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Queensland's multi-year Wet and Dry periods: implications for grazing enterprises and pasture resources

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Abstract. Year-to-year variability in rainfall has long been recognised as a major issue in managing livestock enterprises across Australia's grazing lands. Extension products documenting rainfall variability have been developed over the last 30 years and have been keenly sought by producers and their advisors. This paper describes multi-year rainfall variability from 1889 to 2020 and provides the basis for classifying the 131 years of rainfall into 18 discrete Wet (7), Average (2) and Dry (9) periods as presented in the 'Queensland's Extended Wet and Dry Periods' poster. The classification was consistent with: analysis of fluctuations and trends in the long-term time series of reported livestock numbers; drought declarations for government assistance; and documented periods of pasture resource degradation and recovery. Rainfall during the nine Wet and Average periods was +18% above the long-term average annual rainfall (LTAAR), in contrast to the Dry periods with −17% below LTAAR. Wet periods (including Average) were on average 7 years in duration, ranging from 5 to 9 years. Dry periods were on average 8 years in duration and ranged from 5 to 13 years. Detailed analysis of the effects of the El Niño Southern Oscillation (ENSO) phenomenon indicated that: (a) the Wet/Dry periods were dominated by different frequencies and amounts of rainfall in La Niña/El Niño years; (b) rainfall in ENSO neutral years was generally above and below average rainfall for the Wet or Dry periods respectively; (c) the frequency of ENSO year-types was less important than the overall rainfall surplus (or deficit) in La Niña (or El Niño) years within the Wet (or Dry) periods respectively; and (d) the timing of Wet and Dry periods was correlated with indices of quasi-decadal and inter-decadal variability in components (sea surface temperatures and atmospheric pressures) of the global climate system. Climatic risk assessment systems for grazing management at multi-year timescales are yet to be developed.

Keywords: rainfall variability, drought, El Niño Southern Oscillation, ENSO, El Niño, La Niña, quasi-decadal, Inter-decadal Pacific Oscillation, degradation, pasture recovery, livestock production.

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Introduction

Year-to-year and multi-year climatic variability (in particular, rainfall) have long been recognised as a major challenge in global rangelands used for livestock production (e.g. Ratcliffe 1936; Beadle 1948; Derrick 1977; Kgosikoma 2006; Sloat *et al.* 2018). Approximately three-quarters of Australia is classified as rangelands, with 58% occupied by pastoral enterprises (ANZECC and ARMCANZ 1999). These rangelands have high year-to-year rainfall variability (e.g. Fatichi *et al.* 2012) by world standards, with consequential challenges for grazing and land managers (e.g. McKeon *et al.* 2004). In addition, in some rangeland regions (e.g. north-western Queensland, Australia) temporal rainfall variability has increased over the past 100 years (e.g. Cobon *et al.* 2019). Multi-year variability in Queensland's rainfall has long been recognised as a dominating feature of Queensland's climate (e.g. Foley 1957; Gibbs and Maher 1967; Day and McKeon 2018). Wet and dry multi-year periods (including drought and flood episodes) have affected the wellbeing of individuals, communities, enterprises, and governments (e.g. Daly 1994; Cobon *et al.* 2017; McCartney 2017; Paxton 2019), and the degradation and recovery of pasture resources (Stone *et al.* 2003; McKeon *et al.* 2004). To better document climatic risk across Australia's rangelands, the ~130-year history of annual and multi-year variability in Queensland's rainfall has been presented in two educational posters (e.g. 'Australia's Variable Rainfall' poster (AVR) https://data.longpaddock.qld.gov.au/static/products/pdf/australiasvariablerainfall2020.pdf); and the 'Queensland's Extended Wet and Dry Periods' (QEWDP; https://data.longpaddock.qld.gov.au/static/products/pdf/WetDryDroughtPoster2020.pdf; Stone *et al.* 2019). These posters have been popular, with over 5000 of each type distributed since 2017, predominantly to the Queensland grazing sector, but also to the broader Australian community. This paper describes the importance of both year-to-year and multi-year variability in rainfall, and a new approach classifying the historical record into multi-year 'wetter and drier' periods as displayed in the QEWDP poster.

Spatially, livestock production is the major land use in Queensland, with ~90% (160 Mha) of the state used for extensive livestock grazing (Day and McKeon 2018). In 2020, there were 10.5 million cattle (including dairy cattle and cattle in feedlots) and 2.0 million sheep in Queensland (Australian Bureau of Statistics, ABS 2021). In addition, there are significant but variable populations of feral (e.g. goats and camels) and native herbivores (e.g. ~17 million macropods; DES 2020). Production from livestock is dependent on native, naturalised and sown pastures. The majority of grazing occurs over a wide range of climate types (arid, semiarid, subhumid and dry monsoonal), with pasture production strongly dependent on warm season (November–March) rainfall (Day and McKeon 2018). Both warm season and cool season (April–October) rainfall (Fig. 1*a, c*), have high variability at year-to-year and multi-decadal time scales (Pittock 1975; McKeon *et al.* 1998; Crimp and Day 2003). From 1889 to 2020, across Queensland's grazing lands, the coefficients of variation for warm and cool season rainfall are 33 and 43% respectively.

The effects of global remote climate drivers, such as the El Niño Southern Oscillation (ENSO) phenomenon on temporal rainfall variability in global rangelands have been well described (e.g. Stone *et al.* 1996; Meinke *et al.* 2005). For Australian rangelands, Risbey *et al.* (2009) have detailed the major remote climate drivers (e.g. ENSO, Indian Ocean Dipole) for different regions. ENSO is the major source of year-to-year variability in rainfall across Queensland's grazing lands (e.g. Risbey *et al.* 2009; Klingaman *et al.* 2013). Other studies have shown the influence of quasi-decadal and inter-decadal climatic influences on eastern Australian rangelands (including Queensland) rainfall (Crimp and Day 2003; White *et al.* 2003; McKeon *et al.* 2004; Klingaman *et al.* 2013).

The majority of extensive commercial grazing enterprises in Queensland are based on retaining a 'self-replacing' breeding nucleus, with additional buying/selling depending on pasture availability. As a consequence, the historical year-to-year variability in rainfall and pasture production has had major impacts at multi-year timescales. These impacts affect the pasture resource and animal management (e.g. stocking rate, pasture burning, livestock supplementation, disease and pest control), livestock production (beef, wool), herd/flock dynamics (reproduction, mortality), and financial performance. Most importantly, the difficulties of retaining a breeding nucleus during multi-year 'droughts' (more than 2 years) are greater than managing for 1- or 2-year drought periods, when tactical short-term responses are available (e.g. Miller *et al.* 1973; McCartney 2017).

Over the past ~130 years, the retention of livestock in years with below-average warm season rainfall has led to heavy pasture utilisation, with palatable perennial pastures damaged and ground cover reduced. Historically, multi-year/decadal periods of below-average rainfall have exacerbated pasture resource deterioration (e.g. Tothill and Gillies 1992; Mott and Tothill 1993; McKeon *et al.* 2004). Fortunately, multi-year periods of above-average rainfall have provided opportunities for pasture resource recovery – provided no irreversible vegetation or soil degradation has occurred. However, some of these wet periods have also led to inflated industry and government expectations of livestock carrying capacity (e.g. Gardener *et al.* 1990; Pressland and McKeon 1990). Over-optimistic expectations have reduced recovery of the pasture resource and increased the risk of lower pasture production in subsequent dry periods (Stone *et al.* 2003; McKeon *et al.* 2004). In addition, restocking too quickly when the wet periods arrive after dry periods is likely to not allow enough time for pasture recovery (e.g. Lauder 2008; McIvor 2010).

In this paper (as sections), we: (a) describe the method of classification into Wet and Dry periods; (b) evaluate the Wet and Dry Periods with regard to spatial variability and the lack of 'average' periods; (c) evaluate the relationship between multi-year Wet and Dry periods and Queensland livestock numbers; (d) analyse the relationship between multi-year Wet and Dry periods and El Niño Southern Oscillation (ENSO); (e) assess relationships of decadal and inter-decadal variability in the global climate system with Wet and Dry periods; and (f) discuss the implications for pasture resource and enterprise management.

Method of classification into Wet and Dry periods

Our analyses of historical rainfall concentrate on the region (59% of Queensland's area) where over 80% of cattle and sheep graze (Queensland Grazing Lands; QGL; Fig. 2). Day and McKeon (2018) identified QGL as having a different climatic regime based on 'warm season' (November–March) climatic variables when compared to semi-arid far-western Queensland and dry monsoonal/tropical far-northern Queensland. Day and McKeon (2018) showed that the region's 'borders' are consistent with the boundaries between different air masses (e.g. Tropical maritime Pacific, Tropical continental, Equatorial maritime). Because the QGL region is dominated by a single air mass (especially in the warm season, e.g. Tropical maritime Pacific), year-to-year rainfall variability at most locations (other than south-east Queensland) is highly correlated ($r > 0.7$) with QGL rainfall (Day and McKeon 2018). Hence QGL rainfall provides a useful indication of rainfall variability likely to occur at individual locations, especially with respect to the impact of remote climate drivers of year-to-year variability such as ENSO (e.g. Risbey *et al.* 2009; Klingaman *et al.* 2013) and other remote drivers of multi-year variability (White *et al.* 2003; Meinke *et al.* 2005).

In the following classification and description of the multi-year Wet and Dry periods, we use the annual period of 1 April to 31 March (as in the AVR poster) rather than the calendar year. This is based on: (a) the northern Australian wet season includes seasons from 2 consecutive calendar years, with the major proportion (e.g. 68% for QGL) of annual rainfall falling in the

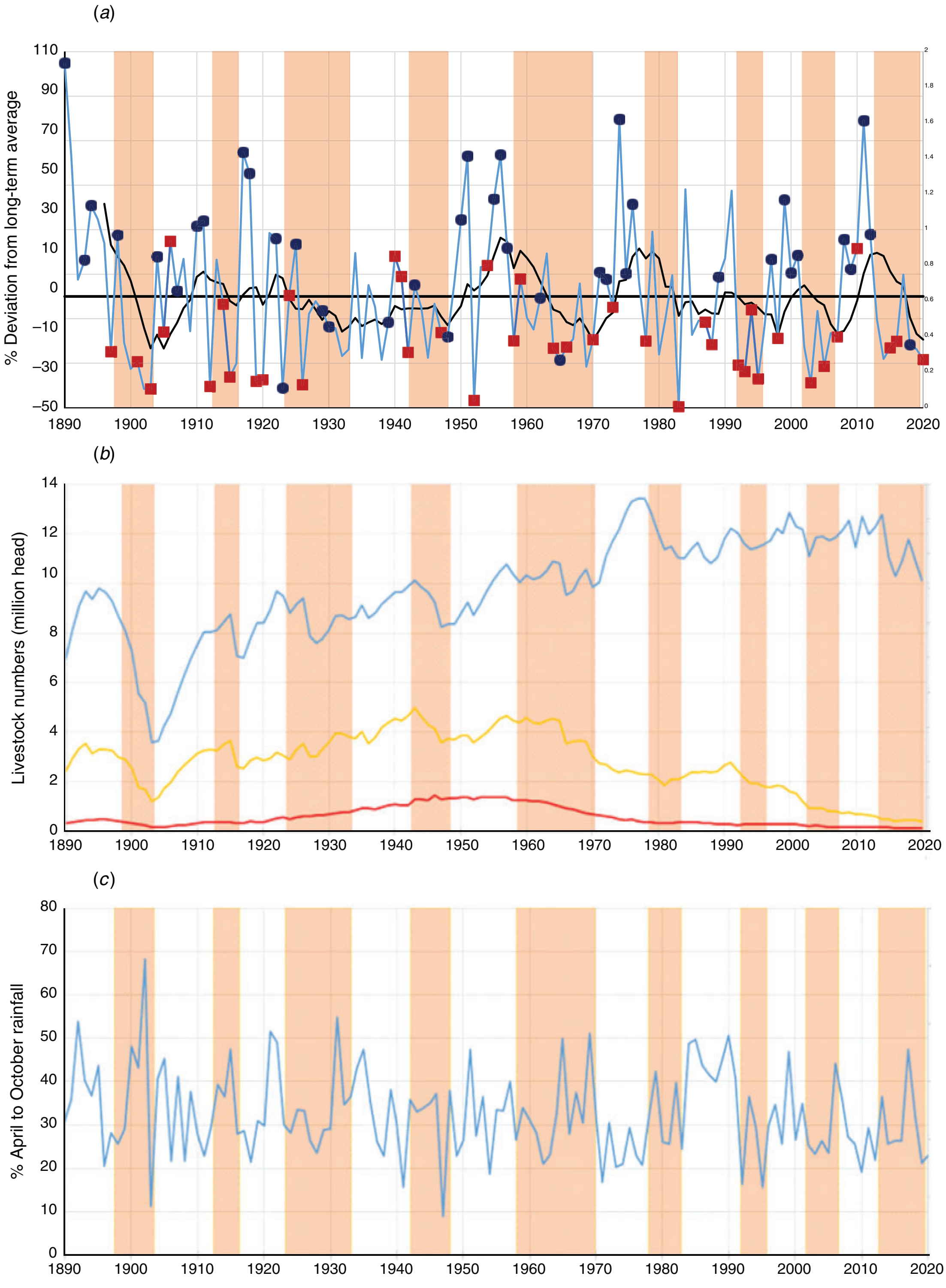

Fig. 1. (*a*) Time series of annual rainfall (light blue line) and 7-year running average (black line) for Queensland Grazing Lands (Day and McKeon 2018). Shading shows Dry periods (orange) and Wet periods (blank) from the classification described in the text and presented in the QEWDP poster. El Niño years are indicated by the red squares and La Niña years are indicated by dark blue circles. (*b*) Time series of annual livestock numbers (million head) expressed as cattle equivalents on pasture for dairy (red line), dairy+sheep (orange line) and total cattle equivalents on pasture (i.e. beef+dairy+sheep; blue line). Shading shows Dry periods (light orange) and Wet periods (blank) from the classification described in the text. (*c*) Time series of % cool season rainfall (April to October; blue line) for Queensland Grazing Lands (Day and McKeon 2018). Shading shows Dry periods (orange) and Wet periods (blank) from the classification described in the text and presented in the QEWDP poster. The two Average periods (1933–1941 and 1983–1991) have been grouped with the Wet periods. Warm season rainfall (November to March) is 100% minus cool season rainfall.

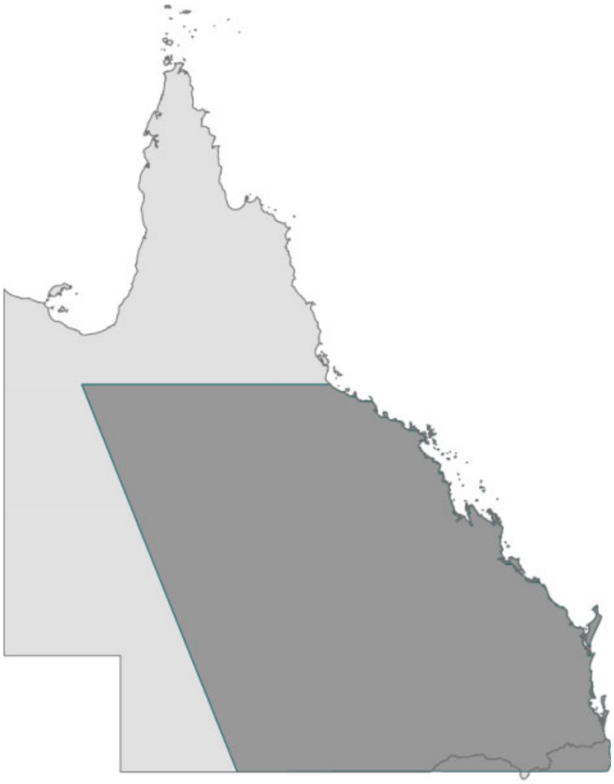

Fig. 2. The dark shading within the map shows the region of Queensland Grazing Lands as defined by Day and McKeon (2018). The region's 'borders' are consistent with the boundaries between different warm season air masses (e.g. Tropical maritime Pacific, Tropical continental, Equatorial maritime). The region (59% of Queensland's area) is where over 80% of cattle and sheep graze.

November to March seasonal period; and (b) that the 'ENSO-year' runs approximately from April to March (Day and McKeon 2018). For ease of nomenclature and consistency with the QEWDP poster, we have labelled each period (e.g. 1889–1896) by the 'start' year (1 April 1889) and 'end' year (31 March 1896).

Our specifications for dividing the 131-year record into multi-year periods were derived from: (a) the responses of herd/flock dynamics to rainfall variability at 5- to 10-year time scales; and (b) the understanding of the long-term non-stationary nature of 'average' rainfall especially in eastern Australia (e.g. Pittock 1975; Russell 1981; Lough 1991). From the viewpoint of livestock carrying capacity and financial performance, QGL rainfall (Fig. 1*a*) has relatively high variability at annual and multi-year time scales, as well as at 20-year time scales (−10% to +8%; McKeon *et al.* 1998, 2009). However, the major climatic issue for extensive grazing enterprises (and support of government policy) is maintaining a breeding nucleus (cattle or sheep) through shorter multi-year (e.g. 5–10 years) dry and drought periods (Daly and Dudgeon 1987; Anon. 1996).

Shorter term variability (e.g. 1- to 2-year 'droughts') is considered here to be part of 'normal' management expectations with conservative and tactical responses available. For example, McCartney (2017, p. i) found in a survey of rural specialists that:

> 'There was also a distinction made between single and multi-year droughts. In general, it was thought that many graziers were doing some preparation and management for single years, but that it was extremely difficult, if not 'impossible' to prepare for droughts lasting longer than 2 years.'

Examples of tactical responses to short-term variability include: destocking; agistment; feeding hay, grain and fodder tree browse; supplementation; use of feedlots; early weaning: and delayed mating or joining. However, longer periods (e.g. >4 years) have had greater impacts on the pasture resource and enterprise performance (e.g. Miller *et al.* 1973), and on the need for government drought assistance (e.g. Daly 1994; Irvine 2021).

Specifications for classification of individual years into 18 Wet and Dry Periods

The specifications for the classification of each year of the historical record into Wet and Dry periods were:

1. the procedure for classifying individual years should be reproducible and evidenced-based;
2. there should be approximately equal numbers of Wet and Dry periods to support a more balanced perception of rainfall expectations (Daly 1994, p. 93); and
3. multi-year periods should be equal to or longer than 5 years consistent with the herd and flock dynamics that underpin grazing enterprises.

Development of an algorithm for the classification of year-by-year sequence into Wet or Dry periods

Several approaches have been used to identify multi-year variation in long-term rainfall time series such as cumulative residual analysis (Fig. 3; Foley 1957; Russell 1981; G. Curran pers. comm.) and percentile analysis (e.g. Day *et al.* 2003). Day *et al.* (2003) have previously demonstrated that simple rules for drought declaration and for revocation could be developed based on percentile thresholds of rainfall to accurately represent historical official drought periods across Queensland. Day *et al.* (2003, p. 144) used 12-month rainfall for a 'shire' (i.e. Local Government Area; LGA) to calculate percentage of Queensland in 'drought'. However, the 'percentile' and 'cumulative residual' approaches require hindsight knowledge of percentiles (including median) and long-term average rainfall.

In the following algorithm, we have adopted a different approach of expressing annual rainfall relative to the immediate past Wet or Dry period and hence the algorithm does not require knowledge of the whole long-term rainfall record to classify each year. Previous analyses (Pittock 1975; Lough 1991) suggest that average QGL rainfall has varied at timescales of 20–40 years and hence the long-term (~100 years) average is only known with the benefit of hindsight. Given the time scale of herd and flock dynamics (e.g. 5 years or greater), we hypothesised that the average rainfall of the previous Wet or Dry period was a more relevant indicator of the likely impact of current rainfall conditions and did not require knowledge of the long-term average. Such an approach is also more consistent with the mechanistic hypotheses of White *et al.* (2003), Meinke *et al.* (2005) and Jin *et al.* (2020) with regard to the range of timescales of variability in the components of the global climate system (e.g. inter-annual to

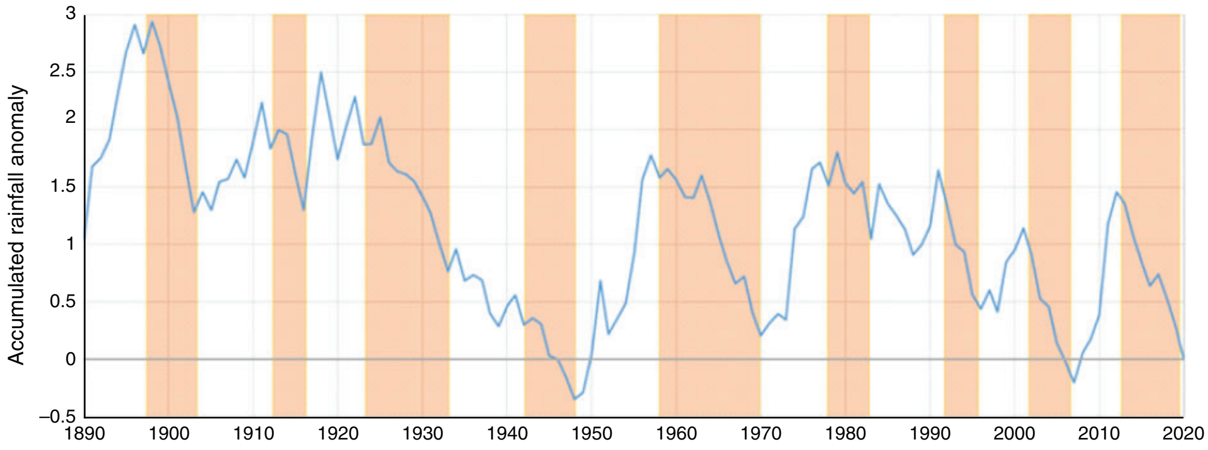

Fig. 3. Accumulated rainfall anomalies for Queensland Grazing lands are calculated by accumulating the annual deviations from the long-term average (577 mm), following the approach used by Russell (1981). The yearly anomaly is calculated as (rainfall – long-term average) ÷ long-term average. The time series of accumulated rainfall anomalies allows identification of 'break points' and support for the classification of the Wet and Dry periods. Shading shows Dry periods (orange) and Wet periods (blank) from the classification described in the text and presented in the 'Queensland's Extended Wet and Dry Periods' (QEWDP) poster. The two Average periods (1933–1941 and 1983–1991) have been grouped with the Wet periods.

inter-decadal variation in sea surface temperatures and atmospheric pressures).

Our analysis commenced with the well-documented drought and wet periods of the 1880s and the early 1890s, when widespread rainfall records were becoming more available (Gibbs and Maher 1967; Day and McKeon 2018). The Wet period (1889–1896) followed a general drought period across Queensland in the mid-1880s (Gibbs and Maher 1967; Daly 1994).

The yearly classification algorithm requires the following *key parameters*:

1. Thresholds for the start and finish of Wet or Dry periods. To estimate rainfall thresholds for cessation of Wet or Dry periods, we reviewed the year-to-year transitions from historical Wet to Dry periods in terms of yearly and seasonal rainfall. For example, in the case of initiating Drought Declarations at an LGA spatial scale, warm season (October–March) rainfall had to be below 40% of long-term average (Daly 1994, p. 14). Similarly, for seven degradation episodes in Australia's rangelands, McKeon *et al.* (2004, p. 170) found that the initial 'dry' year averaged 40% below the last year of the previous Wet period. For QGL rainfall, years with ~40 ± 3% deficit in warm season rainfall had a corresponding deficiency of 33% (ranging from 14 to 46%) for the whole 12-month period (April–March rainfall). Given the larger spatial extent of QGL (compared with LGA areas) and with varying contributions of cool season (April–October; Fig. 1*c*) rainfall, we adopted a more conservative threshold of −20% for potentially starting Dry periods and +20% for potentially 'breaking' Dry periods. We hypothesised that years with 'average' rainfall (i.e. $> -20\%$ and $< +20\%$) were not sufficient to result in the cessation of the current period (either Wet or Dry), in terms of impact on pasture and livestock production.
2. Number of future years required to identify that changes from a Wet to a Dry period (or the converse) have occurred. Analysis of livestock numbers following the onset of multi-year drought periods indicated that rainfall deficits in second and third years further exacerbated the impact of the first dry year (McKeon *et al.* 2004, p. 170; Stone 2004, p. 234). For the cessation of multi-year drought periods, analyses of drought revocations (Irvine 2021; Fig. 4) indicated that several years of above-average rainfall were likely to be needed for livestock production to return to previous levels. Examination of Drought Declarations for droughts in the 1960s, 1990s and 2000s (Irvine 2021) indicated that complete state-wide revocation did not occur until 4 years after the last dry year of the drought period. From the viewpoint of pasture condition recovery, a period of 2 years rest from grazing is suggested for the improvement in pasture condition (McIvor 2010, p. 114). Hence, in the algorithm, we hypothesised that the current and future 3 years determined if the current year was in fact a turning point between periods.

Procedure for classifying individual years

The classification of each year is incremental and depends on previous classifications as well as 'knowledge' of rainfall in the future 3 years. The current year is expressed as a %Deviation from the average of the previous Wet or Dry periods (*PPaverage*). As indicated above, the required threshold for commencement of a Dry period (*Dry-Threshold*) was −20% and the threshold for commencement of a Wet period (*Wet-Threshold*) was +20%. Rainfall for subsequent years 2, 3 and 4 (*Y234 average*) was expressed as the %Deviation from average of the previous Wet or Dry period. The required threshold (*Y234 threshold*) for assessing the future 3 years (*Y234 average*) was initially set to zero.

The rules for the classification of each year (described as a *Rule Type*) were:

- *Rule Type 1* was used to flag if the previous Wet or Dry period had ended (see *Rule Types* 4 or 7) and the duration was less than five years (Table 1).

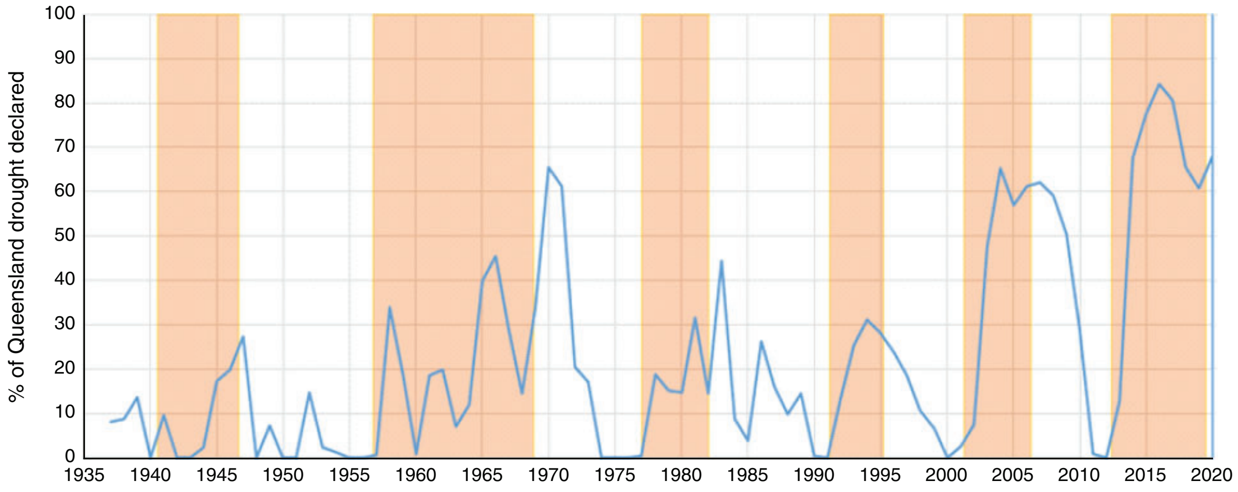

Fig. 4. Time series of percentage area of drought declared since 1936 (Irvine 2021). Data from 1936 to 1964 are sourced from Queensland Railways; data from 1964 to 1995 are sourced from Rural Risk Strategies Unit, Queensland Department of Primary Industries; data from 1995 to 2020 are sourced from the Long Paddock Website (https://www.longpaddock.qld.gov.au/drought/drought-declarations/). Shading shows Dry periods (orange) and Wet periods (blank) from the classification described in the text and presented in the 'Queensland's Extended Wet and Dry Periods' (QEWDP) poster. The two Average periods (1933–1941 and 1983–1991) have been grouped with the Wet periods.

Table 1. The number of years classified in each of the nine Rule Types

Rainfall for each year and average rainfall for years 2, 3 and 4 (Y234) is expressed as %Deviation (%Dev) from the average of the previous Wet or Dry period

Rule Type	No. of years	% of years	Rule description	Year description
1	0	0	Period less than 5 years	
2	13	10	If previous year Wet and %Dev > −20% and < +20%	Wet continues
3	38	29	If previous year Wet and %Dev ≥ +20%	Wet continues
4	9	7	If previous year Dry and %Dev ≥ +20% and Y234 ≥ −3%	Wet starts
5	0	0	If previous year Dry and %Dev ≥ +20% but Y234 < −3%	Dry continues 'false break'
6	37	28	If previous year Dry and %Dev ≤ −20%	Dry continues
7	9	7	If previous year Wet and %Dev ≤ −20% and Y234 ≤ −3%	Dry starts
8	3	2	If previous year Wet and %Dev ≤ −20% but Y234 > −3%	Wet continues 'false start to Dry'
9	22	17	If previous year Dry and %Dev > −20% and < +20%	Dry continues
Total	131			

- If the %Deviation is > −20% and < +20% of *PPaverage*, and the current period is Wet, then the current period (Wet) continues (*Rule Type 2*).
- If the current year is ≥ +20% of *PPaverage*, and the current period is Wet, then the Wet period continues (*Rule Type 3*).
- If the current year is ≥ +20% of *PPaverage* and the current period is Dry, then the future 3 years are assessed. If the *Y234 average* is ≥*Y234 threshold*, then the Dry period has finished and a new Wet period commences at the current year (*Rule Type 4*); otherwise, the current year is only a single 'wet event' (i.e. 'false break') and the Dry period continues (*Rule Type 5*).
- If the current year is ≤ −20% of *PPaverage* and the current period is Dry, then the Dry period continues (*Rule Type 6*).
- If the current year is ≤ −20% of *PPaverage* and the current period is Wet then the future 3 years are assessed: if the *Y234 average* is ≤*Y234 threshold*, then the Wet period has finished and a new Dry period has commenced at the current year (*Rule Type 7*), otherwise the current year is only a single 'dry event' (i.e. 'false start' to a multi-year Dry period), and the Wet period continues (*Rule Type 8*).
- If the %Deviation is > −20% and < +20% of *PPaverage* and the current period is Dry then the current period (Dry) continues (*Rule Type 9*).

In the first simulation test of the algorithm, there were no restrictions on the length of Wet or Dry period (i.e. no *Rule Type 1* classification); thresholds (*Dry-threshold* and *Wet-threshold*) were ± 20% for potential change of period. %Deviation thresholds for the average of years 2 to 4 (*Y234 threshold*) were set to zero. The first simulation test agreed with the hypothesised classification in 17 of the 18 periods derived from a qualitative review of Queensland's drought history (Fig. 4; Gibbs and Maher 1967; Irvine 2021) and cumulative residual analysis (Fig. 3).

The first simulation test classified the period 1977/78 to 1990/91 as a long Dry period of 11 years, from 1977/78 to 1987/88, followed by a relatively short 3-year Wet period 1988/89 to

Table 2. The 18 'Extended Wet and Dry Periods in Queensland' from 1889 to 2020

The 131 years from 1889 to 2020 were classified by analysis of annual rainfall 1 April to 31 March. Annual rainfall was for Queensland Grazing Lands (QGL, Day and McKeon 2018). Period rainfall has been expressed as %Deviation from long-term average (577 mm), and as %Deviation from the previous Wet or Dry period. Average rainfall for 1882 to 1889 was calculated from SILO Surfaces (Jeffrey *et al.* 2001) as 530 mm. The percentile rank for each period was calculated comparing rainfall with all sequences that have the same duration of years. For later analysis, the two Average (Ave) periods (1933–1941 and 1983–1991) have been grouped with the Wet periods

Period No.	Period label	Period type	No. of years	First year (1 April)	Last year (31 March)	QGL rainfall (mm)	%Deviation from long-term average	%Deviation from previous period	Rank of period rainfall (percentile)
1	1889–1896	Wet	7	1889	1896	817	+42	+54	100
2	1896–1903	Dry	7	1896	1903	443	−23	−46	2
3	1903–1911	Wet	8	1903	1911	646	+12	+46	85
4	1911–1916	Dry	5	1911	1916	469	−19	−27	7
5	1916–1922	Wet	6	1916	1922	672	+16	+43	87
6	1922–1933	Dry	11	1922	1933	498	−14	−26	1
7	1933–1941	Ave	8	1933	1941	562	−3	+13	52
8	1941–1948	Dry	7	1941	1948	503	−13	−11	14
9	1948–1957	Wet	9	1948	1957	714	+24	+42	99
10	1957–1970	Dry	13	1957	1970	508	−12	−29	3
11	1970–1977	Wet	7	1970	1977	701	+21	+38	97
12	1977–1983	Dry	6	1977	1983	513	−11	−27	23
13	1983–1991	Ave	8	1983	1991	620	+7	+21	78
14	1991–1996	Dry	5	1991	1996	438	−24	−29	2
15	1996–2001	Wet	5	1996	2001	658	+14	+50	83
16	2001–2007	Dry	6	2001	2007	448	−22	−32	3
17	2007–2012	Wet	5	2007	2012	769	+33	+71	99
18	2012–2020	Dry	8	2012	2020	472	−18	−39	1

1990/91. The 8-year period 1983/84 to 1990/91 was difficult to classify, because the first year was very wet (1983/84) followed by 4 below-average or average years (1984/85 to 1987/88) and then 3 above-average years 1988/89 to 1990/01. The 4 'dry' years had below-average warm season rainfall, but abnormally high cool season rainfall (Fig. 1*c*), mitigating to some extent the overall impact on livestock production and numbers (Fig. 1*b*). Some regions were drought declared in the mid-1980s (30% of state; Fig. 4) but all declarations had been revoked by 1990.

In a second simulation, with *Y234 threshold* %Deviation set to −3% of *PPaverage*, the Dry period was reduced to 1977/78 to 1982/83, and the remaining 'anomalous' period 1983/84 to 1990/91 was classified as 'Average' (abbreviated as Ave in Table 2). The division of the longer dry period (1977/78 to 1987/88) was consistent with variation in Queensland livestock numbers (Fig. 1*b*). However, we recognise that in some regions (south-western Queensland (Stone 2004, p. 227); north-eastern Queensland (Landsberg *et al.* 1998)), the severe drought impacts and conditions of the mid-1980s had substantial negative impacts on some grazing enterprises.

Over the 131 years, *Rule Types* 3 and 6 had the highest occurrence (29 and 28% respectively; Table 1), when the large %Deviations in rainfall from the previous period markedly contributed to the continuation of the current Wet or Dry period. The use of the *Y234 threshold* (*Rule Type* 8) detected only three 'false break' years to Wet periods (1918/19, 1919/20 and 1951/52). In these years, there were severe droughts and impacts on livestock. However, average or above-average rainfall occurred in subsequent years 1920/21, 1921/22 and 1952/53 to 1956/57, and hence these 3 drought years are included in their otherwise Wet period. In the case of Dry periods, there were no 'false breaks' (*Type 5*). All Dry periods ended with an individual wet year with rainfall ≥+20% of *PPaverage* and the *Y234 average* ≥ *Y234 threshold* (*Rule Type 4*).

Thus, the algorithm showed that the multi-year Wet and Dry periods could be derived objectively with 'common sense' parameters consistent with the historical experience of the grazing industry.

Evaluation of Wet and Dry Periods

The rule-based algorithm divided the historical record into 18 Wet and Dry periods (Table 2) by assessing year-by-year 12-month QGL rainfall expressed relative to the previous Wet or Dry period rainfall and thresholds derived from historical experience. Importantly, the long-term (131 years) average rainfall (LTAAR, 577 mm) was not used by the algorithm, and hence the periods have been classified as Wet or Dry depending on their relativity to the immediately previous period rainfall. As detailed below, two of the classified Wet periods (1933–1941 and 1983–1991) had rainfall closer to LTAAR and have been labelled as 'Average' (Ave, in Table 2). These two Average periods have been included in the group of nine Wet periods in subsequent analyses.

From the viewpoint of LTAAR, the nine Wet periods were +18% above-average in contrast to the Dry periods with −17% below-average. Wet periods averaged 7 years, ranging from 5 to 9 years. Dry periods averaged 8 years ranging from 5 to 13 years.

For 16 of the 18 periods, the percentage difference in rainfall from the previous period was greater than ± 20%. For the nine Dry periods, the average %Deviation from the previous Wet period was −30%, ranging from −11 to −46% (Table 2). For the nine Wet periods, the average %Deviation from the previous Dry period was +42%, ranging from +13 to +71% (Table 2).

These results highlight the historical climate-driven challenge that grazing enterprises and governments have had to manage for over the past 131 years (Daly 1994; McKeon *et al.* 2004; Stone 2004; Irvine 2021). Two periods (1933–1941 and 1941–1948) had relatively small changes in average rainfall from their previous period (+13% and −11% respectively) and are discussed below in the following section.

The percentile rank for each period was calculated comparing the period rainfall with all sequences that have the same duration of years (Table 2). The rank was divided by the total number of periods with the same number of years and multiplied by 100. For the Dry periods, seven were ranked in the lowest 10% of percentiles (for their respective period). Two Dry periods, 1922–1933 and 2012–2020, had the lowest percentile rank (i.e. 1) for 11- and 8-year periods respectively. The 8-year 2012–2020 Dry period shared the lowest rank with the 8 years from 1896/97 to 1903/04. For the Wet periods, seven were ranked in the highest 20% of percentiles (for their respective period). Four periods (1, 9, 11, 17) were ranked in the highest 5% of percentiles (i.e. rank >95). Only one period (1933–1941), was ranked in the middle (or average) of the percentile range (i.e. 30–70). The anomalous period, (1983–1991), which has been classified as Average had a percentile ranking of 78, supporting its inclusion in the group of Wet periods.

Russell (1981) analysed historical time series of Australian regional rainfall using 'cumulative residual' (also known as 'residual mass') analysis. This quantitative approach allows identification of break points in time series, for example the large change in eastern Australian rainfall in the 1950s (Pittock 1975; Russell 1981). Analysis of the cumulative residual rainfall for the QGL (1889–2020) indicated break points consistent with the Wet and Dry Periods (Fig. 3), as well as longer-term periods of below LTAAR (e.g. 1922–1948) and above LTAAR (e.g. 1948–1957).

Spatial variability in Wet and Dry periods

The QEWDP poster presents each of the 18 periods as a map, with each period's rainfall for an individual location (5 × 5 km pixel) expressed as a percentile ranking, derived by considering all other possible April to March periods with the same duration. The classification algorithm (in section *Method of classification into Wet and Dry periods*) did not use statistics derived from the full record of long-term historical rainfall. In contrast, the percentile analysis necessarily uses the whole available rainfall record. There was little variation across the eight Dry periods in the percentage of QGL pixels (70–96%) with period rainfall less than Decile 3. For all nine Dry periods, there were less than 2% of QGL pixels with period rainfall greater than Decile 7. Similarly, for seven of the nine Wet periods, there was little variation in the percentage of QGL pixels (67–99%) having period rainfall above Decile 7. Thus, from a spatial viewpoint, the Wet and Dry periods were generally consistent across QGL in the percentage of the region affected by rainfall surplus, or deficit.

The lack of Average periods

Of the 18 periods, one period (1933–1941) had a very high proportion of QGL pixels (72%) in the Decile 3–7 range, and, therefore it has been classified as Average in Table 2. The periods (1977–1983 and 1983–1991) were the only other periods to have more than 40% of QGL pixels in the Decile 3–7 range. However, the period (1977–1983) had 56% of QGL pixels less than Decile 3, confirming its classification as a Dry period. The two Average periods (1933–1941 and 1983–1991) had low percentages of QGL pixels with period rainfall less than Decile 3 (17 and 14% respectively), supporting their inclusion in the group of nine Wet periods used in subsequent analyses (e.g. Tables 3–7).

Annual rainfall less than Decile 1 is a current threshold for Drought Declaration in Queensland. The frequency of years with annual (April–March) rainfall less than Decile 1 was calculated for 39 Australian Bureau of Meteorology stations across the 63 years in Wet periods and 68 years in Dry periods. Averaged across locations, years with rainfall below Decile 1 occurred three times more frequently in Dry periods (15% of years), in contrast to Wet periods (5% of years).

The classification of years into Wet or Dry periods highlighted the magnitude of multi-year variability in QGL rainfall, with only two periods regarded as 'average'. In the AVR poster, 'average' annual rainfall is represented by the middle 40% of years between Deciles 3 and 7 (Stone *et al.* 2019). For QGL annual rainfall, Deciles 3 and 7 are equivalent to −20% and +14% of LTAAR, and −15% and +21% of median (Decile 5) rainfall respectively. In the year-by-year algorithm, a year with average rainfall (i.e. −20% to +20% of previous period rainfall) resulted in the continuation of the current period classification (either Wet or Dry). As discussed above, these rules (*Rule Types* 2 and 9) represent the view that the biological and financial consequences of average annual rainfall in grazing systems also depend on rainfall in previous years. Thus, an arithmetic consequence of the algorithm rules, in combination with the historical rainfall sequences, was that there were only two periods that were close to LTAAR (Table 2). As these 'average' periods were wetter than their respective previous periods, they have been included in the group of nine Wet periods for the analyses below. Furthermore, the location-based analyses further supported the general spatial consistency of the period classification and the lack of average periods. The following sections demonstrate that the classification of Wet and Dry periods was consistent with the historical variability of the global climate system being dominated by clusters of different year types (i.e. El Niños and La Niñas), as well as global quasi-decadal and inter-decadal variability in sea surface temperatures and atmospheric pressures (Power *et al.* 1999; Allan 2000; White *et al.* 2003; Meinke *et al.* 2005).

Relationship between multi-year Wet and Dry periods and Queensland livestock numbers

Commercial livestock enterprises have been established in Queensland since the 1860s, with annual livestock statistics reported to various government agencies. These statistics provide the time series used below to assess the impact of the 18 multi-year Wet and Dry periods (Table 3). Over the last 150 years, there have been three main types of livestock-based enterprises: beef cattle for meat production and the live cattle trade; dairy cattle for milk products and meat production; and sheep for wool and meat production. In addition, livestock have been imported and exported to and from interstate as well as

Table 3. Changes in livestock on pasture, as expressed as total cattle equivalents from start to end of each Wet and Dry period

The % changes in total cattle equivalents on pasture (TCEonP, beef cattle+dairy cattle+sheep ÷ 7) are compared with period rainfall expressed as (1) %Deviation from long-term average (577 mm); and (2) as %Deviation from previous Wet or Dry period rainfall (Table 2). Rainfall has been averaged for Queensland Grazing Lands (QGL, Day and McKeon 2018). The last Australian Bureau of Statistics agricultural census was in 2015–16 and the most recent estimate of livestock numbers is for 2020 (ABS 2021). For later analysis, the two Average (Ave) periods (1933–1941 and 1983–1991) have been grouped with the Wet periods

Period no.	Wet or Dry Period	Period type	First year (1 April)	Last year (31 March)	Total cattle equivalents on pasture		%Change in TCEonP	%Deviation from average (QGL rainfall)	%Deviation from previous period
					First year	Last year			
1	1889–1896	Wet	1889	1896	6.575	9.659	+47	+42	+54
2	1896–1903	Dry	1896	1903	9.659	3.574	−63	−23	−46
3	1903–1911	Wet	1903	1911	3.574	8.036	+125	+12	+46
4	1911–1916	Dry	1911	1916	8.036	7.059	−12	−19	−27
5	1916–1922	Wet	1916	1922	7.059	9.676	+37	+16	+43
6	1922–1933	Dry	1922	1933	9.676	8.580	−11	−14	−26
7	1933–1941	Ave	1933	1941	8.580	9.630	+12	−3	+13
8	1941–1948	Dry	1941	1948	9.630	8.367	−13	−13	−11
9	1948–1957	Wet	1948	1957	8.367	10.775	+29	+24	+42
10	1957–1970	Dry	1957	1970	10.775	9.864	−8	−12	−29
11	1970–1977	Wet	1970	1977	9.864	13.407	+36	+21	+38
12	1977–1983	Dry	1977	1983	13.407	11.054	−18	−11	−27
13	1983–1991	Ave	1983	1991	11.054	12.219	+11	+7	+21
14	1991–1996	Dry	1991	1996	12.219	11.565	−5	−24	−29
15	1996–2001	Wet	1996	2001	11.565	12.306	+6	+14	+50
16	2001–2007	Dry	2001	2007	12.306	11.869	−4	−22	−32
17	2007–2012	Wet	2007	2012	11.869	11.991	+1	+33	+71
18	2012–2020	Dry	2012	2020	11.991	10.132	−16	−18	−39

exported to overseas markets. Since the 1980s, feedlots have been developed to 'finish' beef cattle from extensive pasture-based grazing (ALFA 2021).

The financial viability of grazing enterprises has fluctuated over the last 150 years, with considerable variation in the costs of production and the prices received for livestock and their products. Global events such as two world wars, the Korean war, depressions and recessions have had major impacts on livestock enterprises, affecting livestock numbers and choice of production system. In addition, producers' responses to price fluctuations have also led to apparent multi-year cycles in herd and flock numbers (Daly 1983, 1994, p. 75). As well as these external factors, it has long been recognised that multi-year variability in rainfall affects livestock carrying capacity through its direct effects on pasture availability (Heathcote 1965; Fordyce *et al.* 2021).

To estimate livestock numbers mainly grazing on pasture, we initially constructed separate time series of annual beef cattle, dairy cattle and sheep numbers (Daly 1994; ABS 2013, 2021; and after Carter *et al.* 2000; Irvine 2016). From these time series we calculated a time series of total cattle equivalents 'on pasture' (TCEonP; beef+dairy+sheep ÷ 7). Prior to 1910, beef and dairy cattle were combined in the historical statistics. From 1910 to 1921, the percentage of dairy cattle was 7±1%; we used this value to estimate dairy cattle numbers from 1889 to 1909. From 1964 to 1982, the two data sources (Daly 1994; ABS 2013, 2021) differ in total cattle by 1.3–2.1% of TCEonP. In the following analyses, we have used the ABS time series, as this is the ongoing source of livestock statistics.

Daly (1994) provides a detailed analysis of cattle and sheep statistics, as well as highlighting potential uncertainties and inaccuracies in the late 1800s and early 1900s. Some of these uncertainties (such as under reporting of numbers) have remained through the 20th and early 21st centuries (e.g. Mortiss 1995; Fordyce *et al.* 2021). Nevertheless, as Daly (1994, p. 62) concluded, that as long as the limitations are recognised, the livestock statistics "…are all we have." and "…can be useful in providing a general overview of trends in the various industries."

From 1889 to 2020, TCEonP in Queensland steadily increased from 6.6 million to a peak of 13.4 million in 1978, then fluctuating between 10 and 13 million until 2020 (Fig. 1*b*). The overall increase in TCEonP reflects the improvements in pasture and livestock production, including the success of adaptive genetic improvement in cattle (Daly 1983) and sheep (Barnard 1958; Hall 1996). In addition, there has been continual property development (i.e. watering points, sown pastures, woodland clearing), and statewide improvements in infrastructure and transport (e.g. Fordyce *et al.* 2021). For the 13 periods up to 1991, each of the nine Wet (and Average) periods had increased rainfall compared to their previous Dry period, and were associated with increases in TCEonP (Table 3; Fig. 5*a, b*). In some periods, episodic rapid changes in commodity prices for wool and beef cattle contributed to the retention of livestock (e.g. late 1920s for sheep, mid-1970s for cattle; McKeon *et al.* 2004). Thus, high cattle numbers of the mid-1970s represent the result

Table 4. Average rainfall in each of the three ENSO year-types (El Niño, Neutral, La Niña) for each Wet and Dry period

Rainfall is expressed as a %Deviation (%Dev) from long-term average for Queensland Grazing Lands (577 mm). The classification of ENSO year-types is given in the poster AVR. The two Average (Ave) periods (1933–1941 and 1983–1991) have been grouped with the Wet Periods

Wet periods	Period years	Period type	No. of years	No. of El Niño years	Rainfall averaged for El Niño years (%Dev)	No. of neutral years	Rainfall averaged for neutral years (%Dev)	No. of La Niña years	Rainfall averaged for La Niña years (%Dev)	%Period Rain of Average
1	1889–1896	Wet	7	0	0	4	+32	3	+54	+42
3	1903–1911	Wet	8	2	+4	2	+1	4	+21	+12
5	1916–1922	Wet	6	2	−38	1	+28	3	+49	16
7	1933–1941	Ave	8	2	+13	5	−7	1	−12	−3
9	1948–1957	Wet	9	2	−16	2	+10	5	+45	+24
11	1970–1977	Wet	7	1	−5	1	+6	5	+30	+21
13	1983–1991	Ave	8	2	−17	5	+17	1	+9	+7
15	1996–2001	Wet	5	1	−19	0	0	4	+22	+14
17	2007–2012	Wet	5	1	+21	0	0	4	+36	+33
	All Wet years		63	13	−8	20	+12	30	+33	+18
Dry periods	Period years	Period type	No. of years	No. of El Niño years	Rainfall averaged for El Niño years (%Dev)	No. of neutral years	Rainfall averaged for neutral years (%Dev)	No. of La Niña years	Rainfall averaged for La Niña years (%Dev)	%Period rain of average
2	1896–1903	Dry	7	3	−32	3	−32	1	+27	−23
4	1911–1916	Dry	5	3	−27	2	−7	0	0	−19
6	1922–1933	Dry	11	2	−20	5	−15	4	−9	−14
8	1941–1948	Dry	7	2	−21	3	−12	2	−7	−13
10	1957–1970	Dry	13	5	−16	6	−8	2	−15	−12
12	1977–1983	Dry	6	2	−35	4	+1	0	0	−11
14	1991–1996	Dry	5	4	−27	1	−13	0	0	−24
16	2001–2007	Dry	6	3	−29	3	−15	0	0	−22
18	2012–2020	Dry	8	3	−24	4	−13	1	−22	−18
All Dry years			68	27	−25	31	−12	10	−7	−17
All years			131	40	−20	51	−3	40	+23	0

Table 5a. Comparison of Wet and Dry periods in terms of frequency of ENSO year-types, and ENSO year-type average rainfall
Rainfall (1 April to 31 March) and %Deviation (%Dev) from long term average annual rainfall (577 mm) for Queensland Grazing Lands (Day and McKeon 2018). The Southern Oscillation Index (SOI) is calculated for the same period as rainfall. Across all listed periods, the effect of the two-way interaction of Wet/Dry periods and El Niño Southern Oscillation (ENSO) year types on the frequencies of years was highly significant (Pearson Chi-square = 17.1; 2df. $P < 0.001$). The two 'average' or 'anomalous' periods (1933–1941, 1983–1991) have been included in the average of the Wet Periods

	Wet periods				Dry periods				All years			
	Years	Rain	%Dev	SOI	Years	Rain	%Dev	SOI	Years	Rain	%Dev	SOI
El Niño	13	529	−8	−8.4	27	434	−25	−8.3	40	465	−20	−8.3
Neutral	20	644	+12	+0.5	31	507	−12	+0.4	51	561	−3	+0.4
La Niña	30	770	+33	+9.3	10	534	−7	+4.1	40	711	+23	+8.0
Total	63	680	+18	+2.9	68	482	−17	−2.5	131	577	0	

Table 5b. Comparison of the separate effects of frequency of ENSO year-types, and ENSO year-type average rainfall on Wet and Dry period rainfall
Rainfall is for average annual rainfall (1 April to 31 March) for Queensland Grazing Lands (Day and McKeon 2018). The table shows the effect of different combinations of ENSO year-type frequencies and rainfall on average Wet and Dry period rainfall. Deviation is from LTAAR (577 mm)

	Observed ENSO year-type frequency Years (%)	Observed ENSO year-type rainfall (mm)	Observed ENSO year-type frequency % Years	Same ENSO year-type rainfall (mm)	Same ENSO year-type frequency % Years	Observed ENSO year-type rainfall (mm)
			Wet periods			
El Niño	13 (20.6)	529	20.6	465	30.5	529
Neutral	20 (31.7)	644	31.7	561	39.0	644
La Niña	30 (47.6)	770	47.6	711	30.5	770
Total	63	680		612		647
Deviation		+18%		+6%		+12%
			Dry periods			
El Niño	27 (39.7)	434	39.7	465	30.5	434
Neutral	31 (45.6)	507	45.6	561	39.0	507
La Niña	10 (14.7)	534	14.7	711	30.5	534
Total	68	482		545		493
Deviation		−17%		−6%		−15%

of several factors: a sequence of good seasons, increase in *Bos indicus* cattle, use of nutritional supplementation, infrastructure improvements, and volatility in beef prices, leading to retention of cattle on properties (e.g. Daly 1994; Fordyce *et al.* 2021).

Over the 131 years from 1889 to 2020, both sheep and dairy based enterprises have undergone transition to mainly beef enterprises, in response to relative changes in markets and profitability (Fig. 1*b*). Dairy cattle as a proportion of TCEonP increased from 5% in 1889 to a peak of 16% in 1949, followed by a continuous decline (especially after the mid-1950s) to 1% in 2020. From 1889 to 1969, the proportion of sheep fluctuated between 27% and 38% of TCEonP. Peaks in the proportion of sheep occurred from 1905 to 1915 and the 1930s and 1940s, with the proportion of sheep steadily declining from 28% in 1969 to 3% in 2020. Thus the overall time series of TCEonP includes long-term changes in the livestock components of dairy cattle and sheep, with a consequent increase in the proportion of beef cattle from 51% in 1943 to 96% in 2020. To assess the importance of changes in the dairy and sheep components of TCEonP, we have also constructed two additional time series for livestock 'on pasture', namely beef+sheep and beef+dairy.

The percentage change in livestock was calculated for each Wet and Dry period (Table 3) from the time series described above. For the TCEonP time series, there were large changes (greater than ±10% increase and decrease) for 12 of the first 13 periods (1889–1991), followed by relatively smaller changes for four periods (1991–2012; Fig. 5*a*). There has been a larger decrease (−16%) in the current ongoing Dry period (2012–2020), reflecting not only its severity (e.g. Fig. 4; Table 3, but also the recent much improved prices for livestock products, supporting the sale of livestock in response to dry conditions.

The beef and TCEonP time series had similar changes in each period with the exception of 1957–1970. This Dry period exacerbated the emerging decline in dairy (−50%) and sheep numbers (−29%), in contrast to an increase in beef cattle (+10%). Overall, there was a small decrease in TCEonP (−8%) over this 13-year Dry period.

For the first 13 Wet and Dry periods (1889–1991), the changes in livestock numbers for the four time series (beef, beef+sheep, beef+dairy and TCEonP) were compared to changes in period rainfall, expressed as either: %Deviation from LTAAR, or as %Deviation from the previous Wet or Dry period (Tables 2, 3; Fig. 5*a, b*). For all livestock time series, correlations of the changes in livestock numbers with rainfall were higher when expressed as a %Deviation from the previous period. The time series which included beef cattle had the highest correlations ($R^2 = 0.70 - 0.75$, $n = 13$, $P < 0.0004$–0.0001). As an example, for the first 13 periods (1889–1991), the relationship

Table 6. Comparison of the last year of the previous period and the first year of the new period
The %Deviation of rainfall is from the long-term average annual rainfall (LTAAR, 577 mm). The indicated year is for the 12 months ending 31 March (i.e. 1889 is for the 12 months from 1 April 1888 to 31 March 1889)

Period no.	Last year	First year	Rain in last year of previous period	Last year ENSO year type	Rain in first year of new period	First year ENSO year type	%Deviation of last year from LTAAR	%Deviation of first year from LTAAR	Net difference in deviations from last to first (i.e. first minus last)	%Deviation of first year from previous period
							Wet periods			
1	1889	1890	267	El Niño	1183	La Niña	−54	+105	+159	+123
3	1903	1904	337	El Niño	680	La Niña	−42	+18	+59	+54
5	1916	1917	404	Neutral	951	La Niña	−30	+65	+95	+103
7	1933	1934	440	Neutral	690	Neutral	−24	+20	+43	+39
9	1948	1949	472	La Niña	612	Neutral	−18	+6	+24	+22
11	1970	1971	465	El Niño	639	La Niña	−19	+11	+30	+26
13	1983	1984	291	El Niño	855	Neutral	−50	+48	+98	+67
15	1996	1997	504	Neutral	673	La Niña	−13	+17	+29	+54
17	2007	2008	472	El Niño	725	La Niña	−18	+26	+44	+62
							Dry periods			
2	1896	1897	715	Neutral	434	El Niño	+24	−25	−49	−47
4	1911	1912	773	La Niña	344	El Niño	+34	−40	−74	−47
6	1922	1923	727	La Niña	339	La Niña[A]	+26	−41	−67	−50
8	1941	1942	629	El Niño	432	El Niño	+9	−25	−34	−23
10	1957	1958	702	La Niña	462	El Niño	+22	−20	−42	−35
12	1977	1978	610	Neutral	462	El Niño	+6	−20	−26	−34
14	1991	1992	852	Neutral	399	El Niño	+48	−31	−78	−36
16	2001	2002	684	La Niña	447	Neutral	+18	−23	−41	−32
18	2012	2013	738	La Niña	518	Neutral	+28	−10	−38	−33

[A]The Dry Period 1923 to 1933 commenced with a very dry year (1922/23) across eastern Australia, despite mostly positive SOI values and a classification as a La Niña year. Other very dry La Niña years include 1964 and 2017 and they resulted in a continuation of their respective Dry periods.

Table 7. Average rain and %Deviation for the first 5 years in each Wet or Dry multi-year sequence
The relationship between the sequence of years in Wet and Dry periods on %Deviation (%Dev) of rainfall from long-term average (131 years, 1889–2020, 577 mm) for Queensland Grazing Lands (Day and McKeon 2018). Year 0 in the sequence is the last year of the previous period and Year 1 is the first year of the new period. The two Average periods (1933–1941 and 1983–1991) have been grouped with the Wet periods.

Sequence	Wet periods			Dry periods			
	Rain	No. of years	%Dev	Sequence	Rain	No. of years	%Dev
0	406	9	−30	0	714	9	+24
1	779	9	+35	1	426	9	−26
2	637	9	+10	2	568	9	−2
3	649	9	+12	3	528	9	−9
4	633	9	+10	4	417	9	−28
5	645	9	+12	5	525	9	−9

between the change in TCEonP and change in rainfall from the previous Wet or Dry period ($y = 5.8 + 1.05x$, $n = 13$, $R^2 = 0.70$, $P < 0.0004$) was stronger than the relationship with rainfall expressed as a %Deviation from LTAAR ($y = 9.8 + 1.59x$, $n = 13$, $R^2 = 0.50$, $P < 0.0072$). Following the devastating severe Dry period (1896–1903), the Wet period (1903–1911) had a very large increase in TCEonP (+125%). When the 1903–1911 period is not included in the above analysis, the correlations between changes in TCEonP and %Deviations in rainfall (either from previous period or from LTAAR) are much greater ($R^2 = 0.88$, $n = 12$, $P < 0.0001$and $R^2 = 0.81$, $n = 12$, $P < 0.00005$ respectively; Fig. 5*b*), highlighting the historical importance of multi-year rainfall on fluctuations in livestock carrying capacity.

For the same 13 Wet and Dry periods, dairy and sheep time series had low or non-significant correlations, suggesting that market and technological changes had stronger influences in fluctuations on numbers than multi-year rainfall variability. However, when only the early periods prior to the long-term declines in dairy and sheep numbers are considered, the correlations were stronger. For example, changes in sheep numbers for the 10 earlier periods (1889–1970) were significantly correlated with %Deviations in previous period rainfall ($R^2 = 0.52$, $n = 10$, $P < 0.0180$). Similarly, changes in dairy cattle numbers for the 9 periods from 1889–1957, were significantly correlated with %Deviation from previous period rainfall ($R^2 = 0.47$, $n = 9$, $P < 0.0410$). Thus, both sheep and dairy time series of livestock numbers also demonstrated the impact of multi-year rainfall

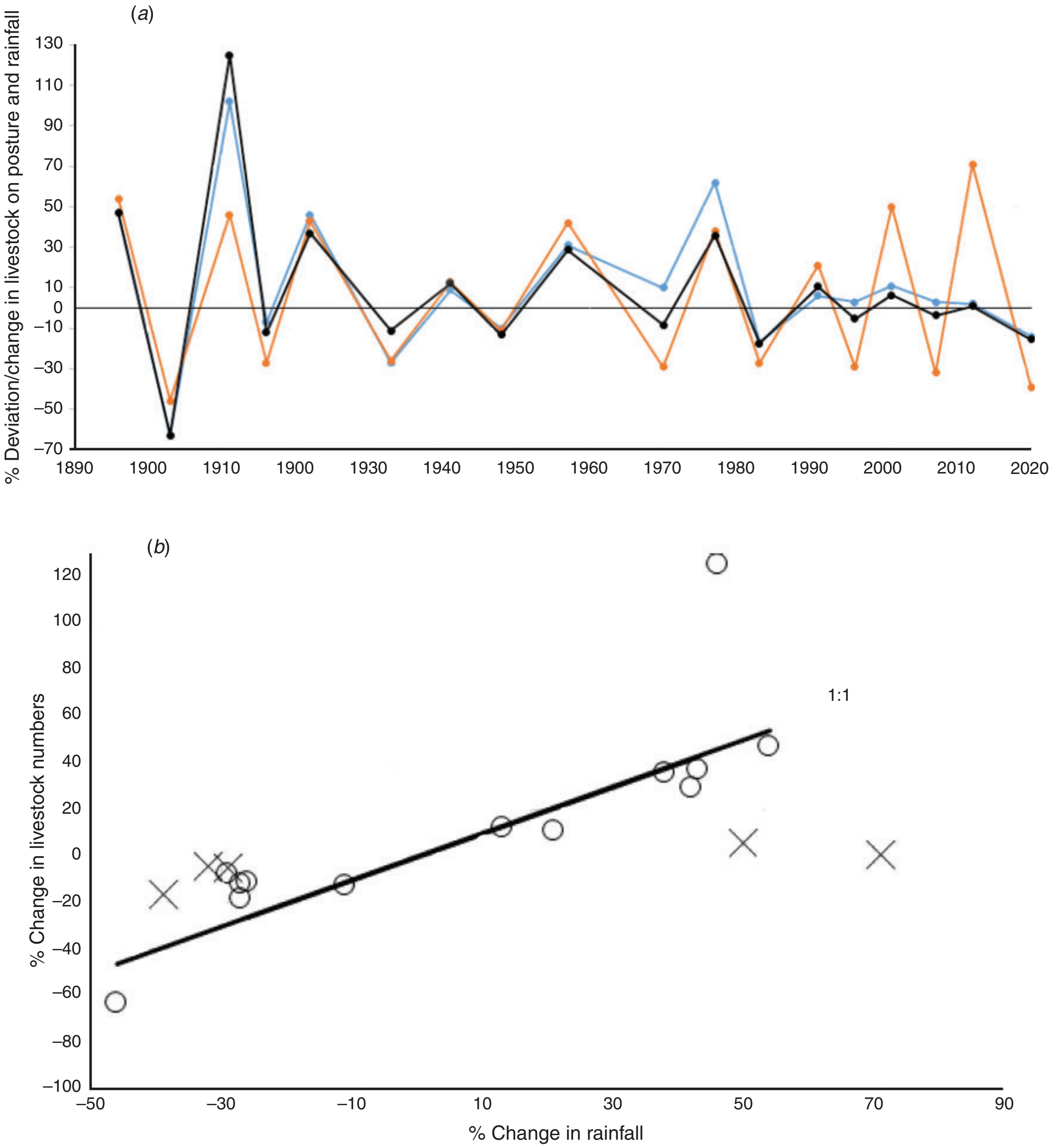

Fig. 5. (*a*) Time series of changes in rainfall (orange line) expressed as % Deviation from previous period, % Changes in beef cattle on pasture (blue line) and % Changes in total cattle equivalents on pasture (TCEonP; black line) over each period. (*b*) Comparison of changes in average rainfall from the previous period for the eighteen Wet and Dry periods, and changes in livestock numbers, expressed as total cattle equivalents on pasture from start to end of each period. The first 13 Wet and Dry periods (1889–1896 to 1983–1991) are represented by open circles (○); The following five Wet and Dry periods (from 1991–1996 to 2012–2020) are represented by (×).

variability, but not as strongly as the time series that included beef cattle.

Rainfall deficiencies of 1- or 2-years within a Wet period (e.g. 1918–1920) were not considered to constitute a break in the overall persistence of the Wet period, as there was an increase in livestock numbers over the period (Fig. 5*a*; Table 3). An important feature in assessing the impact of severe rainfall deficiency is the capacity of cattle and sheep to survive long periods (up to 12 months) on low-quality, senesced pasture. Where perennial grasses and fodder trees still have live (i.e. green) shoots and leaves, small falls of rain (<10 mm/day) can contribute new protein material, aiding rumen digestion of low-quality forage. In addition, the use of supplements (e.g. molasses and urea mixtures) greatly aid the maintenance of herd/flock numbers for periods when no rain occurs, and animals are dependent on senesced forage with low protein concentration (e.g. 1982/83 drought, Wythes and Ernst 1984; Landsberg *et al.* 1998). Thus, individual years with severe rainfall deficiency within a Wet period (e.g. 1918/19–1919/20 drought), while causing deterioration to pasture and livestock condition, did not necessarily represent the start of a longer Dry period, as both the pasture resource and animal numbers recovered in subsequent average or above-average years (e.g. 1921–1922, Fig. 1*b*). Similarly, the severe drought of 1951/52, although resulting in livestock losses, did not halt the overall increase in livestock numbers. Equally, an individual year with above-average rainfall (e.g. 1962/63) was not considered to constitute a break in the Dry period (1957–1970). Although providing some relief to pastures and animals (Ebersohn 1970), the above-average rainfall was considered insufficient to prevent the overall effect of the longer Dry period (Table 3) when followed by a return of 'dry' and 'drought' years (e.g. 1963–1966; Figs. 1*a*, 4).

After the early 1990s, livestock numbers were relatively stable, despite the large variation in rainfall between Wet and Dry Periods, leading to concern regarding the risk of overgrazing in Dry periods. For example, in 2002, the combination of high livestock numbers in Queensland, the emerging Dry Period and the forecast of a developing El Niño, led to a major extension campaign (e.g. Stone *et al.* 2003) to alert the grazing industry and government of the increased risk of land degradation, should cattle prices decline leading to livestock retention. In this instance, cattle prices did remain sufficiently high to allow animals to be sold and/or finished (e.g. through feedlots).

Relationship between multi-year Wet and Dry periods and ENSO

Many studies have recognised the link between ENSO and year-to-year rainfall variability in Queensland (e.g. Pittock 1975; McBride and Nicholls 1983; Allan 1985; Risbey *et al.* 2009; Cobon and Toombs 2013). As well as ENSO, there are several major remote climate drivers also affecting Australian rainfall (Risbey *et al.* 2009, p. 3250), such as blocking, Southern Annular Mode (SAM), and the Indian Ocean Dipole (IOD). For central and northern Queensland, the major climate driver affecting June–February rainfall is ENSO. In south-eastern Queensland, blocking is a more important driver for the autumn (i.e. March–May) and spring (September–November) periods. In southern Australian rangeland regions, the IOD and blocking are the most important drivers affecting rainfall in the winter-spring period (June–November). For June to October rainfall in Queensland, there is a strong interaction between ENSO and the IOD, with above-average rainfall in La Niña and negative IOD years; and below-average rainfall in El Niño and positive IOD years (Risbey *et al.* 2009, p. 3241). However, for QGL, June–October average rainfall is only 21% of the annual average, thus the major climate driver for QGL is ENSO, through its effect on warm season rainfall (as well as the cool season, depending on the interaction with the IOD).

The posters (AVR, QEWDP) and this study use the Southern Oscillation Index (SOI), the atmospheric component of ENSO, to classify individual years as El Niño, Neutral or La Niña. For these ENSO year-types, we have used the same definition as presented in the AVR poster. The El Niño and La Niña year classifications are derived from monthly values of the SOI (calculated using a base period of 1933–1992). An 'El Niño year' is indicated if the 6-month average value of the SOI, ending in any month between November and March, is below a threshold value of negative 6.0; and a 'La Niña' is indicated if the 6-month average value of the SOI, ending in any month between November and March, is above a threshold value of positive 6.0. The remaining years are considered 'ENSO Neutral'. The threshold values of the SOI used in the AVR poster were chosen such that the frequency of El Niño and La Niña years from 1950/51 to 2009/10 was similar to that obtained by the 'WMO RA IV Consensus Index and Definitions of El Niño and La Niña' (NOAA 2005).

Table 4 shows the %Deviation of rainfall for the three ENSO year-types occurring in each Wet or Dry period. For the nine Wet periods over the 63 years, 21% of years were classified as El Niño, 32% as Neutral and 47% as La Niña. In contrast, for the nine Dry periods over the 68 years, there were 40% classified as El Niño, 45% as Neutral and only 15% as La Niña.

Wet periods have been dominated by Neutral and La Niña years (79% of years), with generally above-average rainfall in both year-types. Comparison of La Niña years between Wet and Dry periods indicates that the frequency was three times as great in Wet periods (47%), compared with Dry periods (15%). In contrast, Dry periods are dominated by El Niño and Neutral years (85% of years), with below-average rainfall in both year-types. Not only were there substantial differences in frequency of ENSO year-types between Wet and Dry periods, but the average rainfall in each of the three ENSO year-types was substantially different, when expressed as a %Deviation from long-term annual average rainfall (i.e. LTAAR). Dry-period El Niño years averaged −25% below LTAAR, in contrast to Wet period El Niños which were only −9% below LTAAR ($t = 2.29$, $P < 0.024$); Dry-period Neutral years averaged −12% below LTAAR compared with Wet-period Neutral years, which were +12% above LTAAR ($t = 3.87$, $P < 0.0002$) and Dry-period La Niña years averaged −7% below LTAAR, in contrast to Wet-period La Niñas, which were +33% above LTAAR ($t = 5.22$, $P < 0.000001$).

Over the 18 Wet and Dry periods, there was a strong correlation ($R^2 = 0.7$, $n = 18$, $P < 0.0001$) between QGL rainfall and SOI averaged for the same period (Fig. 6). The major difference in rainfall between Wet and Dry periods was due to both the different frequencies of occurrence of ENSO year-types, and differences in rainfall for each year-type for either Wet or Dry periods (Table 5*a*, *b*). If the frequencies of ENSO year-types had been the same in both Wet and Dry periods, then the Wet periods would have had +12% above-average rainfall, whereas the Dry period would have had −15% below-average rainfall. Alternatively, if ENSO year-type rainfall was the same in both Wet and Dry periods, but frequencies of year-types were different (as observed), then Dry periods would have had −6% below-average rainfall in comparison to +6% above-average for Wet periods.

The above analysis shows that the major influence of ENSO year-types on Wet and Dry rainfall period was that El Niño years have been drier in Dry periods and La Niña years have been wetter in Wet periods. These differences in rainfall and frequency of El Niño and La Niña year-types have been exacerbated or amplified by rainfall in Neutral years for Dry or Wet periods respectively. As discussed in the following section, this finding suggests that ENSO itself is not the only phenomenon affecting Queensland rainfall and that other quasi-decadal and inter-decadal climatic influences should be investigated (e.g. Crimp and Day 2003; White *et al.* 2003). Furthermore, the

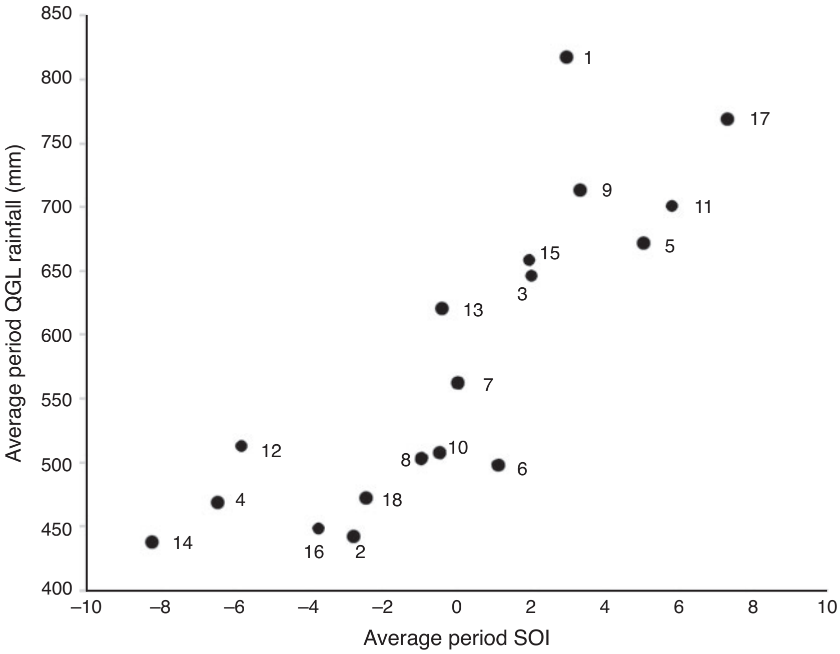

Fig. 6. Relationship between Southern Oscillation Index (SOI) and Queensland Grazing Lands (QGL) rainfall averaged for each of the 18 Wet and Dry periods (1889–2020). The points are labelled with the period number (Table 2).

diversity within ENSO year types (e.g. the type of El Niño) is the subject of current research (e.g. Santoso *et al.* 2019).

First year of each period in relation to ENSO variability

The first 'break year' of each Wet or Dry period has potentially large implications for grazing and financial management, because, by definition the 12-month rainfall at the start of a new period is substantially different to the previous five or more years. Grazing management preparedness would be greatly assisted by climatic indicators of the likely change from Wet to Dry periods (and the converse). For the nine Dry periods, six of the first 'break years' were El Niño years, two Neutral and, perversely, one La Niña (1922/23). For the nine Wet periods, six of the first 'break years' were La Niña years and three were Neutral years (Table 6). No Wet period has started with an El Niño year. For both Wet and Dry periods, the average difference in rainfall between the last year of the previous period and first year of the 'new' period (expressed as %Deviation from LTAAR) was very high (i.e. from −30% to +35% for Dry to Wet periods, and from +24% to −26% for Wet to Dry periods, Table 7), with potentially large effects on pasture growth and livestock production. The %Deviation from average rainfall in subsequent years in Wet periods (Years 2–5; Table 7) was smaller, ranging from +10% to +14%. However, for Dry periods, large %Deviations have also occurred in Year 4 (average of −28%).

Relationships of decadal and inter-decadal variability with Wet and Dry periods

Multi-year variability and the global climate system

Analysis of historical records of global ocean sea surface temperatures (SSTs) and sea level atmospheric pressure (SLP) has indicated variability at different timescales, namely: quasi-biennial, inter-annual, quasi-decadal and inter-decadal (Allan 2000; White *et al.* 2003). White *et al.* (2003, p. 631) showed that QGL warm season (November–March) rainfall included these signals, and found that 'the longer period signals dominate, accounting for the inter-decadal quasi-periodicity of the drought/flood cycle'. They stated that drought depended 'more on the quasi-decadal and inter-decadal signals in the global climate system, than on the inter-annual and quasi-biennial signals' (White *et al.* 2003, p. 633). However, consideration of all four signals was needed to predict the year-to-year changes in QGL rainfall, especially sequences of low rainfall (White *et al.* 2003, p. 633). Thus, the occurrence of multi-year Wet and Dry periods in QGL (Table 2) and other rangeland regions is consistent with this understanding of the different timescale components of the global climate system.

Low frequency (LF) indices representing decadal and multi-decadal variability in the global climate system (after Allan 2000) have been described by Meinke *et al.* (2005). These indices were derived from LF variability in global sea surface temperatures and sea level pressures. To assess the association with rainfall variability (globally), Meinke *et al.* (2005, p. 90) evaluated four series of empirical orthogonal functions (EOF) representing different timescales: (a) 2.5–8.0 year (ENSO); (b) 9–13 year (decadal); (c) 13–18 year (inter-decadal); and (d) 18–39 year (multi-decadal). In addition, they also evaluated the time series of the Inter-decadal Pacific Oscillation (IPO) derived from Pacific Ocean SSTs (Power *et al.* 1999), which includes the 13–18 and 18–39 year timescales (Meinke *et al.* 2005, p. 90). Although the ENSO timescale had the most widespread global association with rainfall, the LF series had statistically significant associations particularly with global rangeland regions in southern and western Africa, western China, eastern Australia and South America.

Meinke *et al.* (2005) reported EOF scores for 1900–1998 (Fig. 7*a–d*), which included 14 of the 18 complete Wet and Dry periods (Table 2). The 14 Wet and Dry periods were most closely associated with the 9–13 year and 13–18 year time-scales (Fig. 7*a*, *b*). For example, Wet periods were associated with strongly negative 9–13 year EOF scores and conversely, Dry periods with strongly positive EOF scores. Rainfall and SOI values averaged for each period were correlated with 9–13 year timescale EOF scores averaged for the same time periods ($R^2 = 0.53$, $n = 14$, $P < 0.0071$ and $R^2 = 0.50$, $n = 14$, $P < 0.0107$ respectively). Overall, the above analyses support the suggestions of White *et al.* (2003) and Meinke *et al.* (2005) that quasi-decadal variability modulates ENSO frequency and amplitude effects on rainfall. Thus, the variation in average rainfall across the 18 Wet and Dry periods, which is strongly correlated with ENSO variability (i.e. SOI; Fig. 6), is linked to LF variability in the global climate system through modulation of ENSO. As such, LF variability (e.g. 9–13 year timescale) should be seen as an additional source of climatic risk in the same way that ENSO has been recognised and considered in grazing management decisions (e.g. McIntosh *et al.* 2005; Marshall 2008; Cobon and Toombs 2013; Partridge 2017).

Interaction of ENSO year-types and phases of Inter-decadal Pacific Oscillation

In this section, we analyse the interaction of ENSO and the Inter-decadal Pacific Oscillation with regard to their association with rainfall in Wet and Dry periods. The IPO represents large decadal changes in Pacific Ocean sea surface temperatures (e.g. Power *et al.* 1999; Folland *et al.* 2002; Henley *et al.* 2015). The IPO is a smoothed index ‘with high-frequency components removed by using a low-pass filter with a 13-yr cut-off, and thus includes both the (Fig. 7*b*) 13–18- and (Fig. 7*c*) 18–39-year time scales’ (Meinke *et al.* 2005, p. 90).

Previous analyses of decadal variability in Queensland and eastern Australian rainfall (Power *et al.* 1999; Crimp and Day 2003; McKeon *et al.* 2004; King *et al.* 2013; Klingaman *et al.* 2013) have shown the importance of phases of the Inter-decadal Pacific Oscillation (IPO positive, IPO negative; King *et al.* 2013) and their interaction with the ENSO phenomenon. McKeon *et al.* (2004) reviewed the emerging understanding of how global climate phenomena (ENSO and IPO) have affected eastern Australian rangelands from the early 1890s to the late 1990s.

In general, above-average rainfall has occurred in regions of eastern and central Australia, especially during IPO negative phases (1889–1894, 1909–1912, 1944–1976, 1999–2012) and La Niña years. In contrast, the extended positive phases of the IPO (1895–1908, 1913–1943, 1977–1998) have been associated with fewer La Niñas and periods of lower rainfall (e.g. Fig. 7*d*). From 1889–2012, in IPO-negative years (56 years) there were 24 La Niñas (43% of years), in contrast to the IPO-positive periods (67 years) with 15 La Niñas (22% of years). Multiple regressions combining indices of IPO (e.g. Pacific Decadal Oscillation, PDO; Mantua and Hare 2002) and ENSO have accounted for a high proportion of year-to-year variation in warm season QGL rainfall (e.g. 33–45%; Crimp and Day 2003, p. 111) and ‘visually’ multi-year (5-year moving average) variability (Crimp and Day 2003, p. 113).

The IPO is a smoothed index and hence the values for the most recent 6-7 years are uncertain (e.g. King *et al.* 2013). For this reason in the following analysis, only IPO values from 1889/90 to 2011/12 were used. Over the 123 years, the 24 La Niña – IPO negative years averaged +30% above long-term average rainfall. In contrast, the 15 La Niña – IPO positive years had +15% above-average rainfall. Twenty-one of the 24 La Niña – IPO negative years which were in Wet periods had +37% above-average rainfall. In addition, the six Neutral – IPO negative years had +22% above-average rainfall. In the Dry periods, there have been only three La Niña – IPO negative years and these years (on average) had below-average rainfall (−16%). The four ‘wettest’ Wet periods have been dominated by the frequency of La Niña – IPO negative and Neutral – IPO negative years (1889–1896, 1948–1957, 1970–1977 and 2007–2012; Table 2). These periods had multi-year conditions suitable for livestock increase, and pasture resource recovery where overgrazing had previously occurred. Thus, La Niña – IPO negative and associated Neutral ENSO year-types have been an important component of the resilience and development of Queensland livestock industries and the recovery of the pasture resource.

The interaction of ENSO and IPO (and other decadal and inter-decadal components of the climate system) is still a subject of debate (e.g. Meinke *et al.* 2005; Power *et al.* 2006; Jin *et al.* 2020). Mechanistic models of quasi-decadal variability in Pacific Ocean sea surface temperatures have been proposed (e.g. Jin *et al.* 2020). The 11-year solar cycle has been suggested as a possible external driver, however, the timescales of the Wet and Dry periods (average 7 and 8 years respectively) indicate that variation in climate forcings at longer inter-decadal time-scales need also to be considered.

Summary and discussion

The ‘Queensland’s Extended Wet and Dry Periods’ (QEWDP) poster was produced to meet a perceived need to better understand the earlier ‘Australia’s Variable Rainfall’ (AVR) poster. While the initial presentation of 130 years of annual rainfall variability highlighted year-to-year rainfall variation, the QEWDP poster shows multi-year impacts, particularly extended droughts (Stone *et al.* 2019; Irvine 2021) and degradation episodes (e.g. McKeon *et al.* 2004). The popularity of both posters has indicated the demand for educational information on historical rainfall variability. The qualitative and quantitative classification of ‘12-month’ rainfall into multi-year Wet and Dry periods (ranging from 5 to 13 years) has highlighted the historical impacts that had been caused by multi-year Wet and Dry periods (Daly 1994; McKeon *et al.* 2004; Stone 2004).

Strategic and tactical approaches to grazing management

There have been several approaches used by graziers to manage for multi-year rainfall variability: (a) conservative pasture utilisation allowing stability in livestock numbers, especially the breeding nucleus (Scanlan *et al.* 1994; Johnston *et al.* 1996); and (b) tactical stocking rate responses to varying forage availability (e.g. Cobon *et al.* 1997; Ash *et al.* 2000, 2002, 2011; Aisthorpe *et al.* 2004; O’Reagain *et al.* 2014). The adoption of a long-term strategy of conservative pasture utilisation minimises the impact

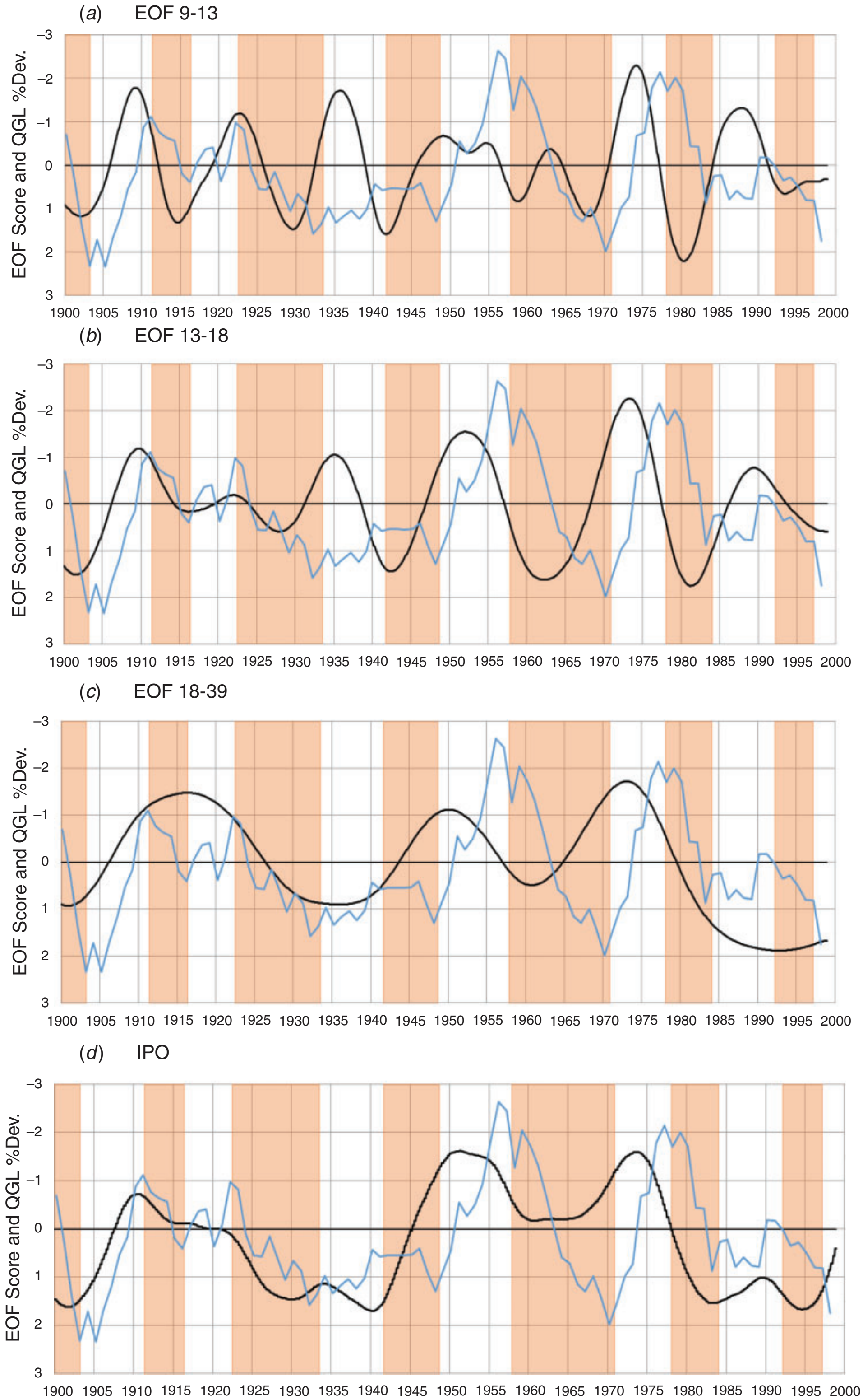

Fig. 7. Comparison of Dry (orange) or Wet periods (blank), 7-year moving average of Queensland Grazing Lands (QGL) rainfall (blue line), and Empirical Orthogonal Function (EOF) scores (black line) for: (*a*) EOF 9–13 year (decadal timescale); (*b*) scores for EOF 13–18 year (inter-decadal timescale); (*c*) scores for EOF 18–39 year (multi-decadal timescale); and (*d*) IPO (inter-decadal timescale) from Meinke *et al.* (2005). Note: Queensland Grazing Lands (QGL) rainfall is shown as a %Deviation (QGL %Dev.; scaled by dividing by 10). The *y*-axis has been inverted for EOF scores to align with the sign of rainfall deviations (e.g. shading for Dry periods and positive EOF scores).

of dry periods (e.g. Johnston *et al.* 1996; Landsberg *et al.* 1998; Stone 2004; Stone *et al.* 2021; Zhang *et al.* 2021). Such a strategy reduces the need for large yearly decreases in livestock numbers and/or drought feeding in response to below-average rainfall. Long-term (>10-years) grazing trials comparing stocking rate and/or utilisation levels have demonstrated the pasture resource and financial benefits of conservative (or moderate) pasture use (e.g. Orr 2005; Phelps 2012; O'Reagain *et al.* 2014; O'Reagain *et al.* 2018). In addition, long-term grazing trials (e.g. Wambiana Grazing Trial; O'Reagain *et al.* 2018, p. 18) have shown that 'moderate' stocking rates around a long-term carrying capacity have reduced the number of 'interventions' (i.e. destocking or drought feeding) in response to inevitable periods of low rainfall and associated pasture growth.

Interactions of Wet and Dry periods with pasture and livestock production

Multi-year Wet periods have also been the major periods of livestock number increase, (Table 3; Fig. 5*a*, *b*) which have been on average twice (+34%) the average of reductions in Dry periods (−17%, Table 3). The extended Wet conditions have provided opportunities for increased pasture growth, pasture resource recovery, expansion of grazed areas, and pasture burning to suppress woody plant regrowth. In addition, the multi-year periods of increased pasture growth have supported greater livestock production (including higher reproduction, liveweight gain, wool growth, and lower mortalities). However, increases in livestock performance necessarily provide 'pressure' to increase livestock carrying capacity leading to heavy pasture utilisation during individual years of low rainfall within the Wet periods. For example, Table 4 indicates that El Niño years have occurred in Wet periods 20% of the time. Rainfall has been −9% (527 mm) of long-term average (577 mm) and −27% below the average of the other year-types (i.e. Neutral and La Niña) years (527/720 mm) in the Wet periods. As a consequence, overgrazing can even occur in individual dry years within Wet periods (e.g. 1951/52, 1972/73) and hence, a reduction in stocking rate is recommended (O'Reagain *et al.* 2018, p. 90).

Detailed studies have shown that perennial tussock grasses have been particularly vulnerable to heavy utilisation during 'dry' growing seasons (Scattini 1973; Hodgkinson 1995; D.M. Orr pers. comm. cited by McKeon *et al.* 2004, p. 70). Thus, the retention of high livestock numbers through 'dry' growing seasons within an overall Wet period increases the likely damaging impact on palatable perennial grasses and can affect pasture production in the subsequent Dry period (e.g. Ash *et al.* 2002, 2011). In addition, the severity of the first years of the nine Dry periods (average −37% of previous Wet period) was likely to have caused damage to perennial pasture plants at the start of the Dry period and reduced the chance of recovery for several years.

Interactions of Wet and Dry periods with social and financial impacts

The classification of 18 multi-year Wet and Dry periods highlights that a major feature of the climate of QGL is the inevitability of Dry periods following Wet periods. Hence, the danger of Wet periods (ranging from 5 to 9 years) is that managers of grazing enterprises may have biased expectations of higher livestock carrying capacity, leading to degradation episodes (McKeon *et al.* 2004), as have occurred in different rangeland regions during dry periods in eastern Australia (e.g. 1896–1903, 1922–1933, 1957–1970 and 1977–1983) and western Australia (1935–1940). 'Collapses' in prices received for livestock (cattle and sheep) and wool have exacerbated the retention of animals, in particular where there have been sharp decreases in prices, for example: wool – 1925 to 1930 (Payne and McLean 1939); and 1991 – after the demise of the wool reserve price scheme (Bardsley 1994); and for cattle – 1975, after the collapse of the USA export beef market (McKeon *et al.* 2004, p. 64; Fordyce *et al.* 2021). Under such circumstances, there have been few options for income from livestock production available to graziers, leading to financial and physical hardship (e.g. McCartney 2017; Paxton 2019), including enterprise failure. Purchase of properties for livestock grazing also represents a particular risk, if early-stage repayments (of principal and interest) coincide with the start of a Dry period, making economic survival of the grazing enterprise precarious.

The economic and natural resource impacts of drought can also be exacerbated with social hardship on pastoralists and rural communities (Cobon *et al.* 2017). Drought has been recognised as an important factor in divorce, suicide, and illness in pastoral areas (Munro and Lembit 1997; McCartney 2017; Paxton 2019), where often decisions are made under stress without consideration of the implications for families. There can be a lack of consideration of how business and family are intricately linked for the majority of farm families, and an absence of planning for business and family decision-making (Drought Policy Review Expert Social Panel 2008).

In recognition of the importance of social hardship, the Australian Government introduced the Farm Household Allowance in July 2014 to provide income support to families in financial hardship, including those suffering loss of income due to drought. To further help the grazing industry transition from crisis management to risk management of drought would require understanding (and forecasting) the onset and duration of Wet and Dry periods (also known as the 'hydrological cycle'; Wilhite 2002), and making livestock management decisions to break the 'hydro-illogical cycle' (Wilhite 2011). In addition, the social impacts on people including emotions, feelings, anxiety, pressures of people, relationship breakdown need to be addressed (Cobon *et al.* 2017; McCartney 2017; Paxton 2019).

Conclusion

The identification of multi-year Wet and Dry periods (Table 2) suggests that the different components of the global climate system (ENSO, IPO, quasi-decadal variability) have interacted to produce the observed high multi-year variability (White *et al.* 2003; Meinke *et al.* 2005). This variability has been a major challenge to grazing managers (e.g. Daly 1994; Landsberg *et al.* 1998; Stone 2004; Ash *et al.* 2007) with potential for enterprise failure and social distress (McCartney 2017; Paxton 2019). The key decision for many graziers is what livestock management options to act upon, in response to severe rainfall deficit (e.g. sell, feed, or agist). The financial, health and social implications of managers' decisions are different for a single-year drought in contrast to multi-year droughts. However, climate science is yet to develop an operational capability to discriminate between (a) a single year of severe rainfall deficit, or (b) the start of a new multi-year Dry period.

Without such a multi-year forecasting capability, our analysis supports the adoption of 'long-term carrying capacity' (Johnston *et al.* 1996; Stone *et al.* 2021; Zhang *et al.* 2021) that reduces the impact of single-year dry/drought events, by maintaining a 'buffer' in the pasture resource. Conservative pasture resource use 'buys time' to consider whether a multi-year dry period is developing or not. Similarly, the early commencement of destocking through sales and/or agistment protects the 'buffer' that is required to support the breeding nucleus as long as possible – and develops the motivation to further respond to emerging drought years should they occur.

The relationship between rainfall and rangeland livestock numbers has been recognised worldwide (e.g. Kgosikoma 2006; Oliva *et al.* 2012; Sloat *et al.* 2018). This paper has further examined the relationship between multi-year variability in rainfall and livestock carrying capacity in Queensland's grazing lands. The classification approach developed here is applicable to other global rangeland regions with high multi-year rainfall variability. The key features of the approach have been: (a) identification of climatic regions consistent with meteorological understanding of air masses (e.g. Day and McKeon 2018) and remote climate drivers (e.g. Risbey *et al.* 2009); (b) review of historical drought episodes to indicate changes in rainfall between Wet and Dry Periods that affect grazing enterprises and pasture resource management (e.g. Daly 1994; Irvine 2021); and (c) documentation of successful experience in property and resource management (e.g. Landsberg *et al.* 1998; Stone 2004). The overall results of this approach have been a better understanding of historical climate risk, the need for multi-year strategic as well as tactical management, and the encouragement of climate science to develop operational monitoring and predictive systems of multi-year variability in rainfall.

Conflicts of interest

The authors declare no conflicts of interest.

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References

ABS (Australian Bureau of Statistics) (2013). 7124.0 – Historical Selected Agriculture Commodities, by State (1861 to Present), 2010-11. https://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/7124.02010-11?OpenDocument [accessed 17 June 2021].

ABS (Australian Bureau of Statistics) (2021). Agriculture. Available at https://www.abs.gov.au/Agriculture [accessed 17 June 2021].

Aisthorpe, J. L., Paton, C. J., and Timmers, P. K. (2004). Stocktake – a paddock-scale grazing land monitoring and management package. *In*: 'Australian Rangeland Society 13th Biennial Conference Papers'. 5–8 July 2004, Alice Springs, NT. (Eds G. Bastin, D. Walsh and S. Nicolson.) pp. 379–380. (Australian Rangeland Society: Alice Springs, NT, Australia.)

ALFA (Australian Lot Feeders Association) (2021). Industry figures. Available at https://www.feedlots.com.au/figures [accessed 17 June 2021].

Allan, R. J. (1985). 'The Australasian Summer Monsoon, Teleconnections, and Flooding in the Lake Eyre Basin.' (Royal Geographical Society of Australasia, SA Branch: Adelaide.)

Allan, R. J. (2000). ENSO and climatic variability in the last 150 years. *In*: 'El Niño and the Southern Oscillation: Multiscale Variability, Global and Regional Impacts'. (Eds H. F. Diaz and V. Markgraf.) pp. 3–55. (Cambridge University Press: Cambridge, UK.)

Anon. (1996). Surviving the Drought 'returning to profitability'. Attachment to Submission No. 00585, Queensland Department of Primary Industries.

ANZECC and ARMCANZ (Australian and New Zealand Environment Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand) (1999). 'National Principles and Guidelines for Rangelands Management.' (Australian Government: Canberra.)

Ash, A. J., O'Reagain, P. J., McKeon, G. M., and Stafford Smith, M. (2000). Managing Climate Variability in Grazing Enterprises: A Case Study for Dalrymple Shire. *In*: 'Applications of Seasonal Climate Forecasting in Agricultural and Natural Ecosystems, The Australian Experience'. (Eds G. L. Hammer, N. Nicholls and C. Mitchell.) pp. 254–70. (Kluwer Academic Press: Dordrecht, The Netherlands.)

Ash, A. J., Corfield, J. P., and Ksiksi, T. (2002). 'The Ecograze Project: Developing Guidelines to Better Manage Grazing Country.' (CSIRO Sustainable Ecosystems: Townsville, Qld).

Ash, A., McIntosh, P., Cullen, B., Carberry, P., and Smith, M. S. (2007). Constraints and opportunities in applying seasonal climate forecasts in agriculture. *Australian Journal of Agricultural Research* **58**, 952–965. doi:10.1071/AR06188

Ash, A. J., Corfield, J. P., McIvor, J. G., and Ksiksi, T. S. (2011). Grazing management in tropical savannas: utilization and rest strategies to manipulate rangeland condition. *Journal of Rangeland Ecology Management* **64**, 223–239. doi:10.2111/REM-D-09-00111.1

Bardsley, E. (1994). The collapse of the Australian wool reserve price scheme. *Economic Journal* **104**, 1087–1105. doi:10.2307/2235066

Barnard, A. (1958). 'The Australian Wool Market 1840–1900.' (Melbourne University Press: Melbourne: Vic.)

Beadle, N. C. W. (1948). 'The Vegetation and Pastures of Western New South Wales with Special Reference to Soil Erosion.' (Government Printer: Sydney, NSW.)

Carter, J. O., Hall, W. B., Day, K. A., Brook, K. D., McKeon, G. M., and Paull, C. J. (2000). AussieGRASS: Australian Grassland and Rangeland Assessment by Spatial Simulation. *In*: 'Applications of Seasonal Climate Forecasting in Agricultural and Natural Ecosystems. The Australian Experience'. (Eds G. L. Hammer, N. Nicholls and C. Mitchell.) pp. 229–249. (Kluwer Academic Press: Dordrecht, The Netherlands.)

Cobon, D., and Toombs, N. (2013). Forecasting rainfall based on the Southern Oscillation Index phases at longer lead-times in Australia. *The Rangeland Journal* **35**, 373–383. doi:10.1071/RJ12105

Cobon, D. H., Pinington, G., and Scott, Q. B. (1997). GrazeOn – A pasture budgeting strategy for native grasslands. *In*: 'Proceedings of the 18th

International Grasslands Congress'. Winnipeg and Saskatoon, Canada. (Eds J. G. Buchanan-Smith, L. D. Bailey, P. McCaughey.) pp. 141–142. (The Congress 1997.)

Cobon, D. H., Baethgen, W. E., Landman, W., Williams, A., Archer van Garderen, E., Johnston, P., Malherbe, J., Maluleke, P., Kgakatsi, I. B., and Davis, P. (2017). Agro-climatology in grasslands. *In*: 'Agroclimatology: Linking Agriculture to Climate'. (Eds J. L. Hatfield, J. H. Prueger, M. V. K. Sivakumar.) pp. 369–423. (American Society of Agronomy.) doi:10.2134/agronmonogr60

Cobon, D. H., Kouadio, L., Jarvis, C., Mushtaq, S., and Davis, P. (2019). Evaluating the shifts in rainfall and pasture growth variabilities across the Pastoral zone of Australia during the 1910–2010 period. *Crop & Pasture Science* **70**, 634–647. doi:10.1071/CP18482

Crimp, S. J., and Day, K. A. (2003). Evaluation of multi-decadal variability in rainfall in Queensland using indices of El Niño- Southern Oscillation and inter-decadal variability. *In*: 'Science for Drought: Proceedings of the National Drought Forum'. Brisbane, Qld, Australia. (Eds R. Stone and I. Partridge.) pp. 106–114. (Queensland Department of Primary Industries: Brisbane.)

Daly, J. J. (1983). The Queensland beef industry from 1930 to 1980: lessons from the past. *Queensland Agricultural Journal* **109**, 61–97.

Daly, J. J. (1994). 'Wet as a shag, dry as a bone.' (Queensland Department of Primary Industries: Brisbane.)

Daly, J. J., and Dudgeon, G. S. (1987). Drought Management reduces degradation. *Queensland Agricultural Journal* **113**, 45–49.

Day, K. A., and McKeon, G. M. (2018). An index of summer rainfall for Queensland's grazing lands. *Journal of Applied Meteorology and Climatology* **57**, 1623–1641. doi:10.1175/JAMC-D-17-0148.1

Day, K., Ahrens, D., and McKeon, G. (2003). Simulating historical droughts: some lessons for drought policy. *In*: 'Science for Drought, Proceedings of the National Drought Forum, Brisbane'. April 2003. (Eds R. Stone and I. Partridge.) pp. 141–151. (Queensland Department of Primary Industries.)

Derrick, J. (1977). The Great West African Drought, 1972–1974. *African Affairs* **76**, 537–586. doi:10.1093/oxfordjournals.afraf.a096899

DES (Department of Environment and Science) (2020). 2021 Quota Submission for Commercially Harvested Macropods in Queensland. Macropod Management Program.' (Queensland Parks and Wildlife Services and Partnerships, Department of Environment and Science: State of Queensland: Brisbane.)

Drought Policy Review Expert Social Panel (2008). It's About People: Changing Perspective. A Report to Government by an Expert Social Panel on Dryness. Report to the Minister for Agriculture, Fisheries and Forestry, Canberra, Australia.

Ebersohn, J. P. (1970). Herbage production from native grasses and sown pastures in southwest Queensland. *Tropical Grasslands* **4**, 37–41.

Fatichi, S., Ivanov, V. Y., and Caporali, E. (2012). Investigating interannual variability of precipitation at the global scale: Is there a connection with seasonality? *Journal of Climate* **25**, 5512–5523. doi:10.1175/JCLI-D-11-00356.1

Foley, J. C. (1957). Droughts in Australia: review of records from earliest years of settlement to 1955. Bulletin No. 43. Bureau of Meteorology. Commonwealth of Australia, Melbourne.

Folland, C. K., Renwick, J. A., Salinger, M. J., and Mullan, A. B. (2002). Relative influences of the Inter-decadal Pacific Oscillation and ENSO on the South Pacific Convergence Zone. *Geophysical Research Letters* **29**, 1643. doi:10.1029/2001GL014201

Fordyce, G., Shephard, R., Moravek, T., and McGowan, M. (2021). Australian cattle herd: a new perspective on structure, performance and production. *Animal Production Science*. doi:10.1071/AN20342

Gardener, C. J., McIvor, J. G., and Williams, J. C. (1990). Dry tropical rangelands: Solving one problem and creating another. *Proceedings of the Ecological Society of Australia* **16**, 279–286.

Gibbs, W. J., and Maher, J. V. (1967). Rainfall deciles and drought indicators. Bureau of Meteorology Bulletin No. 48.

Hall, W. B. (1996). Near real-time financial assessment of the Queensland wool industry on a regional basis. PhD thesis, Gatton College, University of Queensland, Brisbane, Australia.

Heathcote, R. L. (1965). 'Back of Bourke, Study of Land Appraisal and Settlement in Semi-Arid Australia.' (Melbourne University Press: Melbourne.)

Henley, B. J., Gergis, J., Karoly, D. J., Power, S. B., Kennedy, J., and Folland, C. K. (2015). A tripole index for the interdecadal Pacific oscillation. *Climate Dynamics* **45**, 3077–3090. doi:10.1007/s00382-015-2525-1

Hodgkinson, K. C. (1995). A model for perennial grass mortality under grazing. *In*: 'Rangelands in a Sustainable Biosphere. Proceedings of the Vth International Rangeland Congress. Vol. I'. (Ed. N. E. West.) pp. 240–241. (Society for Range Management: Denver, CO, USA.)

Irvine, S. A. (2016). Mapping historical livestock grazing pressure in Queensland. *Proceedings of the Royal Society of Queensland* **121**(3), 23–37.

Irvine, S. A. (2021). Mapping drought declaration areas from 1936 to 1964 for Queensland, Australia. *The Rangeland Journal* **43**, In Press.

Jeffrey, S. J., Carter, J. O., Moodie, K. B., and Beswick, A. R. (2001). Using spatial interpolation to construct a comprehensive archive of Australian climate data. *Environmental Modelling & Software* **16**(4), 309–330. doi:10.1016/S1364-8152(01)00008-1

Jin, C., Wang, B., and Liu, J. (2020). Emerging Pacific quasi-decadal oscillation over the past 70 years. *Geophysical Research Letters* **48**(2), 1–11.

Johnston, P. W., McKeon, G. M., and Day, K. A. (1996). Objective 'safe' grazing capacities for southwest Queensland, Australia: development of a model for individual properties. *The Rangeland Journal* **18**, 244–258. doi:10.1071/RJ9960244

Kgosikoma, O. E. (2006). Effects of climate variability on livestock population dynamics and community drought management in Kgalagadi, Botswana. MSc thesis, Norwegian University of Life Sciences, Norway.

King, A. D., Alexander, L. V., and Donat, M. G. (2013). Asymmetry in the response of eastern Australia extreme rainfall to low-frequency Pacific variability. *Geophysical Research Letters* **40**, 2271–2277. doi:10.1002/grl.50427

Klingaman, N. P., Woolnough, S. J., and Syktus, J. (2013). On the drivers of inter-annual and decadal rainfall variability in Queensland, Australia. *International Journal of Climatology* **33**, 2413–2430. doi:10.1002/joc.3593

Landsberg, R. G., Ash, A. J., Shepherd, R. K., and McKeon, G. M. (1998). Learning from history to survive in the future: Management evolution on Trafalgar Station, north-east Queensland. *The Rangeland Journal* **20**, 104–118. doi:10.1071/RJ9980104

Lauder, A. (2008). 'Carbon Grazing: The Missing Link.' (Saltbush Systems Pty Ltd: The Gap, Qld.)

Lough, J. M. (1991). Rainfall variations in Queensland, Australia: 1891–1986. *International Journal of Climatology* **11**, 745–768.

Mantua, N. J., and Hare, S. R. (2002). The Pacific Decadal Oscillation. *Journal of Oceanography* **58**, 35–44. doi:10.1023/A:1015820616384

Marshall, N. A. (2008). 'Enhancing Social Resilience to Climate Variability Using Seasonal Climate Forecasts. National Research Flagships, Climate Adaptation.' (CSIRO Sustainable Ecosystem: Townsville, Qld.)

McBride, J. L., and Nicholls, N. (1983). Seasonal relationships between Australian rainfall and the Southern Oscillation. *Monthly Weather Review* **111**, 1998–2004. doi:10.1175/1520-0493(1983)111<1998:SRBARA>2.0.CO;2

McCartney, F. (2017). 'Factors limiting decision making for improved drought preparedness and management in Queensland grazing enterprises: rural specialists' perspectives and suggestions.' (Department of Science, Information Technology and Innovation (DSITI): Brisbane.)

McIntosh, P. C., Ash, A. J., and Stafford Smith, M. (2005). From oceans to farms: the value of novel statistical climate forecast for agricultural management. *Journal of Climate* 4287–4302. doi:10.1175/JCLI3515.1

McIvor, J. G. (2010). Enhancing adoption of improved grazing and fire management practices in northern Australia: synthesis of research and identification of best bet management guidelines. Meat and Livestock Australia Final Report Project B.NBP.0579. Meat and Livestock Australia, North Sydney, NSW.

McKeon, G. M., Hall, W. B., Crimp, S. J., Howden, S. M., Stone, R. C., and Jones, D. A. (1998). Climate change and Queensland's grazing lands: I. Approaches and climatic trends. *The Rangeland Journal* **20**, 151–176. doi:10.1071/RJ9980151

McKeon, G. M., Hall, W. B., Henry, B. K., Stone, G. S., and Watson, I. W. (2004). Pasture degradation and recovery in Australia's rangelands: Learning from History. Queensland Department of Natural Resources, Mines and Energy. Available at: https://www.longpaddock.qld.gov.au/other-products/learning-from-history/ (accessed 19 August 2020)

McKeon, G. M., Stone, G. S., Syktus, J. I., Carter, J. O., Flood, N. R., Ahrens, D. G., Bruget, D., Chilcott, C. R., Cobon, D. H., Cowley, R. A., Crimp, S. J., Fraser, G. W., Howden, S. M., Johnston, P. W., Ryan, J. G., Stokes, C. J., and Day, K. A. (2009). Climate change impacts on northern Australian rangeland livestock carrying capacity: a review of issues. *The Rangeland Journal* **31**, 1–29. doi:10.1071/RJ08068

Meinke, H., deVoil, P., Hammer, G. L., Power, S. B., Allan, R., Stone, R. C., Folland, C. K., and Potgieter, A. (2005). Rainfall variability at decadal and longer time scales: signal or noise. *Journal of Climate* **18**, 89–96. doi:10.1175/JCLI-3263.1

Miller, F. L., Alexander, G. I., and Mawson, W. F. Y. (1973). 'Drought in Queensland: a farm survey into the effects of the 1964–66 drought.' (CSIRO and Queensland Department of Primary Industries: Canberra.)

Mortiss, P. D. (1995). The environmental issues of the Upper Burdekin Catchment. Project report Q095017, Queensland Department of Primary Industries and Land and Water Resources Research and Development Corporation.

Mott, J. J., and Tothill, J. C. (1993). Degradation of savanna woodlands in Australia. *In*: 'Conservation Biology in Australia and Oceania'. (Eds C. Moritz and J. Kikkawa.) pp. 115–130. (Surrey Beatty & Sons: Chipping Norton, NSW.)

Munro, R. K., and Lembit, M. J. (1997). Managing climate variability in the national interest: need and objectives. *In*: 'Climate Prediction for Agriculture and Resource Management'. (Eds R. K. Munro and L. M. Leslie.) pp. 3–20. (Bureau of Resource Sciences: Canberra.)

NOAA (2005). NOAA: World Meteorological Organisation Region IV Adopts Consensus El Niño and La Niña Index and Definitions. Press Release, 28 April 2005. Available at: https://wfile.ait.org.tw/wf-archive/2005/050428/epf413.htm

O'Reagain, P. J., Scanlan, J., Cowley, R., Hunt, L., and Walsh, D. (2014). Sustainable grazing management for temporal and spatial variability in north Australian rangelands – a synthesis of the latest evidence and recommendations. *The Rangeland Journal* **36**, 223–232. doi:10.1071/RJ13110

O'Reagain, P., Bushell, J., Pahl, L., and Scanlan, J. (2018). Wambiana Grazing Trial Phase 3: Stocking Strategies for Improving Carrying Capacity, Land Condition and Biodiversity Outcomes. Meat and Livestock Australia Final Report to Project B.ERM.0107 Meat & Livestock Australia, North Sydney, NSW.

Oliva, G., Ferrante, D., Puig, S., and Williams, M. (2012). Sustainable sheep management using continuous grazing and variable stocking rates in Patagonia: a case study. *The Rangeland Journal* **34**, 285–295. doi:10.1071/RJ12016

Orr, D. (2005). Effects of stocking rate, legume augmentation, supplements and fire on animal production and stability of native pastures. Meat and Livestock Australia Final Report to Project NAP3.207 Meat & Livestock Australia, North Sydney, NSW.

Partridge, I. (2017). Will it rain? The effects of El Niño and the Southern Oscillation on Australia'. 4th edn. (University of Southern Queensland: Toowoomba.) Available at: https://www.usq.edu.au/-/media/USQ/Research/Strengths/Environmental-sciences/QDMC-drought/Will-it-rain.ashx

Paxton, G. (2019). 'Towards greater drought preparedness in Queensland grazing: Lessons from qualitative interviews and discourse analysis.' (Department of Environment and Science, Queensland Government: Brisbane.)

Payne, W. L., and McLean, W. M. (1939). 'Report of the wool advisory commission appointed to inquire into the economic condition of the wool industry in Queensland.' (Queensland Government Printer: Brisbane.)

Phelps, D. (2012). 'Best-bet practices for managing the Mitchell grasslands of Queensland: A technical guide of options for optimising animal production, profitability and land condition.' (Department of Employment, Economic Development and Innovation: Longreach, Qld, Australia.)

Pittock, A. B. (1975). Climatic change and the patterns of variation in Australian rainfall. *Search* **6**, 498–504.

Power, S., Casey, T., Folland, C., Colman, A., and Mehta, V. (1999). Inter-decadal modulation of the impact of ENSO on Australia. *Climate Dynamics* **15**, 319–324. doi:10.1007/s003820050284

Power, S. B., Haylock, M. H., Colman, R., and Wang, X. (2006). The predictability of interdecadal changes in ENSO activity and ENSO teleconnections. *Journal of Climate* **19**, 4755–4771. doi:10.1175/JCLI3868.1

Pressland, A. T., and McKeon, G. M. (1990). Monitoring animal numbers and pasture condition for drought administration: an approach. In 'Proceedings of the Australian Soil Conservation Conference'. May 1990, Perth. (Eds G. J. Hamilton, K. M. Howes and R. Attwater.) pp. 17–27. (Department of Agriculture: Canberra, Australia.)

Ratcliffe, F. N. (1936). 'Soil drift in the arid pastoral areas of South Australia. Pamphlet 64.' (Council for Scientific and Industrial Research, Government Printer: Canberra.)

Risbey, J. S., Pook, M. J., McIntosh, P. C., Wheeler, M. C., and Hendon, H. H. (2009). On the remote drivers of rainfall variability in Australia. *Monthly Weather Review* **137**, 3233–3253. doi:10.1175/2009 MWR2861.1

Russell, J. S. (1981). Geographic variation in seasonal rainfall in Australia. *Journal of the Australian Institute of Agricultural Science* **47**, 59–66.

Santoso, A., Hendon, H., Watkins, A., *et al.* (2019). Dynamics and predictability of the El Niño–Southern Oscillation: An Australian perspective on progress and challenges. *Bulletin of the American Meteorological Society* **100**, 403–420. doi:10.1175/BAMS-D-18-0057.1

Scanlan, J. C., McKeon, G. M., Day, K. A., Mott, J. J., and Hinton, A. W. (1994). Estimating safe carrying capacities in extensive cattle grazing properties within tropical semi-arid woodlands of north-eastern Australia. *The Rangeland Journal* **16**, 64–76. doi:10.1071/RJ9940064

Scattini, W. J. (1973). A model for beef cattle production from rangeland and sown pasture in south–eastern Queensland, Australia. PhD thesis, University of California, Berkeley, CA, USA.

Sloat, L. L., Gerber, J. S., Samberg, L. H., Smith, W. K., Herrero, M., Ferreira, L. G., Godde, C. M., and West, P. C. (2018). Increasing importance of precipitation variability on global livestock grazing lands. *Nature Climate Change* **8**, 214–218. doi:10.1038/s41558-018-0081-5

Stone, G. S. (2004). Analysis of grazing pressure from the long-term livestock records of two western Queensland pastoral properties. *In*: 'Pasture Degradation and Recovery in Australia's Rangelands: Learning from History'. (Eds G. M. McKeon, W. B. Hall, B. K. Henry, G. S. Stone and I. W Watson.) pp. 191–235. (Queensland Department of Natural Resources, Mines and Energy.) Available at: https://www.longpaddock.

qld.gov.au/other-products/learning-from-history/ (accessed 19 August 2020)

Stone, R. C., Hammer, G. L., and Marcussen, T. (1996). Prediction of rainfall probabilities using phases of the Southern Oscillation Index. *Nature* **384**, 252–255. doi:10.1038/384252a0

Stone, G., Crimp, S., Day, K., Hall, W., Henry, B., McKeon, G., Owens, J., Power, S., Syktus, J., and Watson, I. (2003). Preventing the 9th degradation episode in Australia's grazing lands. *In*: 'Science for Drought, Proceedings of the National Drought Forum'. (Eds R. Stone and I. Partridge.) pp. 62–73. (Queensland Department of Primary Industries: Brisbane.)

Stone, G., Dalla Pozza, R., Carter, J., and McKeon, G. (2019). Long Paddock: climate risk and grazing information for Australian rangelands and grazing communities. *The Rangeland Journal* **41**, 225–232. doi:10.1071/RJ18036

Stone, G., Zhang, B., Carter, J., Fraser, G., Whish, G., Paton, C., and McKeon, G. (2021). An online system for assessing long-term carrying capacity information for Queensland grazing properties. Part 1: background and development. *The Rangeland Journal* **43**, In Press. doi:10.1071/RJ20084

Tothill, J. C., and Gillies, C. (1992). The pasture lands of northern Australia: Their condition, productivity and sustainability. Occasional Publication No. 5. Tropical Grasslands Society of Australia, Brisbane.

White, W. B., McKeon, G. M., and Syktus, J. (2003). Australian drought: The interference of multi-spectral global standing modes and travelling waves. *International Journal of Climatology* **23**, 631–662. doi:10.1002/joc.895

Wilhite, D. A. (2002). Combating drought through preparedness. *Natural Resources Forum* **26**, 275–285. doi:10.1111/1477-8947.00030

Wilhite, D. A. (2011). Breaking the hydro-illogical cycle: Progress or status quo for drought management in the United States. *European Water* **34**, 5–18.

Wythes, J., and Ernst, A. (1984). Molasses as a drought feed. *Proceedings of the Australian Society of Animal Production* **15**, 213–226.

Zhang, B., Fraser, G., Carter, J., Stone, G., McKeon, G., Whish, G., and Willcocks, J. (2021). An online system for assessing long-term carrying capacity for Queensland grazing properties. Part 2: modelling and outputs. *The Rangeland Journal* **43**, In Press. doi:10.1071/RJ20088