2011*a*; 2011*b*). The key climatic conditions required include suitable temperature and adequate soil moisture. Soil moisture available to the seed is one of the main factors that enables germination and establishment of perennial grass seedlings (Dowling *et al.* 1971; Fowler 1986; Maze *et al.* 1993; Lauenroth *et al.* 1994; O’Connor 1996; Zimmermann *et al.* 2008).

In south-eastern Australia, the Central Tablelands and nearby slopes of New South Wales (NSW) have a relatively uniform seasonal rainfall pattern. The average monthly rainfall does not change much throughout the year except that the rainfall events are large and spaced further apart in summer and there are often only 2 or so events each year. The start of more frequent rainfall periods is often not until late May. Further south less frequent summer rain is the norm, but the start of more regular rainfall occurs progressively earlier, *e.g.* early March in some districts. However, it is unknown whether these earlier rainfall patterns in late summer experienced in the higher rainfall zones across south-eastern Australia are suitable to support perennial grass recruitment. The key climatic requirement for perennial grasses recruitment would be that rain falls when soil temperatures are ~20°C, which results in faster seedling growth and less recruitment of weeds such as annual grasses.

Using data on recruitment obtained from three field sites, combined with a small plot study using irrigation and seed addition through the year, this paper aims to first identify the soil moisture conditions associated with initial recruitment events during February- March period and then to predict the frequency that those conditions occurring for the 30 years from 1975-2004. Historical climate data from a number of sites across NSW, Victoria and Tasmania were then analysed to determine the probability of obtaining suitable soil moisture conditions (as determined from the field sites) for a recruitment event to occur. Emphasis in this paper is placed on the soil moisture conditions needed to achieve initial seedling recruitment. The prevalent competition between adult plants and seedlings, and the subsequent drought years resulted in a low frequency of survival of young plants (Thapa *et al.* 2011*a*; 2011*b*), which was insufficient to extend the climatic analysis to identify the soil moisture conditions required to support plant survival through the subsequent summer.

Methods

Field experiments

Five field experiments, two each on *Phalaris aquatica* L. (C_3) and *Austrodanthonia* spp. (C_3), and one on *Bothriochloa macra* (Steud.) S.T. Blake (C_4), were undertaken through a sequence of drier years 2005-08. The *P. aquatica* experiments were located at Orange on the Central Tablelands of NSW (149°07' E, 33°14' S) within the Orange campus of Charles Sturt University. The site had an elevation of 826 m (a.s.l.) and an average annual rainfall of 890 mm. There was a slight easterly slope on the site and the soil type was a Vertosol

(Isbell 1996) with a light clay surface texture. The experiment was established in October 2005 within an existing *P. aquatica* dominant pasture (40 plants/m^2). The *Austrodanthonia* experiments were at Trunkey Creek on the Central Tablelands of NSW (149°19' E, 33°49' S). The site had a mean elevation of 840 m (a.s.l.), an average annual rainfall of 800 mm, and the soil was a sandy clay loam surface texture identified as a Chromosol (Isbell 1996). The experiments were established in August 2006 within an existing *Austrodanthonia* pasture (39 plants/m^2). The *B. macra* site was at the Wellington Research Services Centre on the Central Slopes of NSW (148°58' E, 32°30' S). The site had an elevation of 300 m (a.s.l.), an average annual rainfall of 618 mm and a red soil with loam texture classified as a Dermosol (Isbell 1996). The experiment was established in August 2006 within an existing *B. macra* dominant pasture (33 plants/m^2). The *P. aquatica* and *Austrodanthonia* experiments were repeated over two years, whereas only one year was possible at the *B. macra* site.

The experimental design at the *P. aquatica* and *Austrodanthonia* sites were based on a factorial combination of seed delivery mechanism and biomass manipulation × viable seed level × site preparation treatments. The *B. macra* experiment was a split-plot design of ungrazed, grazed and pasture cropping treatments combined factorially with seed and herbicide treatments. All experiments were laid out in a randomised block design with 4 replicates. Details on treatments have been provided earlier in Thapa *et al.* (2011*a*; 2011*b*).

Sampling frequency for seedling monitoring varied with time from germination events. Emergence immediately following treatment application and a subsequent substantial rainfall event was the major event to be monitored throughout the year. Initial counts were taken within 2-3 weeks of seedling emergence after treatment application and then after ~6, 24 and 52 weeks. Based on these criteria, seedling counts were done in March, April, August and March (next year) in each experiment.

The treatment application occurred mostly in the month of January and the next rainfall event was not until late February or early March. Seedlings observed in March resulted from February rainfall events. Since perennial grass recruitment occurred in early March and no recruitment was recorded at other times of the year across all sites, emphasis was put on identifying the soil moisture conditions needed to achieve a recruitment event from rainfall events in February and March. The recruitment data and the associated rainfall events in the February-March period therefore formed the dataset for analysis in this paper. The rainfall events in January and earlier months were not considered as they occurred before seed maturation and seed fall in most instances, and no recruitment was observed at this time.

Irrigation experiment

An experiment using irrigation and perennial grass seed addition was done at the field sites in Orange, Trunkey Creek and Wellington. The experiment started in January 2007 and continued until February 2008, except at the *B. macra* site where the experiment was terminated in October 2007. Water was applied at approximately 6 weekly intervals at a rate equivalent to 50 mm rainfall (50 L/m^2) over 2 days at 25 mm/day. Plots were 1 x 1 m with a 1 m buffer and were replicated 3 times. The centre 0.9 x 0.9 m of each plot was divided into 3 × 3 quadrats of 0.3 × 0.3 m for biomass measurements, and each quadrat was further divided into 3 × 3 sub-quadrats of 0.05 × 0.05 m for seedling counts. Seedlings were recorded approximately 2 weeks after each watering. A 1 x 1 m galvanised metal plate (0.15 m high) was used to retain water. Plots were covered with shade cloth for 2-3 days following irrigation to reduce evaporation. Irrigation treatment at each time was applied on different plots. Initially no perennial grass seed was added to test recruitment from soil seed bank. To overcome constrains of poor soil seed bank, 50 kg of seed/ha of *P. aquatica* and *Austrodanthonia* was added to the watered plots at the *P. aquatica* and

Austrodanthonia sites, respectively, from November 2007 to February 2008. Of the total 21 watering events across the three field sites, 8 coincided with rainfall events and a further 6 had seed addition and rainfall occurrence. Occurrence of rainfall at irrigation increased the number of days of moist soil.

Climate analysis of experiments

Climate data including relative humidity, air and soil temperatures, solar radiation, wind speed, and rainfall were recorded using data loggers (Tain Electronics, Box Hill North, Vic., Australia). Soil moisture was measured in the soil surface layer using gypsum blocks located at 50 mm depth. At Wellington, the site for the *B. macra* experiment, rainfall data were obtained from the weather station located <0.5 km from the experimental site. Long-term climate data were obtained from the National Climate Centre of the Australian Government Bureau of Meteorology (NCC 2009).

Volumetric soil moisture was modelled using the Sustainable Grazing Systems (SGS) pasture model (Johnson *et al.* 2003) using Version 4.5.4 (Johnson 2008), which has been used for several national research programs. The SGS model uses daily climate data (rainfall, temperature, relative humidity, wind speed, vapour pressure, evaporation, solar radiation), soil physical properties based on the generic soil type, soil nutrient status based on initial inorganic values for NO_3 and NH_4, pasture species and latitude to predict volumetric soil moisture values. Pasture type used in the analyses were *Phalaris*, C_3 perennial native and C_4 perennial native for *P. aquatica*, *Austrodanthonia*, and *B. macra* experimental sites, respectively. When data was not available for a particular climate parameter (e.g. vapour pressure, evaporation), the model used the generic patterns based on the latitude, longitude and other relevant factors. The soil physical properties were used for the generic soil types present at the respective sites. Analyses focused on moisture conditions in the top 0-50 mm of the soil profile resulting from rainfall events that started immediately before the time of seedling recruitment events. Soil moisture potential at each site was measured using gypsum blocks, but data obtained did not cover all germination events as values were missing or faulty numbers were recorded. The volumetric soil moisture values from the SGS model were then used in the analysis as the gypsum block data was considered insufficient to characterise soil moisture trends. The model showed patterns in soil moisture that, in general, agreed with the gypsum block data when the gypsum block functioned properly (Fig. 1). General linear regression analysis showed positive relationship ($P<0.001$; adj. $R^2 = 0.6$ at *P. aquatica* site; adj. $R^2 = 0.4$ at *Austrodanthonia* site; adj. $R^2 = 0.8$ at *B. macra* site) between soil moisture conditions determined by gypsum block data and predicted by SGS pasture model (Fig. 1), which provided greater confidence in using the modelled data. However, there was a poor correlation between soil tension and simulated volumetric soil water content especially at Orange (Fig. 1). This is due to the fact that there are very few points to validate the permanent wilting point (PWP) but this is a common problem with using gypsum blocks. One shortcoming of the measurements was that calibration between soil tension and measured volumetric soil water content was not done, which might have helped plot the simulated against the measured soil water content.

[Fig. 1]

After initial modelling of the volumetric soil moisture status and a review of the associated seedling recruitment events, the periods when the volumetric soil moisture content was between ~40% (i.e. close to field capacity in these soils and where free water was available for a seedling to emerge) and ~20% (i.e. close to PWP where there would be little available moisture for a seedling) were identified, as these best coincided with the periods when successful recruitment occurred. While actual values for field capacity and PWPs may not have been exactly at 40 and 20% respectively, across the sites, they were considered close to actual values for the three sites and enabled consistent estimates of how long the surface soil would have some moisture available for seedling growth. If the estimated volumetric soil moisture was below or near 20% and stable, this suggested proximity to PWP and plants had little capacity to extract any water. In these cases the surface soil was then considered to be effectively too dry for seedling growth.

During the February-March period when recruitment occurred, there was the occasional day when the soil water content was estimated at 20% or less, but soon after, some rain fell and soil moisture content returned to within the range where water would be available. As these ‘dry’ events occurred after several ‘wet’ days that initiated the recruitment event, it was considered that the radicles of seedlings had probably extended below 50 mm depth and were still able to access water. A close examination of the modelled estimates associated with each recruitment event suggested that up to 2 ‘dry’ days could be allowed in estimating the total length of the period when soil moisture conditions suitable for establishment applied. For analytical purposes, the sum of these 2 rainfall events was considered to constitute the single significant rainfall event that resulted in seedling emergence.

Historical climate data recorded close to each of the field sites were analysed to determine the duration of a rainfall event that kept the soil in the top 0-50 mm moist (~40-20%; from SGS model) in the months of February and March over 30 years (1975-2004). The rainfall event was identified based on the experiment results and where applicable included a maximum of 2 dry days. This information was then used to estimate the probability of achieving soil moisture conditions in any given year for a recruitment event to occur.

The soil moisture level immediately before the recruitment events in the field and irrigation experiments were used to determine the minimum and ideal conditions required to encourage recruitment. Recruitment in irrigation experiments was minimal and hence the results were used to set minimum soil moisture conditions needed for a recruitment event to occur. In few instances when recruitment events occurred, extra seeds were added and the irrigation mostly overlapped rainfall extending the number of continuous moist days in soil surface layer (0-50 mm). Across the sites, there were 6 irrigation events that did not coincide with rainfall, had no seed added, and did not result in recruitment. The resulting surface soil moisture conditions in these 6 irrigation events were considered inadequate for recruitment. On average, the model estimated that soil in the top 0-50 mm was moist for an average of 7 continuous days in these 6 irrigation events. Therefore, this estimated period of moist surface soils (i.e. 7 continuous days) constituted the minimum level below which recruitment was highly unlikely.

Often there were 2 sequential rainfall events separated by no more than 2 dry days in February and early March associated with successful recruitment events in field experiments. On average, the rainfall events leading to recruitment kept the surface soil moist for at least 14 continuous days. This provided the criteria for ideal number of days that the soil needed to be moist. Therefore, the safe criterion that should result in a high possibility of recruitment occurring was set at 15 continuous days with wet surface soil.

Extrapolation of climate analysis

To determine if the criteria developed in central NSW would apply elsewhere, several sites in a north-south transect through south-eastern Australia were investigated. The sites chosen were Armidale, Tamworth, Mudgee, Bathurst, Goulbourn, Canberra, Cooma, and Bombala in NSW; Tallangatta, Beechworth, Warrenbayne, Creighton’s Creek, Mansfield, Highlands, and Tambo Crossing in Victoria; and Launceston, Cressy, Avoca, Swansea, Hobart and Dunalley in Tasmania (Table 1). Each of these sites has natural perennial pastures, which indicates that recruitment does occur there at times. These sites receive broadly similar amounts of annual rainfall (~600-800 mm) to our experimental sites in central NSW that are typical of where natural perennial grasslands occur in south-eastern Australia, although the distribution of rainfall over the year differs. Rainfall events from late summer, through autumn occur in many of these sites, but it was not clear whether the probability of sufficient rainfall was high enough to encourage recruitment. The assumption in this work was that the events and timing that resulted in recruitment of seedlings at the experimental sites would apply across the region.

Similar to the experimental sites, daily rainfall data (NCC 2009) were used to estimate soil moisture profiles in the top 50 mm using the SGS pasture model. The climate analyses then predicted the frequency of attaining the required soil moisture conditions using climatic data for the 30 years from 1975-2004. The analyses were confined to the February-March period.

Results

Recruitment and rainfall events in the field experiments

The emergence of *P. aquatica* seedlings at Orange was first observed on 7 March 2006 after two sequential rainfall events in year 1. The rainfall event preceding recruitment was from 15-18 February with a total of 33 mm over 3 rain days (Fig. 2*a*). The surface soil was moist for around 9 days from 15 February to 23 February, which was followed by 2 days of dry soil before a second rainfall event on 26 February (24 mm over 2 days) rewet the soil surface for another 9 days until 6 March (Fig. 2*a*). Collectively the rainfall between 15 and 27 February (57 mm over 5 rain days) resulted in moist soil surface conditions for a total of 18 days over the whole 20 day period (15 February to 6 March) giving rise to the seedlings recorded on 7 March (Fig. 2*a*).

In year 2 at Orange, *P. aquatica* seedlings were observed on 21 March 2007 after two rainfall events. The first occurred from 23 February to 1 March (54 mm over 6 rain days), the effect of which lasted for 8 days (23 February to 3 March); this was then followed by further rainfall starting on 5 March (Fig. 2*b*). There were 5 continuous rain days (45 mm) with kept the surface soil moist for 8 days until 12 March (Fig. 2*b*). In total, 99 mm of rain fell over 11 days keeping the soil moist for 16 out of a total of 18 days (Fig. 2*b*). This resulted in the recruitment observed in the third week of March. Again there were 2 ‘dry’ days observed between these rainfall events.

At Trunkey Creek, initial recruitment of *Austrodanthonia* seedlings in year 1 was observed on 13 March 2007. The surface soil became moist on 18 February and the moisture remained for the next 6 days from 35 mm rain falling over 4 continuous rain days (Fig. 2*d*). The next rainfall event occurred 2 days later, between 26 to 28 February (33 mm over 3 rain days) resulting in moist soil conditions until 2 March (Fig. 2*d*). Consequently, between 18 February and 2 March, 68 mm of rain fell over 7 days providing soil moisture for 11 out of a total of 13 days (Fig. 2*d*) sufficient for recruitment. Note that the 2 dry days in the middle of this rainfall sequence did not seem to have thwarted recruitment.

In year 2 at Trunkey Creek, *Austrodanthonia* seedlings were first recorded on 10 March 2008 though this was one of the less successful recruitment events recorded (the highest yield was 53 seedlings/m^2). Low seedling numbers in this case were in part attributed to the previous dry summer and limited seed set (Thapa *et al*. 2011*b*). There were 2 rainfall events in February that would have enabled the emergence of seedlings (Fig. 2*e*). The first occurred between 1 and 8 February (59 mm over 3 days) making surface soil moist for 9 days (Fig. 2*e*). The second event occurred on 12 February which kept the soil moist for 4 days from 18 mm rainfall received over 2 days (Fig. 2*e*). The combination of these two events (77 mm rainfall over 5 days keeping the soil moist for 13 days; Fig. 2*e*) created suitable moisture conditions for the recruitment recorded in the second week of March. The estimated 2 dry days between the events again did not seem to reduce seedling numbers. There was a third rainfall event on 28 February (17 mm over 2 days; Fig. 2*e*) before the sampling for the recruitment was made but this event was considered less important in the analysis as the earlier events essentially created the appropriate soil moisture conditions for seedling emergence. This third rainfall event had limited effect on volumetric soil moisture, though it would have aided seedling growth.

At Wellington, recruitment observation in the *B. macra* experiment occurred on 14 March 2007. Rainfall had started on 26 February and ended on 1 March with 32 mm over 4 rain days (Fig. 2*f*). As a result, the soil surface remained moist for 6 days until 4 March (Fig. 2*f*) possibly initiating the first instances of seedling emergence. The next rain event from 5 to 8 March (33 mm over 3 days; Fig. 2*f*) kept the soil surface moist for a further 8 days (Fig. 2*f*). This combined rainfall from 26 February to 8 March (65 mm over 7 rain days; Fig. 2*f*)) maintained adequate volumetric soil moisture for 14 continuous days and enabled seedling recruitment.

[Fig. 2]

Recruitment events in the irrigation experiments

Across all sites, there was no recruitment where the soil surface was moist for an average of 6 continuous days from irrigation and did not coincide with rainfall. Where some recruitment occurred due to either irrigation, seed addition or rainfall, there was at least 10 continuous days of moist soil. Recruitment was observed in 8 irrigation events, 3 at the *P. aquatica* site and 5 at the *Austrodanthonia* site. All instances with irrigation and seed addition coincided with rainfall events.

At Orange, all 3 recruitment events had seed added and coincided with rainfall where volumetric soil water was above PWP (Fig. 2*c*). More *P. aquatica* seedlings (11/m^2)

were observed in early March 2008 from the irrigation treatment applied in late February. At Trunkey Creek, 13 *Austrodanthonia* seedlings/m^2 were recorded in mid January 2007 when water was added without seed addition. This event coincided with a rainfall event that extended the period of moist soil to 10 days (Fig. 2*d*). In mid September 2007, 2 *Austrodanthonia* seedlings/m^2 was recorded after water application in the preceding month but did not coincide with rainfall. Limited recruitment (9 seedlings/m^2) in a seed addition treatment occurred in early March 2008 from a watering event in late February followed by rainfall shortly afterwards.

The irrigation treatments provided soil moisture conditions that did not often result in recruitment. While irrigation may have resulted in the priming of seeds, the lack of follow-up rainfall meant that recruitment did not eventuate. Estimates of surface soil moisture conditions in the irrigation treatments (50 mm over 2 days) showed in most instances that when watering did not coincide with any rainfall, the soil (0-50 mm) was moist for only about 7 days. When the watering did coincide with a rainfall event, the soil remained moist for an average of 24 days across the sites and resulted in some recruitment within the irrigation experiments.

Frequency of recruitment events

Analyses for the 30 year period (1975-2004) showed that Orange, the *P. aquatica* site, had an average of 20 moist days each year following a rainfall event in the February-March period, whereas in the native perennial grasses experiments, this period was only 16 days at Trunkey Creek and 10 at Wellington (Table 1). The shortest moist period in February-March was 2 days at both Trunkey Creek and Wellington, and 9 days at Orange, while the longest was 31 days at Orange, and 24 days at both Trunkey Creek and Wellington (data not presented).

The probability of exceeding 7 continuous days of moist soil at the *P. aquatica* site was 98% and in 78% of years soils remained moist for more than 15 continuous days (Table 1). The *Austrodanthonia* site would achieve the minimum moisture conditions of 7 continuous days in 91% of years, while there was a high chance of recruitment (> 15 continuous days of moist surface soil) in 49% of years (Table 1). The driest was the *B. macra* site where minimum moisture conditions of 7 continuous days would be achieved in 73% of years, while there was a high chance of recruitment in only 30% of years (Table 1).

In most instances for the perennial grasses sites across NSW, Victoria and Tasmania and the 30 years modelled, there was a single rainfall event during the February-March period that kept the surface soil sufficiently moist between 7-15 continuous days. The probability of exceeding 7 continuous days of moist surface soil was >55% across all sites, i.e. at least one year in two; the range being from 92% at Armidale to 56% at Creighton's Creek and Avoca (Table 1). The probability of obtaining 15 continuous days of moist surface soil was lower. The highest was at Armidale (39%; Table 1). Two sites, Creighton's Creek and Highlands had 0% probability of exceeding 15 continuous days of moist soil (Table 1). The other sites had some chance (3-35%) of obtaining 15 continuous days of moist soil (Table 1).

[Table 1]

Discussion

Earlier research on sown temperate perennial grasses in Australia (Lodge 1979; Dowling *et al.* 1996; Waller *et al.* 1999; Virgona and Bowcher 2000; Lodge 2002, 2004) has suggested that recruitment within existing swards is infrequent as often few new plants were found to have established over time. The research reported here shows that this is not necessarily the case, though the factors that enable perennial grass seedlings to survive through the entire first year do need to be resolved. The five recruitment events recorded across the five experiments occurred at a similar time of the year, soon after seed set and were associated with significant periods of moist soil. Differences between species, *B. macra* is a C_4 whereas *P. aquatica* and *Austrodanthonia* are C_3, were neither apparent in the timing of the recruitment events, nor in the general climatic conditions under which they occurred. The three field sites used are affected by similar weather systems but differ in the amount of rain that falls, due primarily to differences in altitude and distance from the western edge of the Great Dividing Range. Over the five field experiments there were three different sequences of weather systems that resulted in successful recruitment.

A key finding in our study is that the critical rainfall events are at the end of summer, soon after seeds have set and matured. Previously it had been thought that recruitment would more likely occur through autumn, winter and spring when rainfall in southern Australia is more reliable. However at those times more intense competition from annual species would be expected (Bowcher 2002) causing most recruitment of perennial grass seedlings to fail as in general they are not very competitive (Groves *et al.* 2003). For most annual grasses due to their Mediterranean origins, the peak period of germination is later in autumn under mild temperature conditions. Our field experiments did not detect many perennial grass seedlings establishing through autumn, winter or spring (Thapa *et al.* 2011*a*, 2011*b*). This shows that there is only a narrow window between seed maturation of perennial grasses and the occurrence of a suitable rainfall event in late summer wherein significant levels of recruitment can occur each year, before subsequent rainfall events and the onset of milder temperatures create opportunities for annual grasses to readily germinate and offer substantial competition to establishing perennial grasses.

Late summer recruitment depends upon adequate and current seed set over summer, and there seems to be little perennial grass seed in the soil seed bank to germinate and establish at other times. The soil cores taken through the year and tested for readily germinable seed found few perennial grass seedlings emerged (Thapa *et al*. 2011*a*, 2011*b*). Other studies (King *et al.* 2006) found almost no perennial grass seedlings emerging from cores kept in a glasshouse for a year. Previous research (Virgona and Bowcher 2000; Lodge 2001, 2004) has shown that soil seed banks of perennial grasses are usually at low levels. These collective results explain why natural recruitment rates are low outside the 'window of opportunity' found around February and March soon after seed is produced. Ecologically, recruitment in late summer is preferable as competition from annual grass seedlings is low which allows perennial grass seedlings to grow and be more competitive when annual plant species germinate.

An important finding from our analyses is the frequent occurrence of significant rainfall events at the end of summer. Rarely did no rain fall at this time at any sites. Traditionally in these regions there has been a focus on the 'autumn break' as the important rainfall event for regeneration of pastures, preparing of land for crops and signalling the start of the winter growing season. The analyses done here did not indicate that rainfall events through March and April into May were as frequent as these late summer events though the frequency of rainfall through autumn did increase at more southerly sites. Late summer events are often dismissed as being too early and likely to result in the death of pasture plant seedlings. Therefore, managing recruitment of perennial grasses should be possible in south-eastern regions of Australia that are characterised by occasional but significant rainfall events in late summer. Often after the event that initiates the first stages of seedling recruitment, there was little rain for the subsequent 2-3 months, yet a reasonable number of seedlings survived (Thapa *et al*. 2011*a*, 2011*b*), indicating that continuing rainfall through autumn is not essential. If high numbers of seedlings are initially established, then with appropriate management enough will survive through to spring to achieve the goal of increased perennial grass densities as long as rainfall is about or above average (not drought as occurred in our study). However there are many other unknowns. Without an understanding of the mechanism driving competition in the first year after emergence within existing swards, which is presumed to be moisture, then it is not possible to determine what is causing mortality. When the canopy closes with annuals in winter, competition for light could also be an issue. Nevertheless, research from the pasture establishment of sown species suggests that the competition beyond the seedling stage towards the establishment of mature plants through the first major stress season is likely to be most influenced by competition for soil moisture and/or nutrients as well as, at times, competition for light (Cook 1980; Cook and Ratcliff 1985; Scott 1997).

In our study, total rainfall amount was not the best indicator of the likely success of recruitment, but the rainfall events that kept the surface soil moist for 7-15 continuous days were important. Late summer rain also coincides with the time when soil temperatures are near optimal for seed germination, ensuring faster recruitment (Baskin and Baskin 1998). Modelling in our study focused on moisture levels in the top 0-50 mm of soil. That was done to best approximate the conditions for seed germination and early seedling growth. Finer scale work on layers down the soil profile would refine the broad analysis provided here and would assist particularly in explaining the frequency of successful rainfall events in drier environments. The sites analysed in this study all had mean annual rainfalls > 600 mm.

In an earlier study examining soil moisture model and risk analysis to predict the optimum time for the aerial sowing of pastures on the Northern Tablelands of NSW, Dowling and Smith (1976) found good establishment of perennial species was associated with high levels of soil moisture after sowing. Recruitment in our study was observed when soil moisture was predicted to reach close to field capacity and lasted for more than 7 days. Dowling and Smith (1976) also found lesser amounts of rainfall in the cooler months were required to maintain a similar quantity of available soil moisture as greater amounts of rainfall during spring and summer suggesting total rainfall is not necessarily the best indicator as was shown from the results in this paper. In field experiments, recruitment was observed 2-3 weeks after a significant rainfall event that increased the soil moisture content. This is in agreement with Dowling and Smith (1976) which determined the mean soil moisture in the six weeks following sowing as the best indicator of establishment.

Seedlings emerge throughout the year (Lodge 1981) depending on whether the species is warm season or cool season, although some months of the year may be more favourable than others (Lodge and Whalley 1981). The period from mid-summer to early autumn was found to be the more favourable period for warm season grasses to establish and mid-autumn to late winter was most favourable for cool season grasses (Lodge 1981). Nevertheless, the findings showed poor recruitment over the 2 year period. In south-eastern Australia the survival of seedlings after successful emergence depends on whether they can endure the first summer. These summer months (December to February) are very demanding on seedlings because of the low moisture and high temperature conditions. Lodge (1981) concluded that the probability of successful seedling recruitment depended on favourable seasonal conditions especially over the first summer after emergence and thereby resulted in episodic recruitment events. Previous studies (Harradine and Whalley 1980; Lodge 1981; Lenz and Facelli 2005) indicate seedling establishment in native pastures is controlled primarily by moisture availability. In addition, perennial species that germinate in the open spaces between the bases of perennial tussocks can have higher emergence and survival rates (Lodge 1981) which supports the view that a less dense sward comprising open spaces would improve the chances of seedling establishment. Lodge (1981) identified intraspecific competition from neighbouring mature plants of the same species as the factor responsible for high mortality of native perennial grass seedlings.

Further research is needed to clarify where the results presented in this paper would apply. Nevertheless, the methods presented on climate analysis can be used to identify the regions where there is a reasonable chance of actively managing for perennial grass recruitment. The species studied in this paper naturally occur in southern regions which suggest that the rainfall patterns experienced in the higher rainfall zones across south-eastern Australia are suitable to support perennial grass recruitment, even though other locations further south have less frequent rainfall events during late summer early autumn but more later in the year. The results reinforce the view that suitable climatic conditions exist during late summer, early autumn across south-eastern Australia for a recruitment event to occur and therefore the principles developed in this paper would in general have wider regional application.

Pasture management is now more focused on working with ‘what you have got’ as simply replacing pastures is considered too expensive (Kemp and Dowling 2000). These factors mean that more consideration needs to be given to how best to use these late summer rainfall events, not only for the regeneration of perennial grass swards, but also to optimise pasture growth for subsequent seasons. Within that context further work is needed to identify those practices that maximise the survival of perennial grass seedlings through the first year so that plant densities can be increased and the sustainability of these systems improved. Perennial species plant survival over the first summer is of more practical importance than per cent establishment (Dowling and Smith 1976). The goal will be to achieve ≥60% perennial grass at significantly lower-cost, at which improved production and environmental outcomes can be achieved.

Acknowledgements

R Thapa was funded by Meat and Livestock Australia (MLA) for this research, and the work was an extension to the PhD project supported by MLA and Charles Sturt University. This work was part of the ‘Evergraze’ program funded by MLA and other Agencies. We thank Geoff Millar, Industry and Investment NSW, Orange for modelling advice.

References

Baskin, CC, Baskin, JM (1998) Ecology of seed dormancy and germination in grasses. In 'Population biology of grasses.' (Ed. GP Cheplick.) pp. 30-83. (Cambridge University Press: Cambridge)

Bowcher, AJ (2002) Competition between temperate perennial pasture species and annual weeds: the effect of pasture management on population dynamics and resource use. PhD thesis, Charles Sturt University.

Cook, SJ (1980) Establishing pasture species in existing swards: a review. *Tropical Grasslands* **14**, 181-187.

Cook, SJ, Ratcliff, D (1985) Effect of fertiliser, root and shoot competition on the growth of Sitaro (*Macroptilium atropurpureum*) and green panic (*Panicum maximum* var. *trichloglume*) seedlings in a native speargrass (*Heteropogon contortus*) sward. *Australian Journal of Agricultural Research* **36**, 233-245.

Dowling, P, Smith, R (1976) Use of a soil moisture model and risk analysis to predict the optimum time for the aerial sowing of pastures on the Northern Tablelands of New South Wales. *Australian Journal of Experimental Agriculture* **16**, 871-874.

Dowling, PM, Clements, RJ, McWilliam, JR (1971) Establishment and survival of pasture species from seeds sown on the soil surface. *Australian Journal of Agricultural Research* **22**, 61-74.

Dowling, PM, Kemp, DR, Michalk, DL, Klein, TA, Millar, GD (1996) Perennial grass response to seasonal rests in naturalised pastures of central New South Wales. *The Rangeland Journal* **18**, 309-326.

Fowler, NL (1986) Microsite requirements for germination and establishment of three grass species. *American Midland Naturalist* **115**, 131-145.

Groves, RH, Austin, MP, Kaye, PE (2003) Competition between Australian native and introduced grasses along a nutrient gradient. *Austral Ecology* **28**, 491-498.

Harradine, AR, Whalley, RDB (1980) Reproductive development and seedlings establishment of *Aristida ramosa* R. Br. in northern New South Wales. *Australian Rangeland Journal* **2**, 124-135.

Isbell, RF (1996) 'The Australian Soil Classification.' (CSIRO publishing: Collingwood)

Johnson, IR (2008) 'SGS Pasture Model.' (IMJ Consultants Pty Ltd: Armidale)

Johnson, IR, Lodge, GM, White, RE (2003) The Sustainable Grazing Systems Pasture Model: description, philosophy and application to the SGS National Experiment. *Australian Journal of Experimental Agriculture* **43**, 711-728.

Kemp, DR, Dowling, PM (1991) Species distribution within improved pastures over central NSW in relation to rainfall and altitude. *Australian Journal of Agricultural Research* **42**, 647-659.

Kemp, DR, Dowling, PM (2000) Towards sustainable temperate perennial pastures. *Australian Journal of Experimental Agriculture* **40**, 125-132.

Kemp, DR, Michalk, DL, Virgona, JM (2000) Towards more sustainable pastures: lessons learnt. *Australian Journal of Experimental Agriculture* **40**, 343-356.

King, WM, Dowling, PM, Michalk, DL, Kemp, DR, Millar, GD, Packer, IJ, Priest, SM, Tarleton, JA (2006) Sustainable grazing systems for the Central Tablelands of New South Wales. 1. Agronomic implications of vegetation-environment associations within a naturalised temperate perennial grassland. *Australian Journal of Experimental Agriculture* **46**, 439-456.

Lauenroth, WK, Sala, OE, Coffin, DP, Kirchner, TB (1994) The importance of soil-water in the recruitment of *Bouteloua gracilis* in the shortgrass steppe. *Ecological Applications* **4**, 741-749.

Lenz, TI, Facelli, JM (2005) The role of seed limitation and resource availability in the recruitment of native perennial grasses and exotics in a South Australian grassland. *Austral Ecology* **30**, 684-694.

Lodge, GM (1979) Effect of fertility level on the yield of some native perennial grasses on the North-West Slopes, New South Wales. *Australian Rangeland Journal* **1**, 327-333.

Lodge, GM (1981) Establishment of warm- and cool-season native perennial grasses on the north-west slopes of New South Wales. II. Establishment and seedling survival in the field. *Australian Journal of Botany* **29**, 121-133.

Lodge, GM (2001) Studies of soil seedbanks in native and sown pastures in northern New South Wales. *The Rangeland Journal* **23**, 204-223.

Lodge, GM (2002) Effects of continuous grazing and seasonal closures on the performance and persistence of some sown temperate perennial grasses, North-West Slopes New South Wales. *Australian Journal of Experimental Agriculture* **42**, 431-438.

Lodge, GM (2004) Seed dormancy, germination, seedling emergence, and survival of some temperate perennial pasture grasses in northern New South Wales. *Australian Journal of Agricultural Research* **55**, 345-355.

Lodge, GM, Whalley, RDB (1981) Establishment of warm- and cool-season native perennial grasses on the north-west slopes of New South Wales. I. Dormancy and germination. *Australian Journal of Botany* **29**, 111-119.

Mason, WK, Kay, G (2000) Temperate pasture sustainability key program: an overview. *Australian Journal of Experimental Agriculture* **40**, 121-123.

Maze, KM, Koen, TB, Watt, LA (1993) Factors influencing the germination of six perennial grasses of central New South Wales. *Australian Journal of Botany* **41**, 79-90.

Michalk, DL, Dowling, PM, Kemp, DR, King, WM, Packer, IJ, Holst, PJ, Jones, RE, Priest, SM, Millar, GD, Brisbane, S, Stanley, DF (2003) Sustainable grazing systems for the Central Tablelands, New South Wales. *Australian Journal of Experimental Agriculture* **43**, 861-874.

Moore, AD, Donnelly, JR, Freer, M (1997) GRAZPLAN: Decision support systems for Australian grazing enterprises. III. Pasture growth and soil moisture submodels, and the GrassGro DSS. *Agricultural Systems* **55**, 535-582.

NCC (2009) 'Climate data.' (National Climate Centre, Australian Government Bureau of Meteorology: Melbourne)

O’Connor, TG (1996) Hierarchical control over seedling recruitment of the bunchgrass *Themeda triandra* in a semi-arid savanna. *Journal of Applied Ecology* **31**, 155-171.

Schroder, PM, Cayley, JWD, Patterson, AP, Quigley, PE, Saul, GR KJ Hutchinson, PJ Vickery (Eds) (1992) 'Achieving the potential of the pasture resource in south-western Victoria, 6th Australian Agronomy Conference.' Armidale. (Australian Society of Agronomy: Parkville)

Scott, J (1997) Pasture Establishment. In 'Pasture Production and Management.' (Eds JV Lovett, JM Scott.) pp. 171-190. (Inkata Press: Melbourne)

Thapa, R, Kemp, DR, Michalk, DL (2011*a*) Recruitment of *Phalaris aquatica* within existing swards 1. Effects of biomass manipulation, seed level modification and site preparation. *Crop & Pasture Science* **62**, 701-711.

Thapa, R, Kemp, DR, Michalk, DL, Badgery, WB, Simmons, AT (2011*b*) Seedling recruitment of native perennial grasses within existing swards. *Crop & Pasture Science* **62**, 591-602.

Virgona, JM, Bowcher, A (2000) Effects of grazing interval on basal cover of four perennial grasses in a summer-dry environment. *Australian Journal of Experimental Agriculture* **40**, 299-311.

Waller, RA, Sale, PWG, Saul, GR, Quigley, PE, Kearney, GA (1999) Tactical versus continuous stocking for persistence of perennial ryegrass (*Lolium perenne* L.) in pastures grazed by sheep in south-western Victoria. *Australian Journal of Experimental Agriculture* **39**, 265-274.

Zimmermann, J, Higgins, SI, Grimm, V, Hoffmann, J, Münkemüller, T, Linstädter, A (2008) Recruitment filters in a perennial grassland: the interactive roles of fire, competitors, moisture and seed availability. *Journal of Ecology* **96**, 1033-1044.

Fig. 1: Relationship between soil moisture conditions determined by gypsum block data as soil tension (kPa) and predicted by SGS pasture model as percent volume (0-50 mm) for the periods when the gypsum block was considered to function properly across the three experimental sites at Orange, Trunkey Creek and Wellington; mean daily data used; quadratic curves fitted.

Fig. 2. Volumetric soil moisture for the 0-50 mm profile without irrigation (solid line) and with irrigation (dashed line) generated from the SGS model from December to April at the (*a*) Orange site, 2005-06, (*b*) Orange site, 2006-07, (*c*) Orange site, 2007-08, (*d*) Trunkey Creek site, 2006-07, (*e*) Trunkey Creek site, 2007-08, and (*f*) Wellington site, 2006-07; (Symbols: triangle = time of identified recruitment events in the field experiments; circle = time of irrigation treatment; square = seed addition in irrigation treatments).

Table 1. Site descriptors (location, altitude, mean annual rainfall and temperatures), median days of moisture in the 0-50 mm of soil, and probability of 7 and 15 continuous days of moist soil

Probability estimates are derived from probability distribution of the number of continuous days of moist soil for each site (not presented); sites arranged in latitude order to indicate the north south transect.

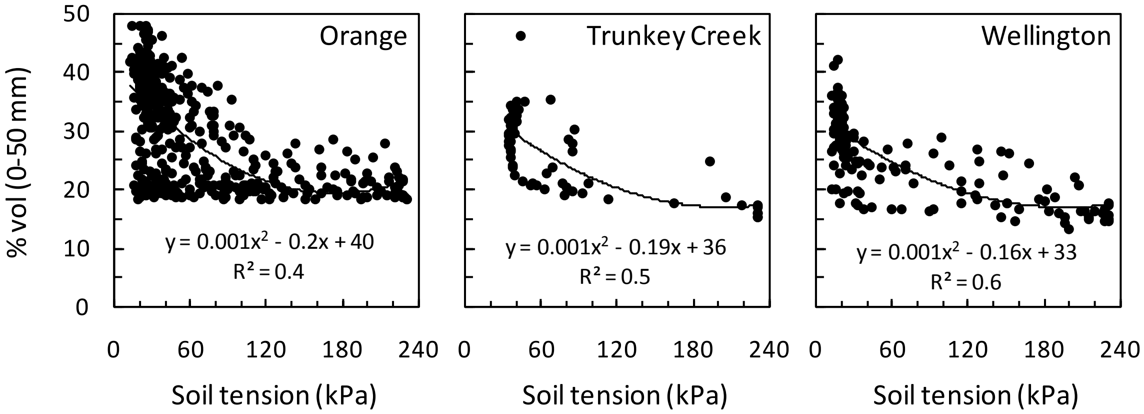
% vol (0-50 mm)
50
40
30
20
10
0
Orange
y = 0.001x² - 0.2x + 40
R² = 0.4
Trunkey Creek
y = 0.001x² - 0.19x + 36
R² = 0.5
Wellington
y = 0.001x² - 0.16x + 33
R² = 0.6
0
60
120
180
240
Soil tension (kPa)
Soil tension (kPa)
Soil tension (kPa)

Fig. 1.

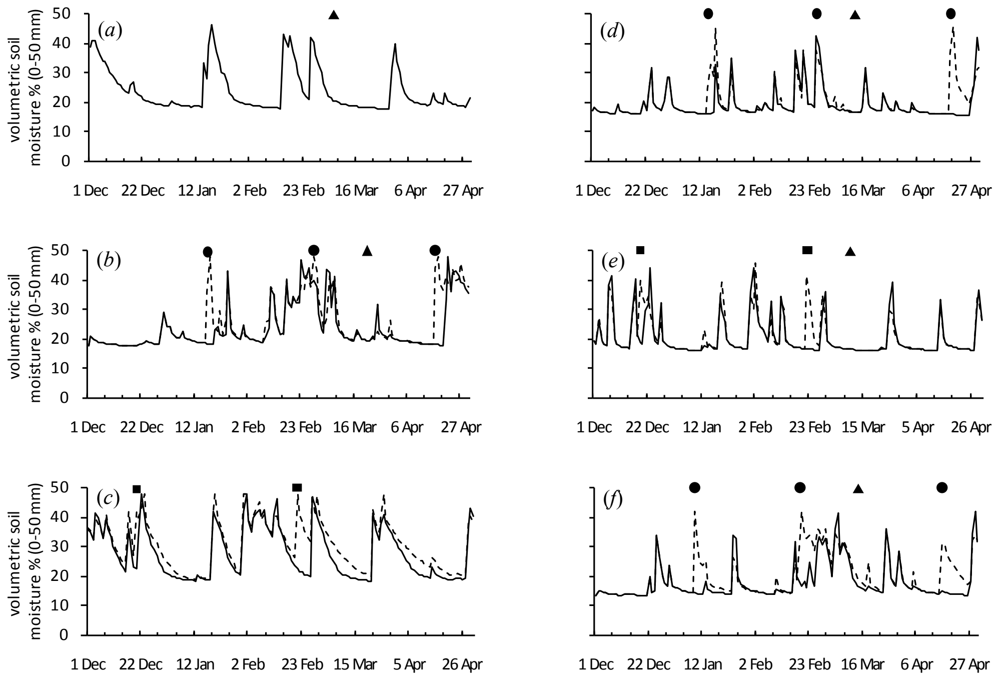
(a)
(b)
(c)
(d)
(e)
(f)
volumetric soil moisture % (0-50 mm)
0
10
20
30
40
50
1 Dec
22 Dec
12 Jan
2 Feb
23 Feb
16 Mar
6 Apr
27 Apr
15 Mar
5 Apr
26 Apr

Fig. 2.

Table 1.

Site	**Location** (°S, °E)	**Altitude (m)**	**Mean annual**			**Climatic conditions through Feb-Mar for 30 years (1975-2004)**				**Probability (%) of exceeding**	
			rainfall (mm)	**MaxT (°C)**	**MinT (°C)**	**Mean MaxT (°C)**	**Mean MinT (°C)**	**Median rainfall (mm)**	**Median days**	**7 continuous days of moist soil**	**15 continuous days of moist soil**
Armidale	30.52, 151.67	980	791	20.3	7.1	25.1	12.3	69.5	14.0	92	39
Tamworth	31.09, 150.85	404	673	24.3	10.2	30.1	15.9	50.3	10.0	76	5
Wellington	32.51, 148.97	300	618	22.8	10.5	28.9	16.2	49.6	10.5	73	30
Mudgee	32.60, 149.60	454	675	23.0	8.3	29.0	14.2	49.8	10.0	83	11
Orange	33.23, 149.12	826	890	17.6	7.2	23.8	10.9	52.1	20.0	98	78
Bathurst	33.43, 149.56	713	634	19.8	6.8	25.9	12.1	48.9	14.0	81	35
Trunkey Creek	33.82, 149.32	840	800	19.3	6.9	25.5	12.0	44.9	16.0	91	49
Goulburn	34.75, 149.70	670	638	19.7	7.4	25.3	12.4	48.0	11.0	85	9
Canberra	35.30, 149.20	578	615	19.7	6.5	25.8	11.9	39.6	9.5	84	5
Tallangatta	36.19, 147.36	220	833	21.4	9.9	28.7	15.1	39.2	8.0	61	8
Cooma	36.23, 149.12	778	530	19.4	4.1	25.1	9.3	42.7	9.0	83	8
Beechworth	36.37, 146.71	580	946	18.4	7.8	25.6	12.6	44.4	9.0	71	11
Warrenbayne	36.69, 145.88	225	853	18.5	6.0	25.7	10.3	28.3	10.0	62	18
Creighton's Creek	36.90, 145.52	276	841	18.5	6.0	25.7	10.3	30.4	8.0	56	0
Bombala	36.91, 149.24	705	641	18.4	4.8	23.8	9.5	47.7	11.0	87	26
Mansfield	37.05, 146.09	316	719	20.9	5.1	27.3	11.5	33.5	8.5	67	3
Highlands	37.07, 145.42	565	852	20.3	7.8	27.7	13.2	23.6	9.0	66	0
Tambo Crossing	37.51, 147.85	195	767	18.9	9.9	23.4	13.4	46.7	13.0	79	22
Launceston	41.54, 147.20	166	676	17.0	6.2	22.2	9.6	26.7	8.0	64	8
Cressy	41.72, 147.08	148	628	17.2	5.1	22.5	8.7	22.4	10.0	64	18
Avoca	41.78, 147.72	205	551	17.7	5.2	22.2	8.9	24.5	9.0	56	13
Swansea	42.12, 148.07	6	595	17.9	7.8	21.6	11.1	26.3	10.0	83	15
Hobart	42.89, 147.33	51	616	16.9	8.3	20.9	11.5	27.3	10.5	65	13
Dunalley	42.90, 147.87	12	697	17.5	8.0	21.5	11.4	40.7	11.0	83	26