

Research Paper

Exploring the green break of season and green date over northern Australia

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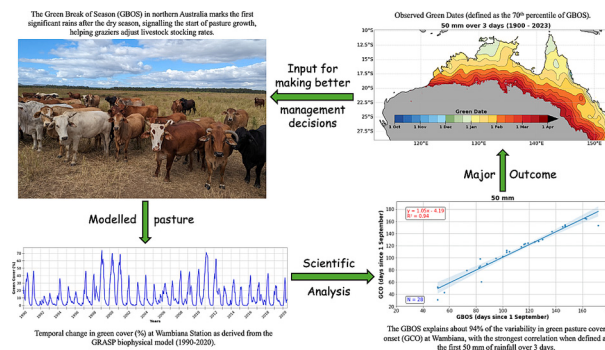
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HIGHLIGHTS

- Northern Australia's 'green break of season' (GBOS) date is when the first significant rains appear after the long dry season.
- Graziers can use GBOS to establish appropriate livestock stocking rates using fodder remaining after the previous wet season.
- GBOS estimates the timing of productive pasture onset more accurately than NRO at a long-term grazing trial in Queensland.
- A seasonal GBOS prediction product could assist graziers in making more informed management decisions.

GRAPHICAL ABSTRACT



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ABSTRACT

Context: In northern Australia, livestock production relies heavily on dryland pastures, whose growth is strongly controlled by wet season rainfall. Knowledge of the likely timing of the first productive pasture after the long dry season – marked by the green cover onset (GCO) – can help graziers establish an appropriate stocking rate based on the available fodder at the end of the previous growing season.

Objective: This study focuses on the 'green break of season' date (GBOS), defined as the first day after 1 September when a threshold amount of rainfall (e.g., 50 mm) is accumulated over a 3-day period. This rainfall-based metric aims to coincide with the annual onset of effective pasture growth (GCO) in northern Australia.

Methods: Using robust model-derived estimates of green pasture cover at a representative location in northeastern Queensland we compute the Green Cover Onset (GCO), defined as the first day after 1 October on which modelled green cover reaches or exceeds a specific threshold. This study explores the relationship between GCO and the GBOS for different 3-day accumulated rainfall thresholds (10–80 mm, in increments of 10 mm). We further explore the 'green date' (GD), defined as the 70th percentile of the distribution of GBOS dates, calculated over a long historical period (1900–2023) in northern Australia using daily rainfall observations from the Scientific Information for Land Owners (SILO). We then analyse, how the phase of the El Niño–Southern Oscillation (ENSO) influences the GBOS distribution.

Results and conclusions: The strongest relationship between GBOS and GCO is found defining the GBOS as the first occurrence of 50 mm of rainfall accumulated over 3 days ($R^2 > 0.94$). This correlation is stronger than that

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between the commonly used Northern Rainfall Onset (50 mm accumulated after 1 September) and GCO ($R^2 = 0.62$), with a regression slope closer to 1 and a y-intercept closer to zero, indicating a better one-to-one relationship with the GCO. This suggests that the GBOS is a more effective indicator for estimating the onset of productive pastures. Additionally, our analysis reveals that during El Niño years, the reliable GBOS (the 70th percentile of GBOS for ENSO-influenced years) occurs slightly later than the GD for all years, with no significant difference. In contrast, during La Niña years, it occurs significantly earlier. This pattern is consistent across regions in northern Australia, showing that El Niño delays and La Niña advances the northern wet season.

Significance: This study paves the way for the development of a seasonal GBOS prediction product, which will help livestock producers in making more informed and effective management decisions.

1. Introduction

Australia is the world's third-largest exporter of beef, contributing about 4 % to global beef production,¹ and significantly impacting world trade with an annual worth of over 16 billion AUD.² Cattle raised in northern Australia (10°S–29°S, 112°E–154°E) heavily depend on pasture as their primary food source (McCown, 1981; Bortolussi et al., 2005; Burrow, 2014), with pasture growth strongly controlled by rainfall that occurs predominantly during the October–April wet season (Lisonbee et al., 2022; Balston and English, 2009; Park et al., 2001), followed by a long dry season during which little to no growth occurs.

The October–April wet season in northern Australia accounts for over 90 % of the region's annual rainfall (Lisonbee et al., 2022; Nicholls et al., 1982). Wet season rainfall typically begins sporadically with isolated thunderstorms (Pope et al., 2009), progressively intensifying until the onset of the Australian monsoon. This is accompanied by widespread and heavy rainfall, typically first occurring around late December or early January (Lisonbee et al., 2020; Drosowsky, 1996). Northern Australia is known for its significant seasonal and interannual rainfall variability, causing droughts (Thi Tran et al., 2016; Gillard and Monypenny, 1990) and floods (Johnson et al., 2016). Such conditions significantly impact the management of cattle enterprises and livestock production (Cobon et al., 2019), posing challenges in matching stock numbers with forage supply with stock numbers (Cobon et al., 2020b), and presenting major risks to the income of producers and land condition. Understanding the effect of annual rainfall on pasture growth is therefore crucial for the long-term sustainability and profitability of grazing enterprises (Johnston et al., 2000; Cobon et al., 2019; Brown et al., 2019).

In this study we investigate the onset of new green pasture that occurs around the time of wet season rainfall onset. In the literature, there are numerous definitions used to determine the timing of this onset in northern Australia. For example, based on a water balance model, McCown (1981, 1973) defined the beginning of a 'green season' when certain rainfall thresholds (such as, 50 mm in 3 days) are met. For their northeast Queensland study region, Balston and English (2009) incorporated pasture growth models, defining a 'green break of the season' as the date when 57 mm of rainfall accumulates over 21 days between 1 October and 31 March. Similar to the concepts of the 'green season' and the 'green break of the season', the Northern Rainfall Onset (NRO) is defined as the date when 50 mm of rainfall accumulates from 1st September (Cowan et al., 2020; Drosowsky and Wheeler, 2014). The NRO typically occurs between October and February, and like the other definitions, marks the date at which new pasture growth is expected following the preceding dry season (Lo et al., 2007). The NRO is relatively straightforward to comprehend by producers in the agricultural sectors, making it a valuable tool for grazing and cropping decisions across northern Australia (Lo et al., 2007). For example, producers may

use the NRO to organise livestock movements, adjust stocking rates, or plan the sowing of forage and crops in anticipation of the wet season, thereby reducing climate-related risks and improving resource allocation. These diverse definitions reflect the complexity of determining an onset date for productive green pasture. All these definitions are based on rainfall, as it has historically been more consistently observed than pasture growth itself.

Producers are primarily concerned with the timing of the first substantial rainfall, as it signals the onset of pasture growth. This information is critical, as it allows them to determine an appropriate pasture budget for the dry season and a safe stocking rate for their property, ensuring their animals have sufficient forage and pastures are not overgrazed leading to land degradation. However, having multiple definitions for the onset of pasture growth can create confusion. Therefore, establishing and adhering to a standardised onset definition is essential for improving climate-informed management decisions across the agricultural sector.

In northern Australia, the distinctive dry and wet seasons make it possible to calculate a forage budget for the dry season based on the amount of feed at the end of the wet season (usually April or May) and the expected onset of rains when growth will occur in the next wet season (typically December to April; Brown et al., 2019). Stocking rates can then be proactively adjusted at the start of the dry season based on its expected length to ensure sufficient forage for animal production and to prevent overgrazing and land degradation.

In the tropics, where rainfall is highly variable, livestock usually gain weight during the wet season (October–April) and maintain or lose weight during the dry season (June to December or even later) (McCown, 1981, 1982; McCown et al., 1981). The green break of season (GBOS) marks the time when pasture is expected to grow, initiating green cover and, thus, animal liveweight gain (Balston and English, 2009; Garnett and Williamson, 2010). A reliable estimate or forecast of the GBOS is therefore crucial for making a range of grazing management decisions, such as, setting appropriate stocking rate, the timing of calving, supplementation and marketing (Balston and English, 2009; Cobon et al., 2020a).

The reliable, long-term climatological start of the pasture growing season is called the Green Date (GD), and is defined as the first day after 1 September when a location can expect to receive 50 mm of rain across 3 consecutive days in 7 out of 10 years.³ These GD conditions can be refined depending on soil type and geographical location of the property. It is a definition that has received widespread use in the livestock industry, albeit with little justification of why a 3-day accumulation should be better than the longer accumulation period of the NRO, or the 21 days used for the GBOS definition of Balston and English (2009). Nevertheless, communication in the livestock industry has emphasized that the GD, when combined with the likely end date of the growing season, allows producers to determine an appropriate dry season stocking rate³. Matching the stocking rate with the forage supply reduces stress on livestock and the extent of supplementary or drought

¹ Meat & Livestock Australia, Global Beef Report (2022): <https://www.mla.com.au/globalassets/mla-corporate/prices-markets/documents/os-markets/stainer-reports-and-other-insights/global-beef-report-2022.pdf>.

² Beef Central, 2024: URL <https://www.beefcentral.com/news/australia-now-produces-more-than-16-billion-worth-of-beef-a-year/>.

³ FutureBeef, 2021: Budgeting your pasture. Queensland Country Life, URL <https://futurebeef.com.au/wp-content/uploads/2021/04/2021-04-29-CQBeef.pdf>.

feeding. Implementing an appropriate stocking rate also plays a key role in preventing overgrazing and maintaining land and pasture condition (O'Reagain et al., 2009; O'Reagain et al., 2018; McKeon et al., 2000). A safe stocking rate for available pasture has the potential to reduce the extent of supplementary feeding and reduces stress on pastures and livestock in the dry season. Knowing the GD can thus ensure graziers have adequate feed for their stock and can maintain adequate ground-cover to reduce runoff with the first storms, minimizing sediment and nutrient loss to downstream ecosystems like the Great Barrier Reef^{3,4}.

In northern Australia, our defined GBOS is conceptually similar to the 'green season' (McCown, 1981; McCown et al., 1981), although distinct in its reliance on a single rainfall threshold (e.g., 50 mm over 3 days). Moreover, it also differs from the 'green break of the season' (Balston and English, 2009), which is based on a longer rainfall accumulation period (57 mm over 21 days). Our study aims to explore the applicability of a 3-day accumulation GBOS definition, and the related GD, for pasture growth across two locations in northern Australia. This involves an initial assessment of the 3-day GBOS in individual years and then estimating the historical GD based on the 70 % chance of occurrence of the GBOS using high-quality gridded rainfall observations (1900–2023). As such, this study will determine the role of short accumulations of rainfall at the start of the pasture growing season. This research also tests the applicability of a range of rainfall accumulation thresholds over 3 days to calculate the GBOS over different locations over northern Australia, and compares that to the applicability of the longer-duration NRO definition. Ultimately, this study investigates the influence of rainfall patterns on the onset of the pasture growing season and aims to provide producers with practical guidance for determining these critical dates at their specific locations.

This manuscript is organised as follows: Section 2 details the data and methodology, Section 3a describes the 3-day GBOS and reports on the occurrence of 'false starts', Section 3b illustrates the historical GBOS in all years over northern Australia, Section 3c describes the pasture-defined Green Cover Onset (GCO) and its relationship to GBOS in comparison to the NRO, and lastly, Section 4 presents the study's conclusions and future work.

2. Data and methodology

2.1. Datasets and biophysical model

All calculations and figures of the GBOS and GD shown in Sections 3a and 3b are based on the Scientific Information for Land Owners (SILO) database of historical gridded daily rainfall observations (from 1900 to 2023) for Australia (Jeffrey et al., 2001). SILO is an enhanced climate database developed in collaboration between the Australian Bureau of Meteorology with the Queensland Government (Jeffrey et al., 2001). The SILO daily data has a $0.05^\circ \times 0.05^\circ$ spatial resolution across Australia and is extensively used for crop and pasture modelling (Stone et al., 2019; Thayalakumaran et al., 2018). The dataset is interpolated from Bureau weather station measurements using smoothing splines and kriging techniques and is known for its robustness and reliability (Zajackowski et al., 2013). We select the time period starting from 1900 since the Bureau's reliable records begin from that year onwards. Additionally, to validate our results obtained from SILO, we compared them with the Bureau of Meteorology's Australian Gridded Climate Data (AGCD; Evans et al., 2020; Jones et al., 2009), as shown in Fig. S3 of the Supplementary.

To illustrate the concept of the GBOS (as described in Section 3a), we select Darwin Airport (12.41°S, 130.88°E) as an example location. Darwin is situated in the Top End of northern Australia, south of the

tropical Maritime Continent (Ramage, 1968; May and Ballinger, 2007). It is a central area for one of the largest sources of latent heating systems globally (Keenan et al., 1989), and is significantly affected by various convective regimes that bring substantial rainfall to the region (Keenan and Carbone, 1992; Drosowsky, 1996; May and Ballinger, 2007; Caine et al., 2009; Rauniyar and Walsh, 2016). Consequently, Darwin receives rainfall of 50 mm in total in almost all months during the wet season, making it an ideal example to simplify the concept of GBOS.

Daily pasture growth and green cover were derived from the grass production model, GRASP (Rickert et al., 2000) using measured data from a long-term grazing trial located at Wambiana Station (O'Reagain et al., 2009; O'Reagain et al., 2018; Owens et al., 2021). The trial, established in 1997, is located 70 km south-west of Charters Towers (20° 34' S, 146° 07' E), in north Queensland and is the longest running grazing trial in northern Australia. It is located in an open Eucalypt-savanna on relatively infertile soils (O'Reagain et al., 2008). Experimental paddocks, each about 100 ha, feature three soil-vegetation associations: Reid River box (*Eucalyptus brownii*) on sodosols and chromosols, silver leaf ironbark (*E. melanophloia*) on yellow-brown earths, and brigalow-box (*Acacia harpophylla*) on grey earths and vertosols (O'Reagain et al., 2008).

GRASP is a biophysical model of soil water and pasture growth developed using datasets from northern Australian rangelands (Day et al., 1997; McKeon et al., 2000; Rickert et al., 2000; Zhang et al., 2021). The GRASP model has numerous practical applications because it integrates knowledge from field experiments, land resource surveys, remote sensing of vegetation, and grazer estimates of carrying capacity for Queensland grazing properties (Zhang et al., 2021; Owens et al., 2021). Extensive field measurements from the Wambiana trial, including pasture biomass, cover, and rainfall, were used to parameterize and validate the GRASP model (Owens et al., 2021), with biomass estimates from dry-weight-rank and assessments informing calibration of soil and vegetation characteristics specific to the site (O'Reagain et al., 2009). All model simulations were run using the Cedar version of GRASP model (version 1.2), incorporating daily rainfall observations from the Wambiana trial (from 1 January 1990 to 30 June 2020). Modelled daily green pasture cover from GRASP was then used for the same period to examine the relationship between pasture growth and the GBOS as described in Section 3c.

2.2. Definitions and thresholds

As mentioned above, we choose to study the applicability of a 3-day burst of rainfall (1 September – 30 April) for defining the GBOS, since this is what is used as the basis for defining the GD. Specifically, for each individual year (from 1 September to 30 April), we find the first 3-day period that receives an accumulation of a certain threshold of rainfall and define the date as the last day of the 3-day period. To be consistent with the widely used GD, we initially set the rainfall threshold as 50 mm, but also test a range of 3-day thresholds from 10 to 80 mm at 10 mm intervals. If the daily rainfall exceeds the threshold on a specific day, then the GBOS is set as that day.

It is important to note that the rainfall threshold that is used to define the GD can vary based on the location and soil-type of the property, with some areas requiring less/more than 50 mm of rainfall to initiate the growing season. For example, regions with sandy or loamy soils typically require lower amounts of rainfall (~10 mm) whereas areas with clay loam soils may require around 30 mm (Anderson et al., 2004; Del Cima et al., 2004).

Once the GBOS is defined for each year, we then compute the GD, which is the long-term historical GBOS date that can be expected in 70 % of years (i.e., 70th percentile of all years, from 1900 to 2023). We also compute the 'reliable GBOS,' which represents the 70th percentile of the GBOS dates during ENSO years (specifically, all years influenced by El Niño and La Niña events within the 1900–2023 period were included, with El Niño and La Niña years analysed separately). We have adopted

⁴ Meat & Livestock Australia, 2018: URL <https://www.mla.com.au/news-and-events/industry-news/archived/2018/three-key-paddock-decision-dates-to-avoid-becoming-a-slow-boiled-frog/>.

the approach by [Allan et al. \(1996\)](#) to define the ‘El Niño’ and ‘La Niña’ years (1900–2023) using the Southern Oscillation Index (SOI). ‘El Niño’ or ‘La Niña’ years are based on average SOI values exceeding a threshold of ± 5 from June to November. We employ a Student’s *t*-test to check for significant differences between the reliable GBOS during ENSO years and the ‘all years’ GD.

The GD maps shown in Section 3b and in the Supplementary (Figs. S1–S4), are based on the condition that locations with no GBOS in more than 33 % of the years are masked and excluded from GD calculations. All maps including those in the Supplementary, are smoothed using a Gaussian spatial filter with standard deviation (σ) of 5.

To estimate the approximate date for the actual initiation of green cover (%), that is, the GCO, we impose the following conditions on the modelled pasture dataset at Wambiana, to ensure accurate extraction of GCO days at this location:

- i. Considering the period starting from 1 October each year, as the modelled pasture growth typically peaks after this date.
- ii. The green cover should be equal to or exceed 5 % (after 1 October).
- iii. The rate of change in the green cover should be positive on the day when it is ≥ 5 % (after 1 October).
- iv. The average green cover in the next 30 days (following steps ii and iii) should be greater than 8 %.

The relationship between GBOS and GCO as shown in Section 3c is calculated using simple statistical regression analysis, with the correlation between the two variables determining how well the GCO days align with the GBOS days. The associated confidence intervals are calculated at the 95 % level.

Additionally, we ensured the accuracy and reliability of our results by comparing our calculations and analyses against two established tools that use SILO daily rainfall observations for calculating GD over Australia⁵:

- i. The GreenDate tool (<https://greendate.dhmssoftware.com.au>) developed by the DHM Environmental Software Engineering for the University of Southern Queensland (UniSQ) and Meat and Livestock Australia (MLA⁶), and
- ii. The CliMate App (<https://climateapp.net.au/>) which is a collaboration between DHM Environmental Software Engineering and UniSQ.

3. Results

3.1. The Green Break of Season and False Start

[Fig. 1](#) displays the observed GBOS for Darwin Airport over the 1900–2023 period, defined with a rainfall threshold of 50 mm over 3 consecutive days. As explained in Section 2a, Darwin is well suited for demonstrating this method due to its climatological characteristics. As shown in [Fig. 1](#), Darwin records a GBOS in all years since 1900, however, this might not be true for all regions over northern Australia, since semi-arid/inland regions frequently observe less intense rainfall bursts during the wet season ([Duvert et al., 2022](#)).

Even if the conditions are met and the first burst of rain happens at the end of a dry season in a particular year, that might not necessarily mean it will be followed by a sustained pasture growth throughout the wet season ([Edye et al., 1971](#)). The first burst of rain might result in immediate pasture growth but might not be adequate to sustain growth unless further effective rainfall occurs ([Gardener, 1982](#)). This abrupt growth in pasture with insufficient follow-up rainfall results in a ‘False Start’ or ‘False Onset’ in green cover ([Edye et al., 1971](#); [Bell et al., 2016](#);

[Taylor and Tulloch, 1985](#); [Bellotti et al., 1991](#)).

3.2. The Green Date

Estimating the duration of the dry season, that is, the time between the end of the growing season date (for any given location) and the expected green date (that is, the start of the growing season) is critical for producers. This allows them to determine a safe dry season stocking rate based on available pasture and the length of time over which it must sustain the herd. Having an appropriate stocking rate not only reduces the stress on existing pastures and stock, but also has significant financial benefits. It helps avoid the costs of drought feeding or forced sale if forage runs out before it rains ([O’Reagain et al., 2011](#)), or alternatively, allowing extra stock to be carried if excess forage is available.

[Fig. 2](#) illustrates the different percentiles of the GBOS (1900–2023) at Wambiana. For example, the Wambiana GD for all years is 149 days since 1 September, or the 28th of January (black dot, [Fig. 2](#)). Similarly, the reliable GBOS using only El Niño years is the 30th January (red dot, [Fig. 2](#)) and for La Niña years, the 6th January (blue dot, [Fig. 2](#)). While there is no significant difference between the ‘all years’ GD and the reliable GBOS during El Niño years based on a Student’s *t*-test ($p > 0.1$), La Niña years show a statistically significant difference ($p < 0.05$), with the reliable GBOS during La Niña years occurring considerably earlier than the GD. This asymmetric behaviour is observed across other locations as well (as shown in [Fig. S4](#) under the Supplementary), indicating that the shift in GBOS timing is largely influenced by La Niña conditions. Furthermore, the reliable GBOS values derived for Wambiana for El Niño and La Niña years, are consistent with the broader ENSO-rainfall relationship across northern and eastern Australia (see Discussion for further detail).

The GD maps (1900–2023) with two different rainfall thresholds, 30 mm and 50 mm, are displayed for northern Australia in [Fig. 3](#). For both thresholds ([Fig. 3a, b](#)), we see that the GDs occur earlier between 1 September and 31 December over much of north and north-east Australia; while towards the arid interior of the continent, they typically occur from January onwards – a spatial pattern that closely resembles the distribution of the NRO.

To identify any potential differences in the temporal and spatial distribution of GDs across northern Australia, we analysed the GD results for a series of smaller climatological periods, including 1950–2023, 1980–2023, 1990–2023, and 2000–2023. In [Fig. S1 \(a–j\)](#), we present GD maps analogous to those in [Fig. 3](#), but for above climatological periods. Our analysis highlights notable differences in GDs across these periods. Longer climatological periods result in smoother, more coherent spatial patterns of GD with reduced noise, while shorter periods exhibit greater spatial variability and more fragmented GD patterns. In some cases, shorter periods also show a tendency towards earlier GDs (e.g. Darwin). These differences are likely due to averaging over a larger number of years in the longer periods, which helps to dampen the influence of seasonal to interannual variability. Despite these variations, the general tendencies remain consistent, with significantly earlier onsets in the north and northeast regions of Australia ($p < 0.05$) and later onsets in the interior and central and northwest coast.

To validate our results with another observational gridded dataset, we compared them with the Bureau of Meteorology’s Australian Gridded Climate Data (AGCD; [Evans et al., 2020](#); [Jones et al., 2009](#)), recreating the GD maps for rainfall thresholds of 30 mm and 50 mm ([Fig. S3](#)). We find that both the SILO and AGCD datasets display similar spatial patterns of GDs across the different climatological periods examined ([Fig. S3 a–j](#)) – specifically, both exhibit comparable spatial gradients in GD timing across northern Australia. This consistency between the observational records enhances confidence in our analysis.

3.3. The Green Cover Onset (GCO) and its relationship with GBOS

In contrast to years like 2011 ([Fig. 4c](#)), where the initiation of green

⁵ Both tools require subscription, which is free.

⁶ <https://www.mla.com.au/>

a. The Green Break of Season and False Start

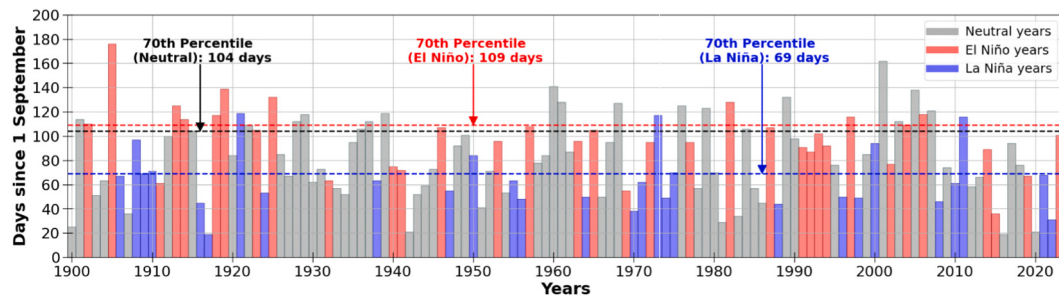


Fig. 1. GBOS (days since 1 September) as defined using the 50 mm rainfall threshold over 3 consecutive days for the years 1900–2023 (September–April) at Darwin Airport (12.41°S, 130.88°E). The red bars correspond to the El Niño years while the blue bars correspond to the La Niña years. Neutral years are represented by the grey bars. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

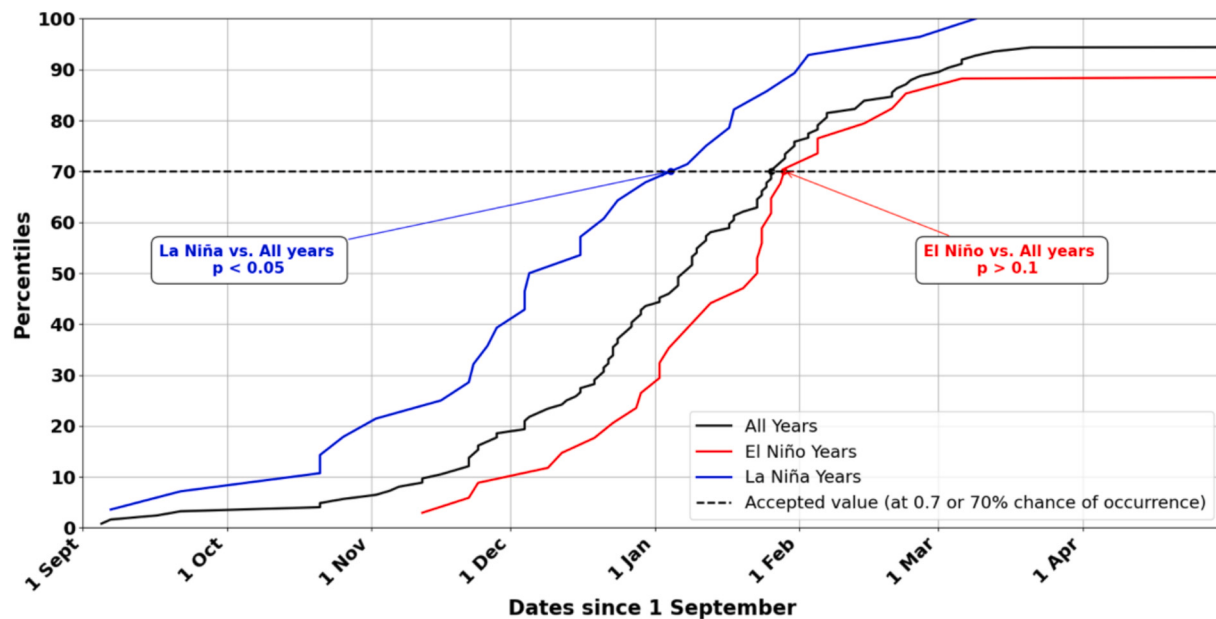


Fig. 2. GBOS percentiles for Wambiana Station (20.34°S, 146.07°E), defined over 1900–2023, using the 50 mm threshold over 3 days; the 70th percentile (marked by the dashed horizontal line) is used to define the Green Date (GD). The black, red and blue curves represent the percentiles of GBOS in all years, El Niño years, and La Niña years, respectively. The p -values are based on the results of a Student's t -test, comparing the reliable GBOS during ENSO years with the 'all years' GD. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cover is notably clear, beginning around late December, there are also instances of 'false starts' like 2017 (Fig. 4d). The false start in 2017 involved an abrupt pasture initiation in late October, followed by a rapid decline to zero by early January, before experiencing a subsequent increase in January. Additionally, there are years where false dry periods in pasture growth occur, such as 1998 (Fig. 4b). During these periods, the pasture cover or growth remains above a certain threshold value (e.g., 5%), and still displays signs of green cover in the dry season before 1 September. Thus, it is important to correctly identify the actual start of the growing season when the green cover is sustained over the subsequent few months as a result of follow-up rainfall.

After estimating the pasture growth dates (i.e., GCO) at Wambiana, based on the aforementioned conditions for different rainfall thresholds (from 10 to 80 mm), we conduct a regression analysis and calculate the correlation coefficient between the GCO and GBOS (Fig. 5). The linear relationship between the two variables weakens as the GBOS threshold exceeds 50 mm or is less than 40 mm. Also, moving from 10 mm to 80 mm, the line of best fit between the two variables shifts from early occurrences towards late occurrences owing to a shift in rainfall and green cover variability. Moreover, the regression line corresponding to the 50

mm rain threshold accounts for about 94 % of the variability (suggested by the R^2 value of 0.94 in Fig. 5d) in GCO days attributable to any changes in GBOS days. This indicates a very strong association with a statistically significant correlation between the two variables, as evidenced by the tight alignment of data points along the regression line. This underscores the suitability of 50 mm rain to be the most suitable threshold for elucidating the GCO-GBOS relationship at Wambiana.

To understand whether the GBOS or NRO is better for pastoralists in determining the onset of green productive pastures, we conducted a correlation analysis of the NRO dates (at a 50 mm rainfall threshold) with the pasture-defined GCO dates (Fig. 6). This was done to compare its effectiveness with the observed GBOS versus GCO correlation (Fig. 5). The analysis shows that the correlation between NRO and GCO is quite low, ($R^2 = 0.62$), compared to the GBOS results ($R^2 = 0.94$) (Fig. 5d). This suggests that 3-day rainfall (e.g., GBOS) is more closely related to pasture growth than accumulation over a longer period (e.g., NRO). Therefore, we may conclude that the GBOS is likely an improvement over the NRO and may be more applicable for estimating the onset of useful pasture growth.

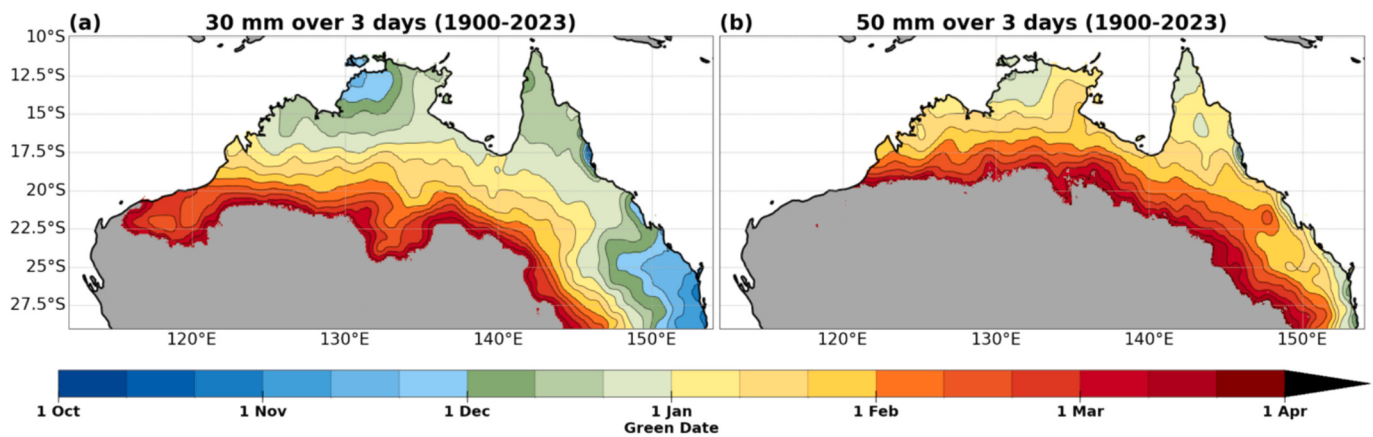


Fig. 3. Observed Green Dates over 1900–2023 for northern Australia, based on (a) 30 mm and (b) 50 mm rainfall thresholds. The dates are shown from 1 October onwards. The grey regions indicate where reliable rainfall typically arrives too late for the Green Date to be defined, based on the rainfall threshold condition imposed. Specifically, if over 33 % of the years at a particular location have no GBOS, we mask those locations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

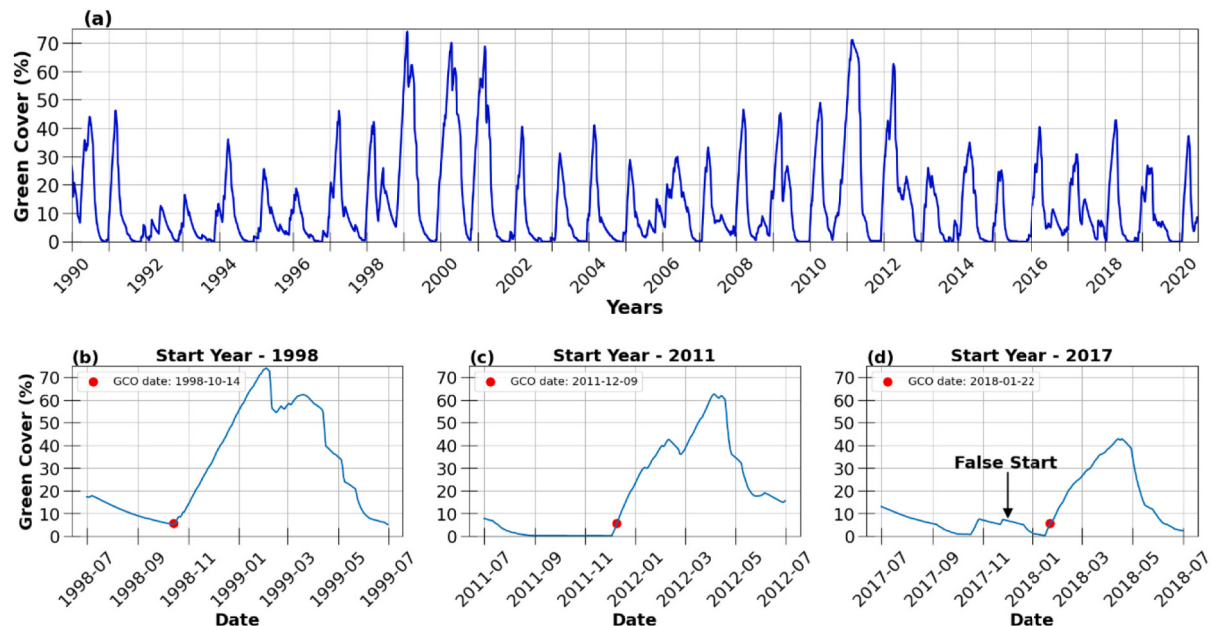


Fig. 4. (a) Temporal change in green cover (%) at Wambiana Station as derived from the GRASP biophysical model (1990–2020). Examples of (b) a 'False dry' in green cover (1998), (c) a clearly observed green cover onset (2011), and (d) a 'False start' in green cover onset (2017). Refer to Section 2b for the definition of the GCO. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

In Australia's northern tropics, where rainfall is highly variable (King et al., 2014; Dey et al., 2019, 2021), livestock typically gain weight during the October to April wet season (Park et al., 2001) due to pasture availability and lose weight during the dry season (McCown, 1981; Bortolussi et al., 2005; Burrow, 2014; Cobon et al., 2019; Brown et al., 2019). To determine the timing of the anticipated onset of the pasture growing season, the GBOS is calculated annually and is defined as the first day from 1 September when a location receives 50 mm of rainfall over a 3-day period. This definition aims to facilitate understanding for producers and prevent any potential confusion amidst other existing definitions (McCown et al., 1981; McCown, 1981; Balston and English, 2009).

Our research endeavours to improve the precision and relevance of the climatological GBOS, commonly referred to as the GD, which marks an important time of the year for pasture growth, across northern

Australia. We initially began by analysing the GBOS for individual years from 1900 onwards (including ENSO years), at individual locations across northern Australia (e.g., Darwin, Fig. 1). Using the GBOS data from all years, we then estimated the GD, which represents the long-term climatological start of the pasture growing season for those regions (e.g., Wambiana, Fig. 2). For both Darwin and Wambiana, we observed that during El Niño years, the reliable GBOS occurs slightly later than the 'all years' GD (a p -value >0.1 at Wambiana suggests no significant difference from the 'all years' GD), whereas during La Niña years, it occurs much earlier (a p -value <0.05 at Wambiana indicates a significant difference from the 'all years' GD). This asymmetric ENSO-related shifts in GBOS/GD timing are consistent in other regions as well (Fig. S4), reflecting that El Niño typically causes a slightly delayed start to the northern wet season, while La Niña leads to an earlier start (Cowan et al., 2020). It is also consistent with the asymmetric influence of ENSO phases on the monsoon onset timing, where La Niña events tend to advance the onset more strongly than El Niño events delay it

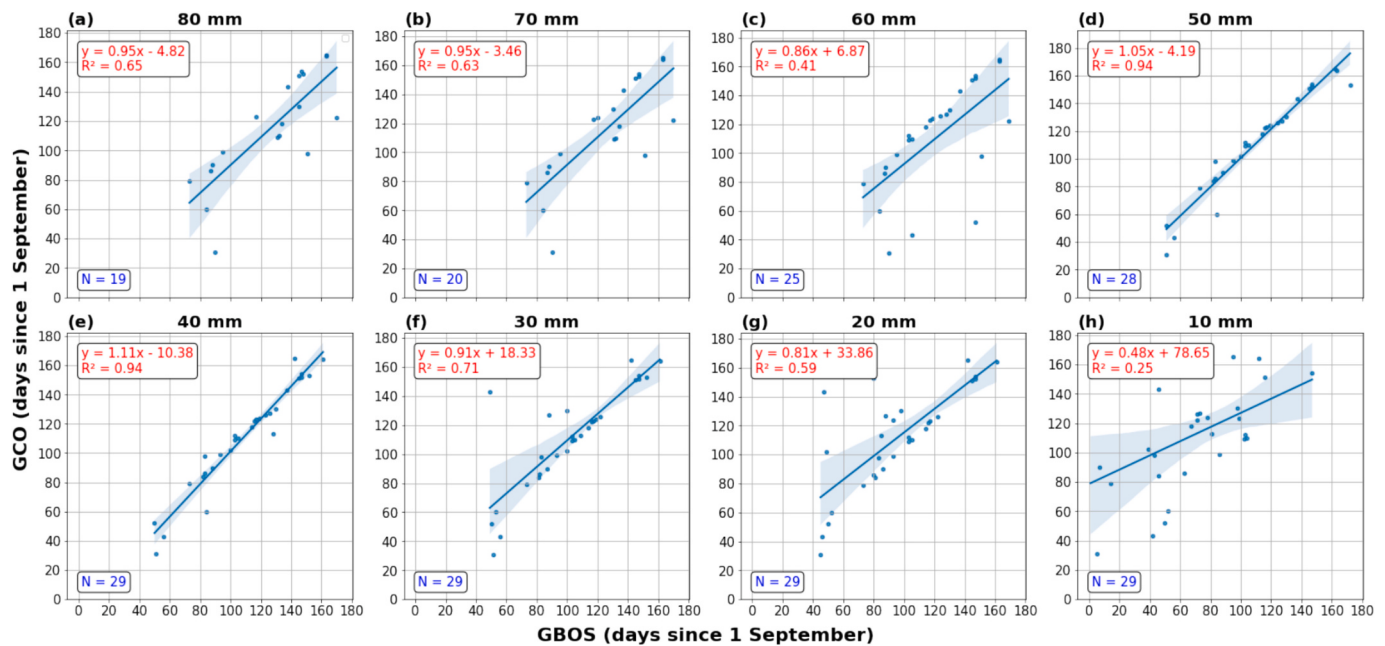


Fig. 5. Scatterplots showing the linear relationship between the GBOS and GCO at Wambiana Station for different rainfall thresholds (10–80 mm in 3 days) over 1990–2020. The background blue shading represents the confidence intervals calculated at the 95 % level. ‘N’ indicates the number of data points used in each regression analysis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

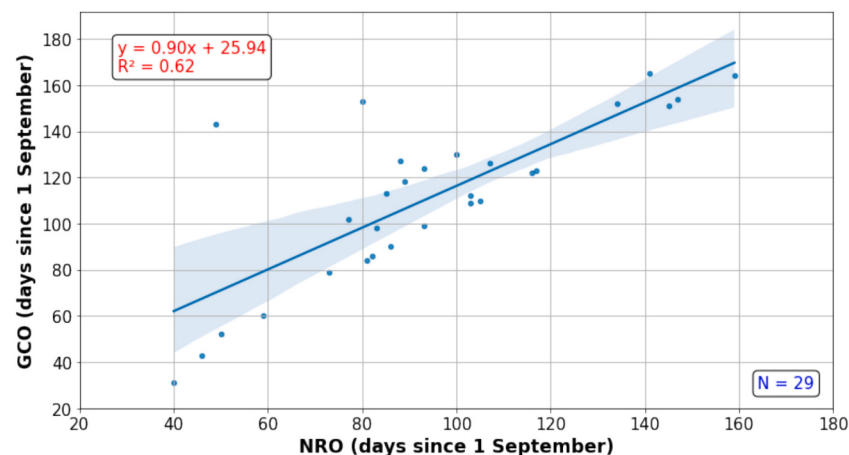


Fig. 6. The linear relationship between the NRO and GCO at Wambiana Station over 1990–2020. The background blue shading represents the confidence intervals calculated at the 95 % level. ‘N’ indicates the number of data points used in the regression analysis. The NRO is defined in Section 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Lisonbee and Ribbe, 2021).

In general, La Niña is associated with above average winter–spring rainfall for eastern and central parts of Australia, and a wetter and earlier start to the northern wet season (Cowan et al., 2020). On the other hand, El Niño results in below average winter–spring rainfall for eastern parts of the country, and a drier start to the northern wet season (Power et al., 1999; Brown et al., 2016). Thus, the reliable GBOS values derived for Wambiana for El Niño and La Niña years, are consistent with the broader ENSO-rainfall relationship across northern and eastern Australia.

Next, we mapped the spatial distribution of GD across northern Australia for various rainfall thresholds. In Fig. 3, for both 30 mm (a) and 50 mm (b) rain thresholds, the GDs occur earlier (in December) in northern Australia, while in interior regions, they occur later, typically after January. Notably, the spatial distribution of GDs is very similar to that of the NRO (Cowan et al., 2020).

When examining the relationship between GCO and GBOS with different rainfall thresholds at Wambiana, we identified instances of ‘False Starts’ or ‘False Onsets’ in green cover, when abrupt pasture growth occurs following an initial burst of rainfall, but is not sustained due to insufficient follow-up rain (Fig. 4d). Conversely, we also observed ‘False dry’ conditions, where green cover persists despite limited rainfall, likely due to residual pasture from the previous season that has not fully browned off (Fig. 4b). These complexities highlight the value of incorporating vegetation responses alongside rainfall thresholds when assessing the true onset of the growing season.

Furthermore, we observed a compelling relationship between the GCO and GBOS days, particularly with the 50 mm rain threshold, which explains approximately 94 % of the variability in GCO days due to changes in GBOS days (Fig. 5d). This indicates that the 50 mm rain threshold is most effective in determining the relationship between GCO and GBOS at Wambiana.

To determine whether the GBOS or NRO is more strongly associated with the onset of green pasture, we analysed the correlation between NRO dates and GCO dates (Fig. 6) at Wambiana, comparing it to the GBOS-GCO correlation (Fig. 5d). The NRO-GCO correlation was low ($R^2 = 0.62$; although statistically significant) compared to the GBOS-GCO correlation ($R^2 = 0.94$), providing the first real evidence that short-term rainfall is more closely related to pasture growth than longer-term rainfall accumulation, making GBOS potentially more effective for estimating the onset of useful pasture.

While both GBOS and NRO show significant correlations with GCO, GBOS demonstrates a stronger one-to-one temporal alignment with GCO, as indicated by a regression slope closer to 1 and y-intercept closer to zero (Fig. 5d). Further, although the 40 mm threshold (Fig. 5e) yields a similar R^2 to the 50 mm threshold and includes one additional data point (29 vs 28 as indicated by the value of 'N'), the 50 mm threshold shows a better temporal alignment with GCO (based on a regression slope closer to 1 and smaller y-intercept), supporting its use in identifying pasture growth onset.

In northern Australia, characterised by distinct dry and wet seasons (Lisonbee et al., 2020; Mollah and Cook, 1996; Lo et al., 2007; Drosowsky, 1996), livestock production is almost totally dependent upon dryland, rainfall-fed pastures (Cobon et al., 2019; Brown et al., 2019). Understanding the GBOS and GD allows graziers to estimate the duration of feed needed from the end of one growing season until sufficient rainfall is expected to promote pasture growth in the next season. By determining their GD and estimating the typical length of their growing season (from the expected start date to the end date), and estimating pasture availability, graziers can pasture budget and make informed decisions about the appropriate dry season stocking rate for their property. Additionally, knowing the GD can help graziers plan the optimal time for calving based on the expected start of the wet season and fresh, high quality forage and reduce financial stress during the dry season³. These insights highlight the practical value of our study in supporting sustainable and resilient grazing systems in northern Australia.

Regarding certain limitations of this study, our calculations and analysis have solely relied on SILO daily rainfall observations for northern Australia, focusing on a single climatological period from 1900 onwards. Although we have validated our GD maps for different climatological periods (Fig. S1) by comparing them with another observational dataset, AGCD (Fig. S3), it would also be beneficial to study other observational and modelled datasets to verify the consistency of our results.

Furthermore, we have established a strong relationship between GCO and GBOS based on data from a single site, Wambiana Station (Fig. 5). Validating this relationship at other locations with available fractional green cover products (such as at Fletcherview Research Station), would enhance confidence in our analyses. Additionally, our analysis of the GCO (Fig. 4) and the relationship between GCO and GBOS with different rainfall thresholds at Wambiana (Fig. 5) is based on the GRASP model. It would be beneficial to validate this relationship with other modelled pasture growth data and potentially with satellite observations (such as LandSat and Sentinel). Moreover, it is important to understand the 'False Starts' and GBOS variability in individual locations across northern Australia that have available pasture growth data.

Further possibilities for future research include predicting the GBOS dates for northern Australia using robust model-derived ensemble rainfall hindcasts. A skillful prediction of the GBOS several months in advance would help producers make important decisions from an agricultural perspective. Besides rainfall, it is important to consider other factors, such as soil moisture, evapotranspiration, soil and vegetation types, that might affect the GBOS in northern Australia. Nevertheless, our results could facilitate the development of a seasonal GBOS prediction product to help producers and graziers make more informed and effective management decisions.

5. Conclusions

Our study in northern Australia examines the onset of the first rains after the dry season, known as the 'green break of season' (GBOS), which is crucial for effective pasture growth. By analysing the relationship between the model-derived GCO and GBOS across various 3-day rainfall thresholds (10–80 mm) at a long-term cattle grazing trial in northeastern Queensland, we found the strongest correlation when GBOS is defined as the first occurrence of 50 mm of rainfall over 3 days ($R^2 > 0.94$). Our results indicate that GBOS is a more accurate indicator than the commonly used NRO for estimating productive pasture onset at the study location. Additionally, we explored the GD, defined as the 70th percentile of GBOS dates from 1900 to 2023, and its variation with the phases of the ENSO. This research supports the development of a seasonal GBOS prediction product to help graziers make more informed management decisions.

CRedit authorship contribution statement

Rajashree Naha: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tim Cowan:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Formal analysis, Conceptualization. **Matthew C. Wheeler:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Jyoteshna Owens:** Writing – review & editing, Writing – original draft, Validation, Data curation, Conceptualization. **David Cobon:** Writing – review & editing, Writing – original draft, Validation, Resources, Project administration, Funding acquisition, Formal analysis. **Chelsea Jarvis:** Validation, Software, Investigation, Conceptualization. **Peter O'Reagain:** Writing – review & editing, Validation, Conceptualization.

Declaration of competing interest

The authors have no conflicts to disclose.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.agsy.2025.104526>.

Data availability

The SILO daily gridded rainfall data is accessible via the Long-Paddock webpage at: <https://www.longpaddock.qld.gov.au/silo/>. All other data and scripts used in this work will be available on GitHub/GitLab for public access and on request after this manuscript is published. Please contact the corresponding author at rajashree.naha@bom.gov.au to request access.

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