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Northern Australia Climate Program: supporting adaptation in rangeland grazing systems through more targeted climate forecasts, improved drought information and an innovative extension program

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Abstract. The Northern Australia Climate Program (NACP) is a fully integrated research, development and extension (RDandE) program operating across extensive pastoral regions of northern Australia. The NACP aims to improve existing climate models and forecast tools, develop new products to meet user needs and build the capacity of rangeland producers to manage the challenges posed by droughts (or failed wet seasons) and climate variability.

Climate information gaps identified through earlier surveys of graziers and communities in rural and remote Australia informed the design of the research component of the NACP, which aims to address the low and variable accuracy of seasonal climate forecasts in many regions, the need for proof of value of forecasts and relevance of existing forecast systems and technologies, and perceived lack of effective support from climate experts for the use of climate resources and technologies in agricultural decision making. The development and extension components of the program aim to improve climate literacy and the use of climate information. Building on the research program, they deliver a climate service that provides local extension and technical support, with a focus on building trust in climate information through locally sourced, industry connected NACP trained and supported extension advisers called Climate Mates. Two-way information flow between decision makers and researchers, facilitated by the Climate Mates, ensures that forecasts and decision- and discussion-support tools developed through the program are regionally relevant and targeted to the needs of end users.

Monitoring and evaluation of the program indicates that this approach is contributing to positive outcomes in terms of awareness and knowledge of climate forecasting and products, and their adoption and use in decision making (i.e. practice change). In the longer term, the Climate Mates have potential for enduring impact beyond the program, leaving a knowledgeable and trusted climate resource across regional northern Australia.

Keywords: agricultural climate risk management, barriers to adoption, climate variability, climate services, decision support, resilience, seasonal climate forecasts.

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Introduction

Northern Australian pastoral grazing systems support almost 60% of Australia's national cattle herd of 24.7 million head, occupying extensive areas of tropical and sub-tropical savannas and semi-arid shrublands that rely on seasonal rainfall between December and March. This wet season is usually followed by a long and variable dry season of 6–8 months (Park *et al.* 2001). Significant seasonal and interannual rainfall variability, with both droughts and floods, can have major impacts on livestock production in the region (Cobon *et al.* 2020*a*). This rainfall variability presents significant challenges to pastoral management (Cobon *et al.* 2019) and is a major source of risk to agricultural productivity, farm income, environmental condition and human wellbeing (Counsell and Houston 2017). Climate risk management to build resource resilience, reduce the risk of pasture and landscape degradation during drought and failed wet seasons and maximise opportunities in higher rainfall years are key to long-term economic and resource sustainability (Phelps *et al.* 2014). It is therefore crucial that producers have access to weather and climate information that allows them to anticipate and develop management strategies to better cope with rainfall variability.

Climate and rainfall variability in many parts of Australia are profoundly influenced by the El Niño–Southern Oscillation (ENSO; Ropelewski and Halpert 1987), which in combination with phases of the Indian Ocean Dipole (IOD; Saji *et al.* 1999) and the Madden-Julian Oscillation (MJO; Wheeler *et al.* 2009), drives the frequency, intensity and spatial distribution of rainfall, including drought (Risbey *et al.* 2009). ENSO peaks in influence during the Austral spring and early summer and directly impacts eastern Australia, with the influence waning further west. In contrast, the IOD has more influence across western and south-eastern Australia. It is active during the Austral winter and spring, so has limited impact on northern Australia's wet season rainfall, although it can affect temperatures during spring when calving generally occurs where high temperatures may increase calf mortality (McGowan *et al.* 2016; McCosker *et al.* 2020). The MJO is a shorter duration system and has direct influence across all of north (north of 20°S) Australia (Wheeler *et al.* 2009). These climate drivers have 'wet' and 'dry' phases that can cause drought (Power *et al.* 1999; Cai *et al.* 2001; Ummenhofer *et al.* 2009) and flooding (Liu *et al.* 2018). ENSO and IOD are able to be predicted 3–6 months in advance (Shi *et al.* 2012; Tang *et al.* 2018), while the MJO has a 21-day prediction lead time (Lim *et al.* 2018) making these climate drivers (including interactions between them) relevant to forecast prediction for livestock production in northern Australia.

Improved understanding of these drivers of climate variability has underpinned increased application of climate science into agricultural decision making using seasonal climate forecasts (SCFs). A SCF provides information about future expected rainfall and temperature conditions at 3-month time scales. Much of the accuracy of these forecasts is related to active phases of ENSO and IOD (Cai *et al.* 2011). With advances in computing technology and power, SCFs are being produced at increasingly finer spatial resolutions and with improved accuracy (MacLachlan *et al.* 2015; Hudson *et al.* 2017), making them more attractive for uptake by producers. However, climate systems dynamics are complex, and SCFs are subject to a level of uncertainty; their accuracy can also vary seasonally and regionally (Schepen *et al.* 2014). For example, of the climate drivers active in northern Australia, the predictability of ENSO is most reliable in the Austral spring and summer periods in years with strong ENSO anomalies (Sohn *et al.* 2016), making SCFs issued during strong ENSO events more accurate (White *et al.* 2014).

Despite evidence that the use of SCFs to aid decision making can be financially beneficial (An-Vo *et al.* 2019; Cobon *et al.* 2020*b*; Parton *et al.* 2019), estimated uptake of SCFs by Australian agricultural producers ranges from 30 to 50% (Cobon *et al.* 2018). Counsell and Houston (2017) indicated that while many primary producers use short-term weather forecast information, scepticism remains regarding the accuracy, and hence, the value of the Australian Bureau of Meteorology (BoM) 3-monthly forecasts. Modest uptake of seasonal forecasts has been attributed to a range of factors. First, a certain level of knowledge around climate systems, terminology and forecasting is required to correctly interpret SCFs. For example, seasonal forecasts are issued as probabilities, which may be problematic where producers do not fully understand how to correctly interpret probability or uncertainty (Keogh *et al.* 2005; McCrea *et al.* 2005). Second, the imperfect accuracy of forecasts, whether actual or perceived, is often cited as a major factor limiting uptake (Childs *et al.* 1991; Nicholls 1999; Meinke and Stone 2005; Marshall *et al.* 2011; White *et al.* 2013). In both cases, the importance of improving forecast accuracy and ensuring that the uncertainty inherent in SCFs is explicitly reported and understood by end-users will likely be critical to addressing the gap between expected and actual adoption of forecasts in on-farm decision making (Kusunose and Mahmood 2016). Third, 1-month and 3-month lead times may be too short and inadequate to allow producers to make meaningful changes in decisions (Keogh *et al.* 2005; Ash *et al.* 2007). Due to the large size of many properties in northern Australia, some decisions need to be made 6–12 months in advance, which is outside the timeframe of currently available SCFs. Fourth, existing tools and forecasts do not provide the information needed by producers. Currently available rainfall and temperature SCFs from BoM are for 'Chance of exceeding median'; however, many producers report being able to manage slightly below or above 'average' rainfall and are more interested in information about the chances of extreme rainfall (or lack thereof) and temperatures (Pudmenzky *et al.* 2017). Fifth, social rather than technical factors are also reported to be important (Marshall *et al.* 2011). All these factors can contribute to a lack of confidence in forecasts and a reluctance to use SCFs, especially where the consequences of such decisions are significant. Similarly, there is little evidence government agencies incorporate seasonal forecasts in managing hydrological systems or in developing and implementing strong policy frameworks ensuring early warning, preparedness and national alerts to prepare pastoralists for drought. These results indicate the need to build awareness and acceptance of the merit and accuracy of medium- and long-term forecasts.

Assisting producers to develop more confidence in and capacity to include medium- and long-term forecasts in decision making, particularly the timing of destocking and restocking decisions, which are critical for effective sustainable pasture management and animal welfare, may partially address these issues (Counsell and Houston 2017). Facilitated collaborative learning among graziers and other stakeholders assists in developing strategic skills and increasing climate awareness and the adoption of climate tools such as SCFs (Marshall 2010). Similarly, having local advisors with expertise in climate science and its applications has proven successful in significantly increasing the use of SCFs in decision making in Australian pastoral enterprises (Cobon *et al.* 2008, 2018; Cliffe *et al.* 2016).

The Northern Australia Climate Program (NACP) is a fully integrated research, development and extension (RDandE) approach with a focus on facilitating the flow of information between producers, extension officers, researchers and product developers. It has been designed to improve: (1) the accuracy of regional climate forecasts; (2) stakeholder knowledge of climate and associated decision tools; and (3) the relevance and use of climate information in tactical and strategic decision making. This paper describes the structure of the NACP and preliminary results, while also providing an assessment of aspects of the program that may inform the implementation of similar approaches in rangeland production systems elsewhere.

Developing the Northern Australia Climate Program

Recent investigations into the climate information RDandE needs within the northern Australia livestock industry (Mushtaq *et al.* 2016; Coutts 2017; Coutts *et al.* 2017; ICACS 2017) identified several key issues that were constraining business resilience and capacity to manage climate risk (Table 1) and provided an indication of how climate risk and drought management might be improved. Together these informed the structure and goals of the NACP, which was specifically designed around producer needs (Pudmenzky *et al.* 2017).

Overall, these studies indicated significant scope for improvements in planning for drought and climate variability for graziers. In particular, they showed the need for an efficient and effective extension service, with improved access to and training of decision makers in the use of relevant and contemporary decision support products to help overcome barriers to adoption and improve the capacity of producers to successfully manage their production systems for drought and climate variability (Coutts *et al.* 2017).

Structure of the Northern Australia Climate Program

Research component of NACP

NACP is led by the University of Southern Queensland (USQ) and collaborates with the BoM and leading modelling and development teams at the United Kingdom Met Office (UKMO). USQ/NACP employees are based at both the BoM and the UKMO to improve the accuracy of the forecast system, to understand the causes of drought at weekly and multi-year timescales and to develop products that respond to the needs of livestock producers. The BoM's Australian Community Climate and Earth System Simulator – Seasonal Prediction System (ACCESS-S) is a forecast model that is based on the UKMO's Unified Model (UM). Any improvements in the UM therefore flow into ACCESS-S, delivering benefits in forecast accuracy to producers. These downstream benefits motivate strong interaction between the three agencies, a relationship which NACP has enhanced.

Development component of NACP

The NACP development delivers products and a website for use by producers and policy makers in drought monitoring, planning and prediction. These include Australia-wide indices, monitoring and prediction of drought, and products for the timing of rainfall burst activity in the wet season. These products are developed to meet industry and policy needs.

Extension component of NACP

The extension and adoption component of the NACP aims to integrate and embed climate forecast information into grazing industry networks by improving climate knowledge and skills to advance resilience to drought and climate variability. It forms an essential link between the NACP research and development programs and producers, enabling producers to receive information on the latest research and product development and to communicate their needs back to the research and development teams.

The NACP extension program is delivered by regionally located industry connected extension specialists called Climate Mates who are supported by NACP climate scientists and project partners including the BoM, UKMO, state government Departments of Primary Industry and regional natural resource management (NRM) groups. There are currently 16 part-time NACP Climate Mates employed across northern Australia (Fig. 1). They are tasked with improving the uptake and use of weather and climate forecasts for on-property decisions by engaging with and providing training to graziers, advisors and related industry professionals. A climate scientist with agricultural expertise

Table 1. Climate issues concerning the livestock industry in northern Australia and the proposed RDandE activities to generate the required predictive reliability, confidence, trust and understanding of producers to use historical and forecast climate information in decision making to increase production and profitability

Climate issue[A]	Activity	Research (R)/Development (D)/Extension (E)
Low and variable forecast skill	Improve climate model skill at multiple timescales	R1
	Mapping forecast skill (by region and season)	R2
Relevance of existing forecast systems and technologies	Longer forecast lead times (seasonal)	R3
	Drought forecasts (multi-year)	R4
	Forecasts of summer wet season	R5
	Forecasts of unseasonal rain in dry season	R6
	Forecasts of extreme heat	R7
	Region and local scale forecast products	D1
Use of climate resources and the technologies	Trained and supported local climate advisers	E1
	Provide an integrated 'end-to-end' climate service targeted for the region	E2
	Targeted, relevant and updated tools	D2
	Climate advice by local advisers	E3
	Integrating forecasts into management	D3, E4
Support from climate experts	Provide an integrated 'end-to-end' climate service with two-way flow of engagement, information and evaluation	E5
Proof of value	Case studies with producers (post-drought assessments, innovative management for reducing drought vulnerability, use of critical indicators and triggers for drought planning and the use of forecasts in better decision making)	D4
	Integrated climate, biophysical and herd modelling to show forecast value	D5

[A]Issues identified in surveys reported in Mushtaq *et al.* (2016), Coutts (2017), Coutts *et al.* (2017), ICACS (2017).

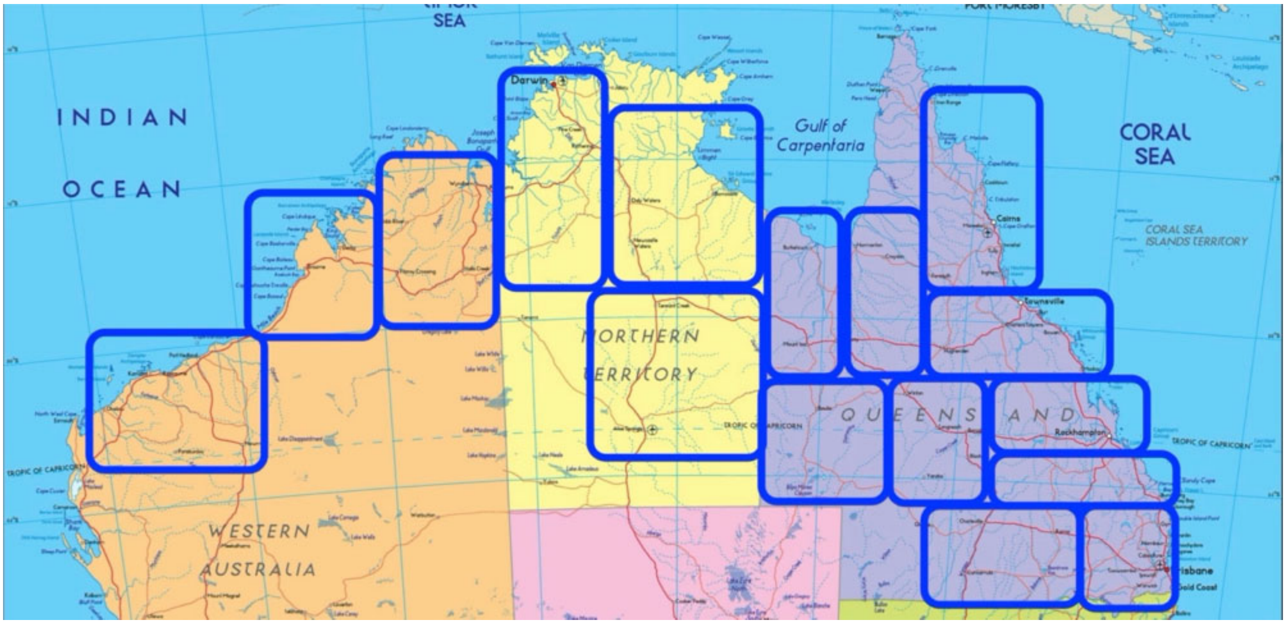

Fig. 1. NACP Climate Mate Regions (outlined in blue).

based at USQ provides training and technical advice and leads the planning and delivery of the extension activities.

The NACP extension is modelled on the 'staircase of engagement' (Hewitt *et al.* 2017), which provides a valuable framework for planning, implementing and evaluating the extension activities. Through this, Climate Mates are tasked with achieving Key Performance Indicator (KPI) targets relating to delivery of awareness ('Category A'), change in knowledge, attitude, skills, aspirations (KASA; 'Category B'), and change in practice ('Category C'). Awareness is achieved through passive engagement by providing information, usually through quick presentations, newsletters, websites and tools. A change in KASA comes through providing dialogue-based activities often in interactive groups such as workshops, and a change in practice (e.g. adoption of SCFs to inform decision-making) often necessitates active engagement with tailored and targeted discussions and focussed relationships, often through face to face interaction between the Climate Mate and an individual producer.

Other evaluation

The value of SCFs was investigated in short-term single decision case studies with producers and in long-term modelling studies.

The value of investing in the NACP was estimated using benefit-cost analysis (BCA) conducted by an independent assessor (Chudleigh *et al.* 2020) according to the Impact Assessment Guidelines of the Council of Rural Research and Development Corporations (CRRDC 2018).

Program results and discussion

Since commencing in 2017, the NACP RDandE components have addressed some of the previously identified barriers to greater adoption of climate information and the limitations to the approaches taken.

NACP research – potential benefits relative to industry needs

The research component of NACP has progressed to address the needs of the livestock industry (Table 1). The primary achievements to date represented by scientific publications are summarised and evaluated against industry needs in Table 2.

Model development driven by NACP includes improvements in the ability of the ocean and atmospheric 'coupled' models in experimental mode (not operational) at the UKMO and the BoM to better represent the base climate in northern Australia, which is a pre-requisite for more accurate forecasts in operational models. The process of model development and improvement takes years and is discussed later in the paper.

NACP research into drought has focussed on flash droughts and multi-year drought prediction. Flash droughts are drought conditions that arise more rapidly (on a scale of weeks) than traditional slower onset droughts, usually due to a combination of high temperatures, low humidity and high winds that provide little opportunity for preparedness (Otkin *et al.* 2018), such as selling stock or buying additional fodder. Risk related to flash droughts for livestock producers includes a sudden reduction in pasture availability and quality leading to reduced duration of pasture budgets, cattle weight and condition, as well as risks to land condition with increased exposure to soil erosion due to loss of protective ground cover (Aubault *et al.* 2015). Predicting flash droughts at the sub-seasonal to seasonal time frame is an area of active research, with Pendergrass *et al.* (2020) advocating the need for early warning forecasts of flash drought to support risk management. Research into the Evaporative Stress Index (ESI) conducted by NACP is contributing to improved understanding and potential to forecast flash drought on sub-seasonal scales, with the ESI shown to effectively capture

Table 2. Summary of NACP research published and its links to address industry needs

RDandE issue	Short title	Scientific references	Industry needs addressed (see Table 1 for codes)
Model development and evaluation	Forecasting extreme rainfall, temperature and wind	Cowan *et al.* 2019*a*	R1, R2
	Ensemble prediction for forecasting extreme events	Hawcroft *et al.* 2021	R1
Flash drought	ESI to monitor flash drought	Nguyen *et al.* 2019	R4, D2, D4
	New challenge for sub seasonal prediction	Pendergrass *et al.* 2020	R4
	Climatology and variability of the ESI and suitability to monitor drought	Nguyen *et al.* 2020	R2, R4, D2, E5
	The 2019 flash drought in sub-tropical eastern Australia	Nguyen *et al.* 2021	R4, D1, D2, D4
Multi-year variability and drought	Mechanisms for multi-year variation	Sharmila and Hendon 2020	R4
Climate variability, extremes and change	Spatial shifts in rainfall and pasture growth variability	Cobon *et al.* 2019	D3, D5, E4
	Impacts of climate change on native pastures and beef cattle	Cobon *et al.* 2020*a*	D3, D5, E4
	Climate information and spatial diversification increase profit and reduce risk	Nguyen Huy *et al.* 2020	D3, D5, E4
Value of SCF	Value SCF. in northern beef industry	Cobon *et al.* 2020*a*	D4
Product development	Improving seasonal prediction of the NRO	Cowan *et al.* 2020	R2, R3, R5, D1, D2
	Forecasting wet season burst activity	Cowan *et al.* 2021	R5, D1, D2
	Prediction of the NRO	Cowan *et al.* 2019*b*	R2, R3, R5, D1, D2
Application of climate forecasts	NACP	(this paper)	D1, E1, E2, D2, E3, D3, E4, E5

drought conditions (Nguyen *et al.* 2020), including flash droughts (Nguyen *et al.* 2019, 2021).

At the other end of the drought temporal spectrum, NACP research has identified large-scale drivers of multi-year droughts across northern Australia (A. Weisheimer, M. A. Balmaseda, T. N. Stockdale, M. Mayer, E. de Boisseson, S. Sharmila, H. H. Hendon and O. Alves, unpubl.). A study by Sharmila and Hendon (2020) found that for north-eastern Australia, ENSO is the main driver of multi-year droughts while in north-western Australia, relationships between rainfall, wind and evaporation related to 'soil moisture memory' were linked to multi-year variations. With this new information into the source of multi-year droughts, NACP is researching the forecasting of multi-year droughts. The ability to provide accurate multi-year drought forecasts to producers would allow them more options for decisions regarding herd size and stocking rates than are currently available. For example, if a multi-year drought is predicted, a producer may make an earlier decision to reduce herd size either by selling when market prices are favourable or by reducing the number of mated cows, as well as buying additional fodder, to ensure the remaining herd can be sustained through multiple years of drought. A poster (Queensland Extended Wet-dry Period) documenting multi-year rainfall variability is a useful product used in NACP extension to explain the duration and extent of these 9–13 year historical cycles of rainfall (McKeon *et al.* in press).

NACP research has shown the variability of annual rainfall over the last five decades has increased compared with the previous five decades across the pastoral zone in Australia (Cobon *et al.* 2019) and the zone is under increasing pressure from climate change (Cobon *et al.* 2020*a*). A strategic management practice to mitigate the risk of climate variability, extremes and climate change is spatial diversification or having access to alternative pasture (e.g. ownership of properties in different locations and agistment of livestock to spread climate related risk) and moving livestock to other locations to optimise production (Larsen *et al.* 2015). NACP research has developed a spatial diversification model that can identify the optimal location of properties, measured by reduced risk and higher profitability, according to the status of ENSO (Nguyen-Huy *et al.* 2020). Integrating spatial diversification and climate information provides better estimates of optimised risk–profit trade-offs in different ENSO years compared with those decisions simulated without climate information. The model allows corporate business and producers to estimate the optimum proportion of total livestock allocated to each property across multiple grazing properties in different locations to achieve optimal targets of profit gain and risk reduction. For example, in making a spatial diversification decision the model can reduce risk by 5% when no climate information is used but incorporating climate information can reduce risk (i.e. losses) by 15, 86, and 22% in El Niño, La Niña, and neutral years, respectively. The model is also applicable to other parts of the world that are subject to climate variability and could be used to decrease exposure to climate risk and increase profitability for a range of agricultural sectors.

NACP has also developed two rainfall forecast products based on the current BoM seasonal prediction system ACCESS-S1, the Northern Rainfall Onset (NRO) and rainfall 'burst' products, to better meet producer needs. The NRO product, which is publicly available on the BoM website (http://www.bom.gov.au/climate/rainfall-onset/#tabs=Outlook), provides a forecast, issued fortnightly from June to August, of whether or not 50 mm of accumulated rainfall after 1 September will occur earlier than usual (Cowan *et al.* 2019*b*). This forecast provides producers with information about

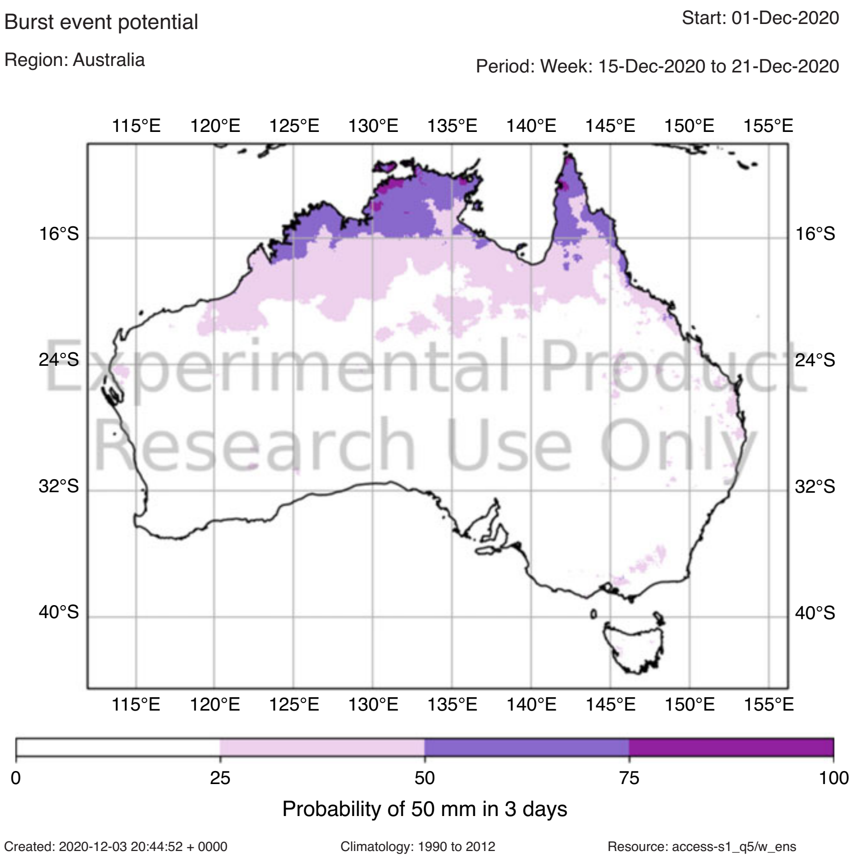

Fig. 2. Example of 'burst event potential' forecast available on BoM/NACP prototype website (private).

the likely timing of the start of the coming wet season, which is important for decisions around pasture availability and stocking rates (Cowan *et al.* 2020). The rainfall 'burst' product (Fig. 2), which is a forecast for a specified amount of rain (20–70 mm) over a short period (3 days), was requested by producers at NACP workshops in 2019 and 2020 (C. Jarvis, pers. comm.). Such information enables producers to evaluate the likelihood of 'useful' rain events, which might inform decisions dependent on access (e.g. passable road conditions for stock transport) or the timing of pasture or forage crop planting. These 'burst' forecasts, available as a prototype forecast product on a multi-week timescale out to 3 weeks, are undergoing verification by USQ researchers and evaluation by Climate Mates (Cowan *et al.* in press).

At a regional level, two NACP-generated papers (Cowan *et al.* 2019*a*; Hawcroft *et al.* 2021) have reviewed the forecasting of an extreme flood event in north Queensland in February 2019, significantly impacting local pastoral enterprises (Bureau of Meteorology 2019). Severe flooding, unusually cold temperatures and high winds resulted in widespread stock losses (Major 2019; Hall *et al.* 2020). Cowan *et al.* (2019*a*) found this event was linked to the MJO in combination with a positive phase of the Southern Annular Mode. A NACP study using new and unreleased research versions of the UKMO UM has shown that the model can be improved to predict the likelihood of these events more accurately at a multi-week timescale (Hawcroft *et al.* 2021), while future improvements to the BoM ACCESS-S model are likely to address current limitations (Vitart and Robertson 2018). Producers have indicated that 2 weeks' notice of an event of this magnitude would have allowed some management decisions to be implemented to reduce the incidence of drowning, such as opening up fence lines to allow cattle to move to higher ground and putting out hay (D. Lynch, pers. comm.). However, for many producers, there was nothing they could do to mitigate the impact of hyperthermia (P. Hick and E. Hick, pers. comm.).

A limitation that has become apparent from the NACP research is the significant time required for research into improving UMs, in this case ACCESS-S, to be made operational. For example, NACP researchers based at the UKMO are currently developing a system to improve the representation of convection in the UM, an improvement that would potentially improve the accuracy of SCFs. However, the new convection component is not expected to be active in the ACCESS-S prediction system until after the end of the current phase of the NACP. As such, when NACP extension personnel communicate to producers that NACP is working to improve SCFs, they need to also explain that those improvements may be years away. While this is a point of frustration among producers, there is currently no avenue to shorten the time from the development of model improvements to an operational component due to the rigorous testing requirements and the significant computational expense of this process.

NACP development – product to monitor and manage drought

NACP development has produced a web-based Australian Drought Monitor or Combined Drought Indicator (CDI), which is based on the United States Drought Monitor (USDM) that seeks to address inefficiencies associated with subjective assessments and provides a data-driven analysis of drought. Where the USDM uses over 30 indices with the output adjusted before publication by ground truthing observations from more than 420 contributors across the US (Svoboda *et al.* 2002), the CDI is developed using only data-driven indices with no manual adjustment. The CDI is based on a weighted combination of four different indicators: (1) Standard Precipitation Index (SPI; Guttman 1999); (2) soil moisture (SM); (3) evapotranspiration (ET); and (4) Normalised Difference Vegetation Index (NDVI; Carlson and Ripley 1997). It is calculated monthly from gridded data at a 5 km × 5 km resolution over Australia. The indices used in calculating the CDI are used worldwide for drought work. For example, the USDM and North American Drought monitor use the SPI and vegetation data, and the African Drought Monitor incorporates SM (Heim and Brewer 2012). Askarimarnani *et al.* (2020) showed that to adequately capture agricultural drought, a drought product should include multiple aspects of the hydrological cycle. This CDI captures both meteorological and agricultural drought.

The CDI provides users with ready access to spatial information on the status of drought in Australia. For ease of interpretation, the CDI is converted into categories ranging from the historically driest to wettest conditions (Table 3). CDI maps (e.g. Fig. 3) are available on the NACP website (www.nacp.org.au) at several rolling timescales, from 1 to 36 months (updated monthly). These different timescales enable users to observe how drought conditions have changed over both short (1 month) and longer time periods, which can be important in northern Australia where winters are seasonally dry. However, presenting the CDI maps on various timescales increases the risk of misinterpretation. For example, if an area that is seasonally dry receives even a small amount of rain (i.e. 10 mm), a 1-month CDI map could potentially show the area as 'wettest on record' even though the area may be suffering from a long-term drought. The use of a 1-month CDI map here has little practical application and does not represent the general drought status reflected in a map with a longer time frames, such as 12 or 24 months. To reduce this risk, descriptions outlining the relevance of the CDI maps based on different time scales (1, 3, 6, 9, 12, 24 or 36 months) are listed on the NACP Drought Monitor website.

Drought monitoring systems currently operate in Australia at the federal and state level. These include monitoring of drought conditions by the BoM, which uses rainfall, soil moisture and water storage levels to independently assess meteorological, agricultural and hydrological drought through an online drought service (http://www.bom.gov.au/climate/drought/knowledge-centre/drought-service.shtml). Other organisations such as the Australian Bureau of Statistics track drought impacts on

Table 3. The combined drought indictor categories expressed as ranked percentiles

Category	Value
Exceptional wet	98–100%
Extreme wet	95–98%
Severe wet	90–95%
Moderate wet	80–90%
Slightly wet	70–80%
Near normal	30–70%
Slightly dry	20–30%
Moderate drought	10–20%
Severe drought	5–10%
Extreme drought	2–5%
Exceptional drought	0–2%

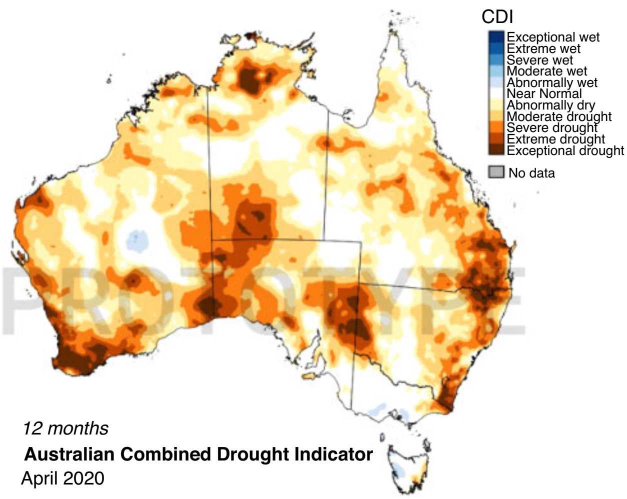

Fig. 3. The Australian Drought Monitor or combined drought indicator (CDI) for the 12 months to and including April 2020.

agriculture (Day *et al.* 2005), and the Department of Primary Industries in New South Wales (NSW) has a CDI of rainfall, SM and pasture growth for NSW (https://edis.d.pi.nsw.gov.au/), which was until now the only CDI available in Australia. Most states use a combination of local committees, single drought indicators and model output to monitor, declare and revoke drought conditions but some are moving towards a more objective, science-based and publicly-accessible indicator (e.g. Queensland, Wade and Burke 2019). The CDI is the first national assessment of drought using a combined indicator that covers both meteorological and agricultural drought, and has the potential for use in state and national drought policy. It fills a gap in currently available Australian drought products by providing country-wide drought information at different time scales to meet a range of end user needs, including indices beyond precipitation, and being data-driven. Using an objective approach means that the CDI output is reproduceable, which will help build trust in drought declaration and revocation processes in the future. A limitation of a CDI produced using interpolation of point data is the large distances in rural regions between data observations on which the interpolated data is calculated. The

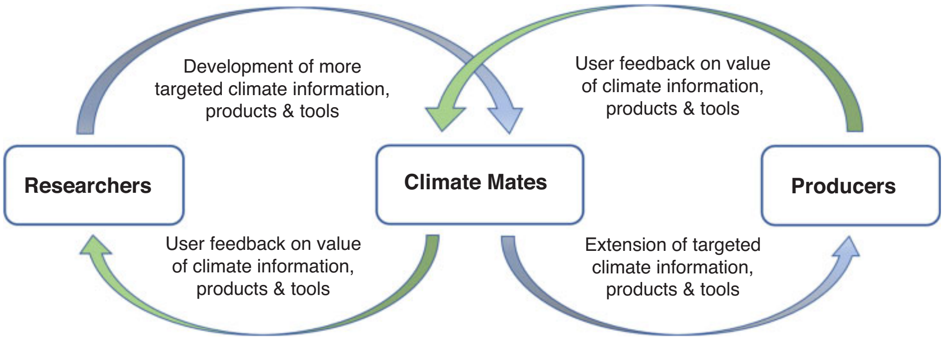

Fig. 4. NACP conceptual RDandE framework.

Table 4. NACP extension KPIs – Category A, B, and C targets and numbers of people meeting these categories current at December 2020

	Target, producers	Target, others	Current, producers	Current others	% Total producers	% Total others
Category A	5500	150	9629	14558	Exceeded	Exceeded
Category B	420	65	748	472	Exceeded	Exceeded
Category C	150	35	91	32	61%	91%

full use of data from satellites may reduce this limitation in future.

NACP extension – results leading to practice change

NACP extension is focussed on three key areas: (1) how to correctly interpret both weather and climate forecasts; (2) where to find reliable weather and climate information; and (3) how to apply this information to relevant grazing management and industry decisions.

NACP extension involves a two-way flow of information (Fig. 4). Specifically, it aims not only to communicate relevant climate information, but to close the loop between the users of climate information and the researchers and developers of the information, products and tools designed to support climate risk decision-making. In this way, the NACP represents a complete climate service, where the climate information needs of industry stakeholders is communicated, through the NACP extension team, to the NACP research and development teams to inform more targeted product development. Content delivered by NACP extension is tailored by region and season to meet the needs of users.

NACP extension results are outlined in Table 4. Many extension activities have occurred across the NACP regions to deliver the Category A, B and C targets reflecting the value of engaging, training and supporting a team of regionally-embeded Climate Mates with strong industry and regional connections. While the end goal of widespread practice change (i.e. livestock producers accessing climate information, interpreting it correctly and applying it in decision-making to improve their climate risk management) is still to be achieved, significant progress has been made in engaging producers and building trust in the program. In particular, feedback from producers indicates that NACP's combination of group-based extension (e.g. workshops co-presented with other Drought and Climate Adaptation (DCAP) projects Grazing Futures (Rolfe *et al.* in press); economic knowledge for better drought management outcomes (Bowen and Chudleigh 2021); InsideEDGE (McKeon *et al.* in press; and other groups) and one-on-one delivery is meeting the different needs of a range of producers, including those who are not comfortable with discussion in a group setting, while also allowing for knowledge sharing among producers at group events, as has been advocated by others (Marsh and Pannell 2000). Narratives and short case studies, which provide examples of how to successfully incorporate climate and SCFs into on-property decisions for better financial or resource outcomes, have also proven useful (examples in Table 5).

NACP has also completed a case study using a modelling approach to show the value of seasonal forecasts (Cobon *et al.* 2020*b*) over 115 years. Stocking rate decisions in October, before the onset of the wet season, are a key climate-sensitive decision. The analysis considered SCF value across economic drivers (steer price in October) and environmental drivers (October pasture availability). A range in forecast value was found (AU$0–14 per head) dependent on pasture availability, beef price and SCF accuracy. These case studies can be considered by graziers to evaluate the costs and benefits of using a SCF in decision making.

The Climate Mates are a critical component of the NACP extension project. The concept is similar to the 'Model Farmer' networks established in India (Taylor and Bhasme 2018) where local producers showcase new knowledge and technology to other producers. 'Climate Champions' programs in Canada (Gislason *et al.* 2021) and Australia (Department of Agriculture Fisheries and Forestry 2013) engage interested primary producer volunteers to work with scientists to further research and development. The Climate Mates program differs in that they are paid employees, and the program provides ongoing training and support from climate experts; however, similarly, it is envisaged that individual Climate Mates will continue to be an asset and an ongoing source of knowledge to their community

Table 5. Examples of practice change achieved by NACP Climate Mates for regions across northern Australia

Region	Activity Leading to Practice Change	Practice Change Action	Reflections
Pilbara	Producer was introduced to an online tool that provides information about when they can expect to receive the first 'good' rainfall of the season (50 mm) that would start pasture growth. Related management decisions were discussed.	Through the use of the tool and consultation with the local Climate Mate, the producer realised that cows were having calves before it was likely to have reliable rainfall and pasture growth. The producer is now working to shift his calving date to better align with likely rainfall.	The better the cattle operation can fit with the climate, the less risk and potential burden on the cattle (cows in poor body condition), land condition (high feed demand from new cows with calves) and business (needing to provide supplement feeding, poor animal and land condition, and reduced calving survival percentage).
Kimberley	New prototype BOM forecast products were shown to producer. Weekly follow-up meetings were then conducted as needed around the forecasts.	After regular evaluation and increases in familiarity with the products, the producer decided to change a planting (forage crop) date based on a forecast indicating very high temperatures during the time originally planned for planting. The temperatures were indeed high during the original planting time and by delaying planting, the producer benefited. The producer is continuing to check the forecast.	The benefits of a forecast product were realised only after regular consultations with the producer. These ongoing meetings were a key to achieving practice change.
North-west Queensland	Producer was regularly emailed NACP's Monthly Climate Outlook by local Climate Mate. In response to a dry forecast, the producer consulted more with the Climate Mate.	Given the dry outlook (November 2019) and likely risk of delayed pasture growth, the producer reconsidered plans to keep the usual number of weaned calves and instead, increased the number sold. Producer also decided to wean calves early.	Use of the Monthly Climate Outlooks that include seasonal rainfall and temperature forecasts, allowed the producer to prepare for the likelihood of a dry year and make a new plan early.
Central Queensland	Climate Mate consulted with a producer who was not seeing the returns they wanted, in large part due to dry conditions and lack of pasture.	The Climate Mate and producer discussed climate variability for the producer's area, with the producer realising that rainfall is much more variable than originally thought. As such, the producer decided to diversify from a cattle breeding property to one that also included more cattle trading and holding cattle just before entry to a feedlot.	By diversifying, the producer is provided more options in dry years, to avoid financial losses and take advantage of good/wet years by holding more cattle via cattle trading and preparation for feedlots.
South-west Queensland	Producer was initially provided with the NACP Monthly Climate Outlook and a pasture growth outlook by the Climate Mate. The producer then requested more information and an on-property visit by the Climate Mate	During discussions with the Climate Mate, it became apparent that the producer's stocking rate (number of cattle per area) was too high, resulting in stress to the cattle and land. A month after the visit, the producer sold cattle, based in large part on the climate and pasture growth outlook (dry).	The producer appreciated the willingness of the Climate Mate to spend time on the property to help better understand how climate and pasture outlooks fit in to stocking rate decisions. Time on the property also resulted in an information exchange with a neighbouring enterprise who joined in discussions and was provided with Climate and pasture reports for their property.

long after the project finishes. This ties into the importance of building and maintaining social capital in regional areas (Curtis *et al.* 2014).

The value of taking a regional approach to extension was highlighted by Siepen and Westrup (2002) who found that incorporating regional knowledge and community understanding was essential to a successful extension program. Taking this one step further, experiences in Western Australia found that producers prefer to listen to other producers, thus making the ideal extension officer a local producer (Parlevliet 1987). In 2021, with seven of the 16 NACP Climate Mates also involved in running cattle properties or employed in the cattle value chain (e.g. transport), NACP extension experience supports this contention. However, Dowd *et al.* (2014) argue that extension is more likely to lead to practice change when the extension officer has extensive knowledge on the topic, but weak social ties and is not confined by local social norms. Others also argue that hiring extension officers from within the community potentially supports existing local power structures and risks disenfranchising a portion of the community (e.g. Naess 2013; Cafer and Rikoon 2017; Taylor and Bhasme 2018). While the NACP Climate Mates program employs well-known local individuals, it also connects the extension program directly with research and provides annual training, monthly climate and weather updates, thus affording an ongoing link to the latest knowledge that in some ways may address the concerns raised by Dowd *et al.* (2014). We are not aware of community disenfranchisement here but the potential for issues such as this arising are worthy of monitoring.

While combining local knowledge and needs with scientific research has been useful to both parties and created a powerful RDandE program (Sinclair and Walker 1999), Leeuwis (2004) warns that programs that involve both academic research and extension components can be challenging due to the tendency for different players to perceive problems differently and apply their own solutions. However, the NACP has not so far encountered cross-disciplinary cooperation issues of this nature. Instead, it has found that the academic researchers involved highly value the interaction with producers and the information they provide, which are driving significant improvements in forecast products, and that the producers greatly appreciate the attendance and input of the BoM at regional meetings and events.

The NACP Climate Mates work closely with other relevant organisations in their regions, contributing to stronger extension networks and increased opportunities to share expertise and resources across multiple projects, providing additional gains in efficiency of planning, organisation and delivery of programs in the extensive and often remote regions. NACP extension also regularly conducts 'train the trainer' workshops (Prokopy *et al.* 2015) with related extension groups, providing opportunities for other extension officers to learn about climate, which can then be further shared with their networks and integrated into their programs.

Online training resources were developed to cope with restrictions imposed by the 2020 COVID-19 pandemic. These include a video module series for producers and other interested stakeholders called 'Forecasting for Decision Making', which presents basic information on the main climate drivers for northern Australia and can be used on its own or more ideally, in conjunction with an in-person or online workshop on how to apply the climate information in decision making. This delivery mode also allows NACP information to reach those in remote areas who may not have the time or finances to attend in-town workshops, a barrier to the success of extension programs as discussed by Marsh and Pannell (2000). To overcome issues with internet connectivity and bandwidth, NACP also mailed course content on a USB with a printed workbook.

While the NACP Climate Mate program has had many successes, there have also been some short comings. First, producer engagement varies by region. For example, producers in the Fitzroy Basin area of Queensland have been very proactive in organising and attending NACP workshops, while in other areas such as the Barkly Tablelands in the Northern Territory, it has been difficult to reach anyone. While there does not appear to be any one reason for this disparity, ownership type, whether by individual or corporation, seems to play a role. Generally, corporations have an interest in learning more about climate information, but it has been difficult to organise presentations to these groups, with the need for participation to be approved by those higher up in the organisation than individual station managers. Second, employee turnover has been an issue and the training of new Climate Mates is both time consuming and inefficient to do on an individual basis. Third, poor seasons (i.e. a 'failed' wet season/drought) or forecasts for rain that did not eventuate can erode confidence in the SCFs and impact attendance at events. This is a major concern and one that has been documented elsewhere (e.g. Ash *et al.* 2007; Marshall *et al.* 2011). NACP extension aims to address this by providing information on how to correctly read and interpret SCFs as a key focus of all workshops and presentations, with experience revealing that once producers better understand probabilistic forecasts, they are less likely to view a forecast as 'wrong' and hence dismiss further forecasts outright. The need for improved SCF accuracy remains an ongoing issue (Cobon *et al.* 2018) as does cost-effective education through extension.

Estimated value of investment in NACP

The NACP RDandE approach, based on integrating high-quality research informed by industry and community needs and robust extension, could be applied in other regions, both domestically and internationally. The positive achievements of the NACP described above are further supported by analysis that indicates the potential for investment in such programs to deliver substantial benefit to agricultural industries and associated rural communities.

The value of investing in the NACP was estimated using BCA (Chudleigh *et al.* 2020). Total funding from all sources over the project duration (cash and in-kind) was approximately AU$15.91 million (present value terms). Past and future cash flows in 2019/20 Australian dollar terms were discounted to the year 2019/20 using a discount rate of 5% to estimate the investment criteria. Potential benefits of the program were estimated for 30 years from the last year of investment in the project (2021/22).

The value of total benefits estimated from the information delivered by the NACP is estimated at AU$83.66 million (in present value terms) with an estimated net present value of AU$67.74 million and a BCA of 5.26:1. The principal impact identified and valued in this assessment was 'improved management decision making by producers in northern Australia leading to increased productivity and profitability of some Queensland pastoral managers'. Further impacts delivered by the program that were valued in the BCA were an improved social licence for grazing activities in pastoral Queensland and a contribution to reduced government costs in delivering drought policy and support.

While positive, this independent BCA of the NACP potentially undervalued the benefits delivered by the NACP because several potentially important outcomes of the program were not valued in monetary terms, including: (1) the benefits to beef producers in the Northern Territory and northern Western Australia. Had these benefits been included, the estimated BCA was 6.2:1; (2) the scientific (climate modelling and product development) capability and future capacity built by the NACP investment will have ongoing benefit across northern Australia beyond the livestock production industry and associated supply chain; and (3) the analysis did not include the benefits to regional communities from reduced variability in producer income, which is likely to be important for the sustainability of local businesses and the socioeconomic health of communities across the region.

Conclusion

The NACP is a fully integrated RDandE framework that enables ongoing interaction between leading climate scientists and forecasters, climate applications specialists, climate advisers, extension and adoption practitioners, producers and policy makers. It represents a transition from top-down programs to provide expert climate information to users in a 'closed loop' model that provides a targeted user-informed climate service.

The NACP builds on a strong history of climate variability and drought RDandE for primary industries conducted in Australia (e.g. Hammer 2000; Meinke and Stone 2005; Ash *et al.* 2007; Marshall *et al.* 2011; Cobon *et al.* 2019), which has and continues to have significant influence internationally. The fully integrated RDandE structure in NACP is addressing identified shortcomings and impediments of currently available climate information and its use, issues that are relevant for decision makers globally. Project partnerships with embedded employees at the BoM and UKMO are working to improve climate models and by extension, SCFs. NACP research and development components are addressing gaps in the currently available range of products to better meet the needs of northern Australian livestock producers and associated industry partners. By linking ongoing research and development with extension, NACP avoids separating knowledge from those who need to pass it along to producers, which is a short coming of many extension programs (Marsh and Pannell 2000). Furthermore, the capacity for two-way information flow between producers and researchers at the BOM and UKMO has proven critical to addressing the climate product needs of producers to the extent possible given current technological limitations and is in line with international calls to encourage demand-driven climate services (WMO 2014).

While the NACP applies specifically to pastoral production systems in northern Australia, it provides a working example of the value of integrated user-informed RDandE to better address the complex issues and decision-making challenges associated with agricultural production systems, especially those operating in highly variable and changing climates.

Conflicts of interest

The authors declare no conflicts of interest.

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