Department of Primary Industries
and Regional Development

Dairy Pastures

Results Report

Climate Vulnerability Assessment

NSW
GOVERNMENT

Authors

The NSW Department of Primary Industries and Regional Development Climate Vulnerability Assessment and Dairy teams.

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Data availability

The geospatial data which was used to prepare this report (including parts of the model not presented in detail) is available on SEED, the NSW Government's environmental data portal: https://datasets.seed.nsw.gov.au/group/climate-vulnerability-assessment.

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Acknowledgement of Country

The NSW Department of Primary Industries and Regional Development acknowledges that it stands on Country which always was and always will be Aboriginal land. We acknowledge the Traditional Custodians of the land and waters and show our respect for Elders past, present and emerging. We are committed to providing places where Aboriginal people are included socially, culturally and economically through thoughtful and collaborative approaches to our work.

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Introduction

Storm and Flood Industry Recovery Package

The Storm and Flood Industry Recovery Package (SFIRP) Program 2a. The Natural Disaster Vulnerability and Risk Assessments project aims to support the preparedness of the NSW Dairy Industry for future climate change by improving understanding of the industry's climate vulnerability as well as potentially exploring opportunities under climate change and assessing the value and effectiveness of adaptation options for overall resilience and continued productivity.

Climate Vulnerability Assessment

The aim of the Dairy Climate Vulnerability Assessment was to deliver a consistent and state-wide understanding of the climate change impacts on primary industries in NSW, providing strategic information for policymakers and industry. This information will help the Dairy industry understand the risks ahead, prepare and adapt to any identified climate vulnerabilities, and take advantage of future opportunities in the Dairy industry in NSW.

Purpose of this report

This report contains results for the dairy pastures model within the Climate Vulnerability Assessment. The report introduces the dairy industry in NSW and provides an overview of the model, key features, assumptions, and exclusions. The main modelling results and findings provide insights into future climate vulnerabilities and opportunities. Where appropriate, the report also provides adaptation options.

Climate within NSW

The climate in NSW varies across the state, influenced by topography, weather patterns, and proximity to the Great Dividing Range and the Tasman Sea. The state's diverse climates include arid and semi-arid inland regions, humid subtropical coastal areas, temperate coastal regions, and alpine areas.

The changing climate is impacting primary industries.

Australia has one of the world's most variable climates, and its primary producers have always managed climate variability. Now, they are planning for and adapting to climate change arising from anthropogenic greenhouse gas emissions. These changes in long-term climate patterns at global and regional scales are adding a new dimension to the challenge of producing food and fibre in Australia. Changes in climate include increasing temperatures and alterations to rainfall patterns, alongside increasing challenges from extreme events.

This $23.1 billion sector supports economic growth and development, contributes to food security at the state and national scale and plays a vital role in biosecurity management. The limited availability of practical and targeted information on the impact of climate change on commodity productivity or the changing prevalence of biosecurity risks has limited adaptation to climate change in this sector.

Projected climate change impacts

A review of research literature on the impacts of projected climate change on primary industries in Australia revealed disparities in research efforts across the primary industry sectors and in our understanding of what is likely to occur.

Climate change is expected to impact both pastures and dairy cows across dairying regions in Australia. The main factors driving these changes in the projections are shifts in rainfall patterns and rising temperatures. Some regions may be impacted less by climate change. For instance, in NSW, projected temperature increases of 1.2–2°C by 2040 under the high emissions scenario would negatively affect the productivity of both dairy cows and pastures[1].

Changing rainfall patterns, higher temperatures and decreased water availability are likely to have negative effects on the pastures and forages[2]. This could lead to poor-performing pastures and ultimately result in changes to the feed base used on these farms.

By 2050, research suggests that the number of moderate to severe heat stress days could increase by 31 to 42 days compared to past levels[3]. This increase in heat stress days in the Riverina Murray dairy region is likely to adversely affect milk production in cows. Therefore, further investigation into future trends in heat stress across all dairy regions in Australia is necessary.

However, it is challenging to draw a consistent and comprehensive understanding of the effects of climate change from these studies because of the differences in methodology, assumptions, and projection data used[4].

Assessing the impacts of climate change

The Climate Vulnerability Assessment applied a consistent method to examine the potential impacts of climate change on a wide range of economically important primary industry commodities and biosecurity risks in NSW, including livestock and grazing systems. This enables us to identify those industries most at risk and, thus, most in need of adaptation strategies, as well as those where climate change might bring new opportunities and relief from existing challenges.

[1] Hennessy, K, Clarke, J, Erwin, T, Wilson, L and Heady, C (2016). Climate change impacts on Australia's dairy regions. CSIRO Oceans and Atmosphere, Melbourne, Australia, 64p
[2] Eckard, R. J., & Cullen, B. R. (2011). Impacts of future climate scenarios on nitrous oxide emissions from pasture based dairy systems in south eastern Australia. *Animal Feed Science and Technology*, 166, 736-748.

[3] Nidumolu, U., Crimp, S., Gobbett, D., Laing, A., Howden, M., & Little, S. (2014). Spatio-temporal modelling of heat stress and climate change implications for the Murray dairy region, Australia. *International Journal of Biometeorology*, 58, 1095-1108
[4] Darbyshire, R. O., Johnson, S. B., Anwar, M. R., Ataollahi, F., Burch, D., Champion, C., Coleman, M. A., Lawson, J., McDonald, S. E., & Miller, M. (2022). Climate change and Australia's primary industries: factors hampering an effective and coordinated response. *International Journal of Biometeorology*, 1-12.

Dairy pastures in NSW

Dairy is a significant agricultural industry in NSW, with most production underpinned by pasture and forage systems. NSW is the second largest dairy-producing state in Australia, and the industry is a major source of employment in regional areas[5]. Over the 2024/25 financial year, the NSW industry produced 1071 million litres of milk, contributing 12.8% of Australia's milk production[5].

The industry is widespread across different climates in NSW (Figure 1), from a subtropical climate in Lismore to semi-arid conditions in Finley. Most dairy farms in NSW are located on the mid-north coast or the far south coast. As of 2025, there are 443 total licensed dairy farms in NSW with an average milking herd size of 343 cows[5].

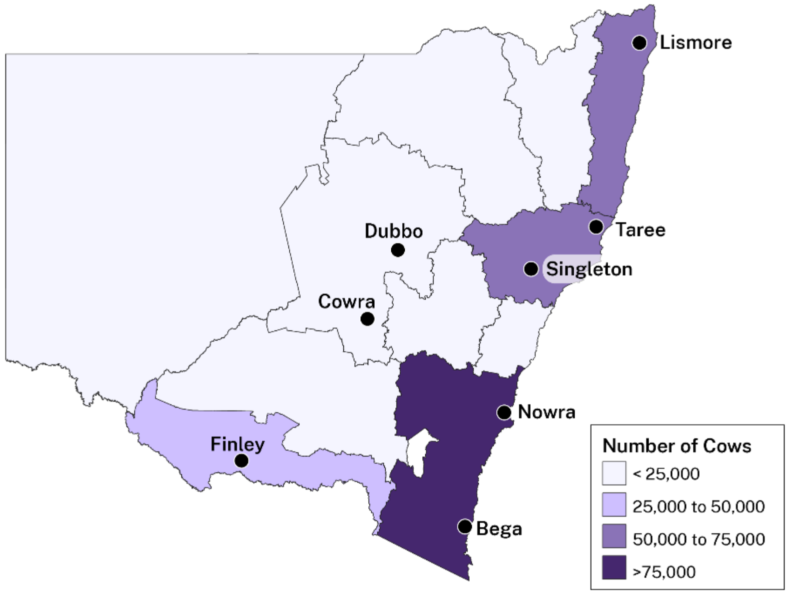


Figure 1: Number of dairy cows by NSW Local Land Services region.

[5] NSW DPIRD, 2025. NSW Dairy Industry Overview

Key pasture species for NSW Dairy Industry

The NSW dairy industry grows a variety of pasture species that underpins the feedbase for dairy cows. Six key pasture species were chosen for the Climate Vulnerability Assessment, including kikuyu, ryegrass, white clover, lucerne, forage oats and chicory. These species were selected based on relevance to the dairy industry and areas across the state where they are found. It is important to note that other forage species still play a role in the dairy industry but may not be as significant due to their lack of persistence or feed quality, or if they are still not yet in widespread use.

For other reports please see the website

The dairy industry also relies heavily on other forage and broadacre cropping species such as maize, barley and wheat. Climate Vulnerability Assessment result reports for these crops are available separately. For further details on these, please see Climate Vulnerability Assessment Broadacre Cropping.

Climate Vulnerability Assessment framework

The Climate Vulnerability Assessment was intended to provide an overview of the impact of future climate change on all stages of production for the commodities and biosecurity risks assessed. To achieve this, a modelling approach was adopted that would produce assessments for the commodities and biosecurity risks in a consistent and therefore comparable way.

Figure 2: Outline of expert engagement in the assessment framework developed by the Climate Vulnerability Assessment. Internal and external experts are involved throughout the process, helping to develop and refine the model of their primary industry commodity or biosecurity risk.

The assessment framework, outlined in Figure 2, provides a rigorous, flexible and transparent process for assessing vulnerability to climate change. It begins with a literature review, used to inform a draft model of the commodity or biosecurity risk. External experts review the model at three points during the model development, as a small focus group. The participation of experts throughout the process was critical for integrating expert knowledge into the models developed by the Climate Vulnerability Assessment.

Six staff from the NSW Department of Primary Industries Dairy Team contributed to this process, and a further 10 experts took part in the focus groups to support the review and refinement of the models. External experts were drawn from industry bodies, producers, and academia.

MCA modelling approach

The steps in the framework developed for the Climate Vulnerability Assessment are designed to identify and compare the climate variables important in the production of each commodity and the survival of each biosecurity risk assessed. The chosen modelling approach, using multi-criteria analysis (MCA) models, allows knowledge obtained about these climate variables from scientific literature, expert focus group knowledge and other sources to be combined in a way that is consistent across all commodities and biosecurity risks.

A simple MCA model with customisable assumptions and exclusions (detailed below) was developed for each commodity and biosecurity risk. A hierarchical structure underpins the MCA modelling approach, and the models were developed using a combination of empirical data and expert judgment. The commodity or biosecurity risk sits at the top of the hierarchy, which is then divided into the key production phases, each of which contains the climate variables that influence that production phases.

Each life stage is weighted relative to the others to reflect the importance of its contribution to the overall success in the growth of the commodity or the survival of the biosecurity risk. The weightings are derived using the analytical hierarchy process[6] and reflect the consensus reached by the focus group experts.

[6] Saaty, T.L. (1980) The Analytic Hierarchy Process, McGraw-Hill, New York

The MCA model is not designed as a yield estimating model but as a *climate suitability* model. *Climate suitability* is defined as the extent to which climatic conditions satisfy the requirements of plant or animal growth in the absence of other limiting factors[7]. The model provides an assessment of climate suitability (ranging from unsuitable to highly suitable) for each climate variable, for each production phase, and for the commodity overall. Climate suitability is modelled for both historical (recent past) conditions and for projected (near future) climate to understand how the climate suitability for the pastures may be affected by climate change.

Experts reviewed the historical and future assessments and provided insights and interpretations, highlighting findings of importance for future planning. The following sections of this report provide an overview of the model structure for pastures and key results showing important changes to future climate suitability for dairy pastures, as identified by the assessment.

For further details on the Climate Vulnerability Assessment Project framework, MCA models, and climate data (historical observations and future projections), please refer to the Climate Vulnerability Assessment Methodology Report.

The project limitations and exclusions are briefly summarised to the right, and the pasture species model-specific assumptions are summarised on the next page.

Project scope and exclusions

The scope was limited to the assessment of vulnerability to future climate change. The assessment captures the response of pastures to changes in future average climatic conditions. The project was designed to support policy and regional investment decisions, not provide farm-scale advice. The following were not considered:

- soil properties,
- topography,
- other non-climatic biophysical parameters,
- socio-economic factors, and
- water availability into the future.

These exclusions should be considered alongside the project's findings when examining the ongoing or future viability at a given location.

Certain climate data were excluded due to future climate projection data limitations. Models excluded wind due to its variability on short timescales and the use of relative humidity on timescales shorter than a month. Extreme weather events such as intense rainfall, heatwaves, storms, drought, floods, and bushfires were also excluded due to their unpredictable nature and the complexities of their interaction with the climate. Future work incorporating more sophisticated future climate projections as they become available is likely to provide an improved capacity for describing the impacts of extreme weather events and climate variability.

[7] Zhao, J., Yang, X., Liu, Z., Lv, S., Wang, J. and Dai, S. (2016) Variations in the potential climatic suitability distribution patterns and grain yields for spring maize in Northeast China under climate change. Climatic Change, 137:29-42.

Overview of the pasture species models

For more information about the MCA modelling used in this project, see the **Climate Vulnerability Assessment Methodology Report.**

Climate variables

The climate variables used in the pasture models include minimum temperature (Tmin, °C), mean temperature (Tmean, °C), maximum temperature (Tmax, °C) and growing degree days (GDD).

Categorising climate variables

The hierarchical structure of the MCA models categorises climate variables to assess their impact on pastures. Each category (for example, a temperature between 15 and 30°C) is assigned a rating, R, between 0 and 1 that indicates how well it suits pastures, from unfavourable (R=0) to optimal (R=1). This is repeated for each life stage.

Modules used in pastures MCA

The pasture MCA models use the following standardised modules to produce ratings from the climate variables:

- **Proportional module:** assigns climate suitability as the average rating of all days during a given month.
- **Threshold module:** assigns climate suitability according to the number of days spent below or above a key climate threshold during the given month**.**
- **Lethal conditions**: Define extreme climatic conditions that are fatal to the pasture or growth stage. If these limits are reached, then the life stage dies (indicated by an R = -2 in Figure 4). During each month, if the threshold for lethal conditions is reached, then climate suitability is set to zero for that entire month.
- **Matrix module**: Matrices assign climate suitability based on the interaction between two climate variables. For example, the ryegrass model used a matrix combining monthly mean temperature with monthly cumulative rainfall, because the pasture is particularly sensitive to the interplay between temperature and rainfall. Matrix categories define different combinations of climatic conditions; for example, again for ryegrass, temperatures between 10 and 18°C and cumulative rainfall of between 75 and 100mm were assigned a rating of 0.5. The matrix ratings identify the suitability of each specific combination, from unfavourable to optimal conditions.

The ratings for each climate variable, together with the weighting assigned to each branch in the hierarchical structure and the climate data itself, produce the climate suitability index for pastures.

Dairy pasture model assumptions

A model represents a simplified version of reality. Assumptions and exclusions simplify complex systems by reducing the number of influencing factors, enabling model development. In addition to the global assumptions and exclusions, the dairy pasture models also contain the following exclusions:

- There is no assigned sowing date.
- No specific pasture varieties were used.
- Best practice grazing management optimises production without land degradation.
- The pastures are free of pests and diseases.
- Competition between weeds and pastures is not considered.
- Pastures were rain-fed with no supplementary irrigation.
- Environmental influences on phenology (e.g., vernalisation, photoperiod, thermal time) were not explicitly modelled for all species.
- Soil properties (fertility, moisture, texture, hydraulic properties, organic matter, nutrients) are assumed non-limiting.

Pasture-specific model assumptions

Each dairy pasture model also contains the following exclusions:

Chicory

- Species is already established.
- Soil water availability is assumed to be at an ideal root depth.
- The vernalisation requirement is assumed to have been met.

Forage oats

- Thermal time accumulation above a defined threshold was assumed to trigger seed head development without the involvement of other environmental factors such as photoperiod or vernalisation.

Kikuyu

- Species is already established.

Lucerne

- The variety was winter active with a ‘dormancy rating’ of 7.

Ryegrass

- Species is already established.
- Thermal time accumulation above a defined threshold was assumed to trigger seed head development without the involvement of other environmental factors such as photoperiod or vernalisation.

White clover

- Species is already established.

Model assumptions and limitations for pastures: why do they matter?

Our primary objective is to assess the climate suitability for pasture growth. The models focus on determining whether pastures can grow and thrive in a given climate rather than quantifying pasture productivity. Our modelling includes certain assumptions, as described. Some project-wide assumptions or limitations are based on the project's methodology and the available data, while others aim to ensure that the modelling outputs are useful for all dairy regions in NSW.

Due to limitations in our methodology and data availability, factors influencing pasture development were not fully considered for all species.

The modelling does not investigate the triggers of seed head development, which leads to senescence and the eventual death of annual pasture species. Several factors influence this process, including the timing of sowing, soil properties, pasture management practices, grazing approaches, and environmental conditions such as temperatures and day length. Most of these factors fall outside the project scope due to the methodology used.

To ensure that modelling outputs were relevant for all dairying regions, we assumed there was no fixed sowing date for each pasture.

Although we could select a specific date, it would vary significantly across dairying regions. By not specifying a particular date, we can accommodate a range of sowing times throughout NSW, allowing individuals to focus on the most relevant months for their region. One disadvantage of not having fixed sowing dates — especially for ryegrass and forage oats — is that while our results suggest it is possible to grow ryegrass during the summer in high rainfall areas, doing so may not be advisable due to the modelling assumptions and management factors that we have not considered.

It is important to be aware of these limitations and assumptions in the modelling outputs when reviewing the findings presented in this report. The project aims to examine broad trends in changing climatic conditions that could affect pasture growth across all of NSW and to highlight significant areas of change. These trends will help identify important shifts and regions where further localised studies should be conducted. Such studies could utilise other modelling approaches, like SGS and GRAZE, which account for additional factors such as soil conditions and stocking rates. These modelling approaches would be more suitable for informing changes on smaller scales and are appropriate for individual farms.

Interpreting the results

The results are presented as panels of 7 maps, comparing historical climate suitability with climate suitability under the two future emissions scenarios (RCP4.5, an intermediate emissions scenario and RCP8.5, a high emissions scenario). For the future emissions scenarios, maps of change and confidence in change in climate suitability are also presented.

The historical climate suitability map shows the mean suitability for 30 years (1981 to 2010). For future projections, the mean suitability for 30 years (2036 to 2065) was calculated for 8 global climate models[8] (GCMs), and the median of these models was used to produce ensemble future projection climate suitability maps.

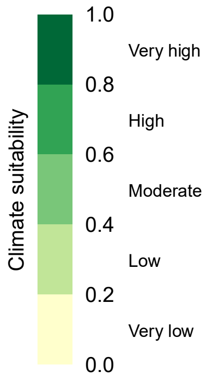


Figure 3: Colour scheme for the climate suitability maps

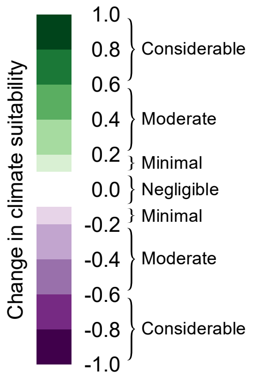


Figure 4: Colour scheme for the change in climate suitability maps

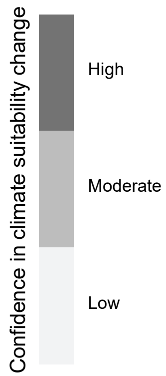


Figure 5: Colour scheme for the confidence in the change in climate suitability maps

Climate suitability maps

The 'climate suitability' maps show the climate suitability on a scale of 0 to 1. Pale yellow is very low suitability, and dark green is very high suitability.

Change in climate suitability maps

The 'change in climate suitability' maps use a green-white-purple colour scheme with 11 categories: positive change in green, where the future becomes more suitable; negative change is in purple. Negligible change is represented by white and occurs for values between −0.1 and 0.1, where the future suitability will be very similar to the historical.

Confidence in the change in climate suitability maps

The 'confidence in change in climate suitability' maps represent the level of agreement across the ensemble of 8 global climate models on the direction and magnitude of change in climate suitability. The lightest shade of grey represents low confidence, and the darkest shade of grey represents high confidence.

[8] Data was sourced from Climate Change in Australia: Application Ready Data

Interpreting the number of highly suitable months

The number of highly suitable months per year is defined as the average number of months with high or very high climate suitability. The results are presented as panels of maps, comparing the historical number with future numbers under the two emissions scenarios.

For the future emissions scenarios, maps of change and confidence in change in climate suitability are also presented.

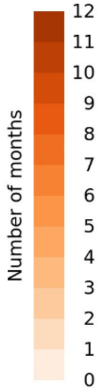


Figure 6: Colour scheme for the number of highly suitable months maps

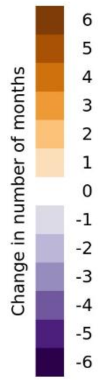


Figure 7: Colour scheme for the change in the number of highly suitable months maps

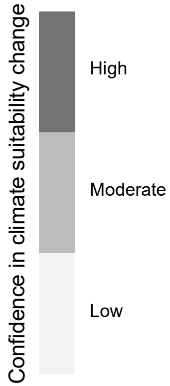


Figure 8: Colour scheme for confidence in the change in the number of highly suitable months maps

Number of highly suitable months maps

The 'number of highly suitable months' maps show the mean number of highly suitable months on a scale of 0 to 12. Pale orange corresponds to a low number of months, and dark orange corresponds to a high number of months. The values represent the mean over all years (historical or future projections periods) and can take any value between 0 and 12 (they need not be whole numbers).

Change in the number of highly suitable months maps.

The 'change in the number of highly suitable months' maps use a purple-white-orange colour scheme with 11 categories. Shades of orange indicate an increase in the number of highly suitable months; shades of purple indicate where the number is likely to decrease. Negligible change is represented by white and occurs for values between -0.5 and 0.5; in these areas, the future number of highly suitable months will be very similar to the historical number.

Confidence in change in the number of highly suitable months maps

The 'confidence in the change in the number of highly suitable months' maps represent the level of agreement between the ensemble of 8 global climate models on the direction and magnitude of change in the number of highly suitable months. These maps use a grey colour scheme with three categories: the lightest grey represents low confidence, and the darkest grey represents high confidence.

Interpreting climate suitability calendars

Climate suitability calendars are shown for individual sites of interest. These plots provide a visual comparison of the change in climate suitability over the year, comparing the mean historical climate suitability with the median future climate suitability for each emissions scenario (RCP4.5 and RCP8.5). Climate suitability calendars for each pasture species are included, showing historical and future climate suitability at sites in each dairy region. Climate suitability calendars comparing all species in each dairy region are also shown.

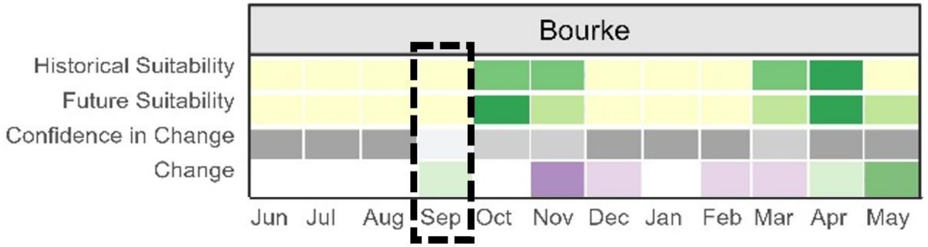
Climate suitability calendars use the same colour categorisation as the climate suitability panels (Figure 3, 5 and 6), except that the 'change in climate suitability' maps use 7 colours instead of 11, condensing them into the following categories: negligible, minimal, moderate and considerable.

There are two important points to note when interpreting climate suitability calendars. One occurs when the historical and future climate suitability categories are the same, but the 'change in suitability' is non-negligible (green or purple; see Example 1). The other occurs when the change from historical to future climate suitability is negligible (white), but the climate suitability is in different categories (see Example 2).

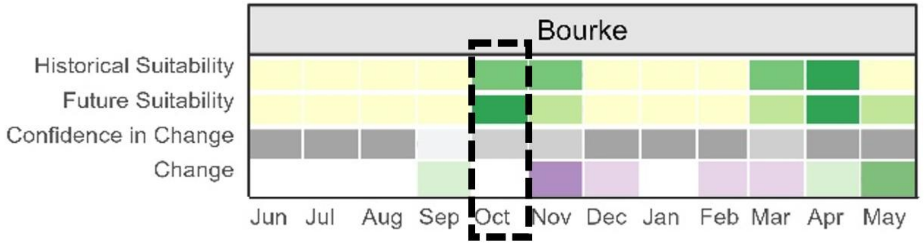
The situation shown in **Example 1** has arisen from a historical September climate suitability of 0.000 and a future (RCP8.5) climate suitability of 0.125. Both fall into the 'very low' suitability category, shown as pale yellow, but the change in the value of +0.125 falls into the 'minimal' change category, shown as pale green.

The situation shown in **Example 2** has arisen from a historical October climate suitability of 0.577 and a future (RCP8.5) climate suitability of 0.666. The category changes from 'moderate' to 'high' (pale green to green), but the change in the value of +0.089 falls into the 'negligible' change category (white).

Example 1. The climate suitability calendar in this example for Bourke shows a 'minimal' change in climate suitability for September, but the historical and future climate suitability categories are the same ('very low'). The amount of change has not been enough to change the suitability classification for this site. This also occurs in December, February, and April.



Example 2: The climate suitability calendar in this example for Bourke shows a 'negligible change' in suitability for October, but when comparing the historical and future suitability rows, there has been an increase in suitability from 'moderate' to 'high'. The suitability category assigned to this site has changed, but the magnitude of change is small.



Projected changes in climate suitability for dairy pastures

Climate change is likely to offer both opportunities and challenges for dairy pastures in NSW by 2050.

This section provides a selection of key results for the dairy pastures climate vulnerability assessment. It begins with an overview of the overall climate impacts and a breakdown of the climate impacts on each pasture species, followed by the relevant maps and climate suitability calendars. The interpretation and findings are provided in the text in the bottom left corner of each map panel and on the right side of the climate suitability calendar panels. The findings have been summarised with key figures and additional maps provided in the Appendix.

Analysis of the model outputs has been undertaken spatially across NSW, presented as maps, and over time (on a monthly basis), presented as climate suitability calendars. Each map of results includes the outline of key dairy regions in NSW, which are shown, along with key towns, in Figure 9. The dairy regions were defined using data from the 2022/2023 NSW Licensed Dairy Farm map[9] and represent the range of climates experienced by dairying in NSW.

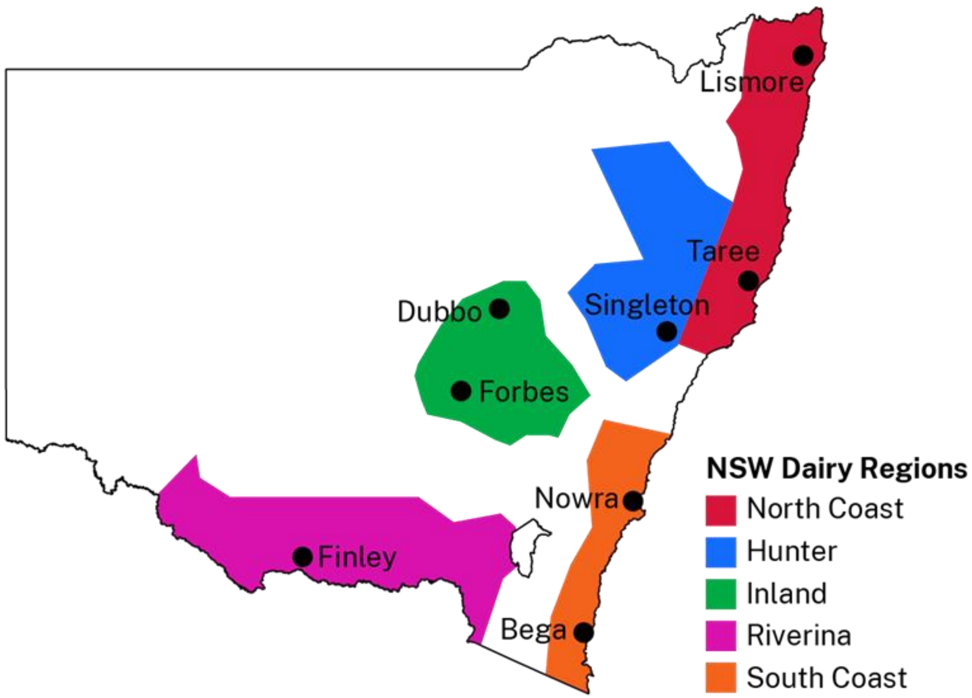


Figure 9: The main dairy-farming regions in NSW. Locations marked by black dots indicate key towns.

[9] NSW DPI, 2023. 'NSW Dairy Industry Snapshot (2022-23)'. Accessed 28/05/2025: https://www.dpi.nsw.gov.au/animals-and-livestock/dairy/nsw-dairy-industry

Kikuyu

Kikuyu in NSW

Kikuyu is a perennial tropical grass species that typically grows from late spring to early autumn, depending on the location. It is mainly found in coastal areas of NSW, particularly in the North and South Coast dairy regions. Kikuyu is primarily used as a grazing pasture, known for its rapid growth, but it can degrade in quality if not managed properly. It complements cool-season annual pastures, such as ryegrass and oats, to establish a year-round feeding base for grazing systems. Kikuyu is sensitive to cooler temperatures and will begin to grow actively only when overnight temperatures become sufficiently warm in late spring. Conversely, growth slows down when temperatures turn cool in autumn.

Final kikuyu MCA model

The kikuyu model is focused on the vegetative growth stage and the key climate variables that impact its suitability. The key climate conditions are the interaction between mean temperature and rainfall and cold days. The final MCA model structure for kikuyu can be found in the Appendix (Appendix Figure A1). Note: The following climate suitability maps do not consider soil properties, and kikuyu was modelled as a rain-fed system, rather than irrigated. See page 8 for all model assumptions and exclusions.

Overall climate impacts

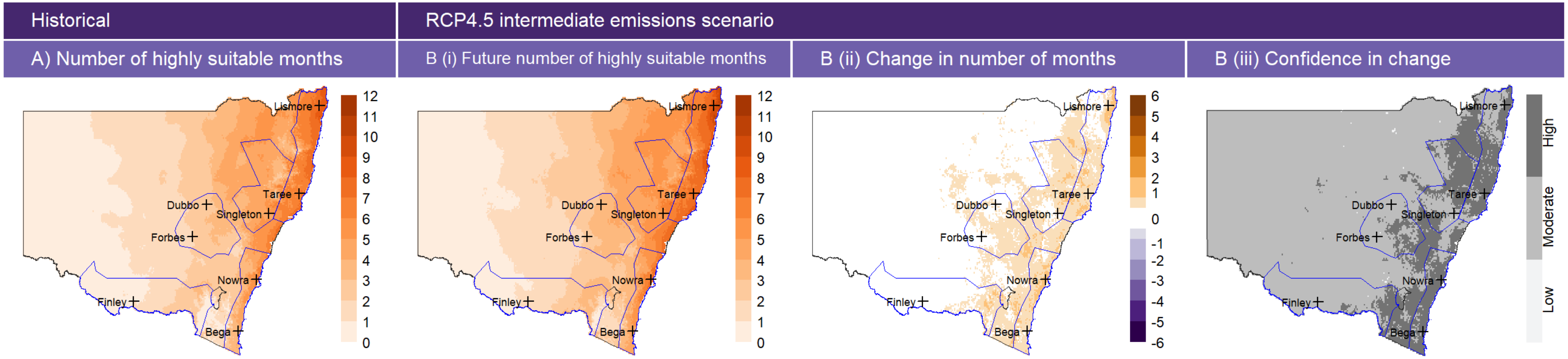
Under both future emissions scenarios, climate suitability for kikuyu is likely to experience a minimal to moderate increase in coastal dairy regions during some autumn and spring months.

The mean number of highly suitable months each year, in which the climate suitability is classified as 'high' or 'very high', is used as a measure of overall climate suitability for pastures, and it varies across the state.

By 2050, the number of highly suitable months for kikuyu (Figure 10) is likely to increase across much of the coastal dairy regions by 0.5 to 2 months per year under both emissions scenarios (*low to high confidence*). There is likely to be a negligible change in the number of highly suitable months in the western half of the Riverina Murray and Inland dairy regions.

The projected increase in climate suitability for kikuyu in the coastal dairy regions of NSW presents a potential opportunity. Results indicate that by 2050, there may be an extended growing season for kikuyu in some dairy regions.

Kikuyu: number of highly suitable months



Findings: The number of highly suitable months each year varies across the state. There is likely to be an increase in the number of highly suitable months across parts of all dairy regions, under both emissions scenarios. The western parts of the Inland and Riverina Murray dairy regions are expected to maintain their historical number of highly suitable months.

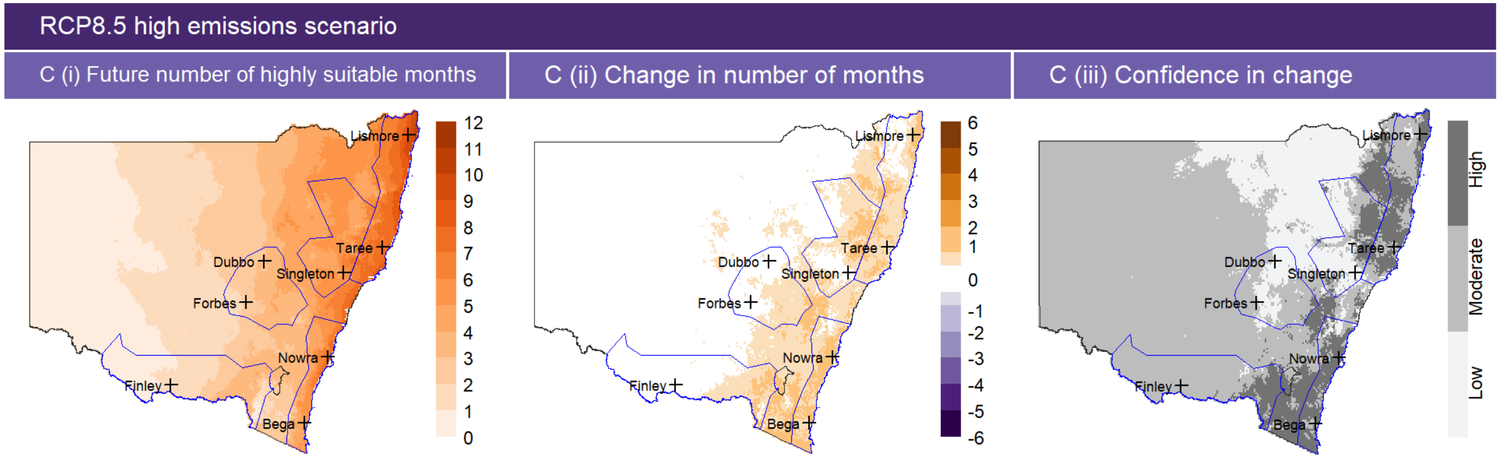


Figure 10: Number of highly suitable months for kikuyu in NSW. The number of highly suitable months measures the months in which climate suitability is 'high' or 'very high'. A) shows the historical number of highly suitable months; B) and C) show the future number of highly suitable months for the intermediate and high emissions scenarios, respectively; (i) shows future number of highly suitable months, (ii) shows the projected change in number of months as negligible (white), increasing (orange) or decreasing (purple) change and (iii) shows the level of confidence in this change (low, moderate or high).

Regional climate impacts on kikuyu

The kikuyu climate suitability calendar (Figure 11) shows the expected change in monthly climate suitability throughout the year at key dairy production sites. These changes in climate suitability vary by dairy region and are summarised as follows:

North Coast dairy region climate suitability

- **Minimal to moderate increases in climate suitability** are likely to occur in winter around Lismore under both emissions scenarios (*high confidence*) and in autumn around Taree under both emissions scenarios (*high confidence*).
- **Historical climate suitability is likely to be maintained** at high to very high in late spring, summer and early autumn under both future emissions scenarios (*low to high confidence*). In the remaining months, suitability is expected to maintain low or moderate climate suitability (*low to high confidence*).

Hunter dairy region climate suitability

- **Historical climate suitability is likely to be maintained** at moderate to high climate suitability in late spring, summer and early autumn under both future emissions scenarios (*low to high confidence*). From winter to early spring, climate suitability is expected to remain very low to low, under both emissions scenarios (*low to moderate confidence*).

Inland and Riverina Murray dairy regions climate suitability

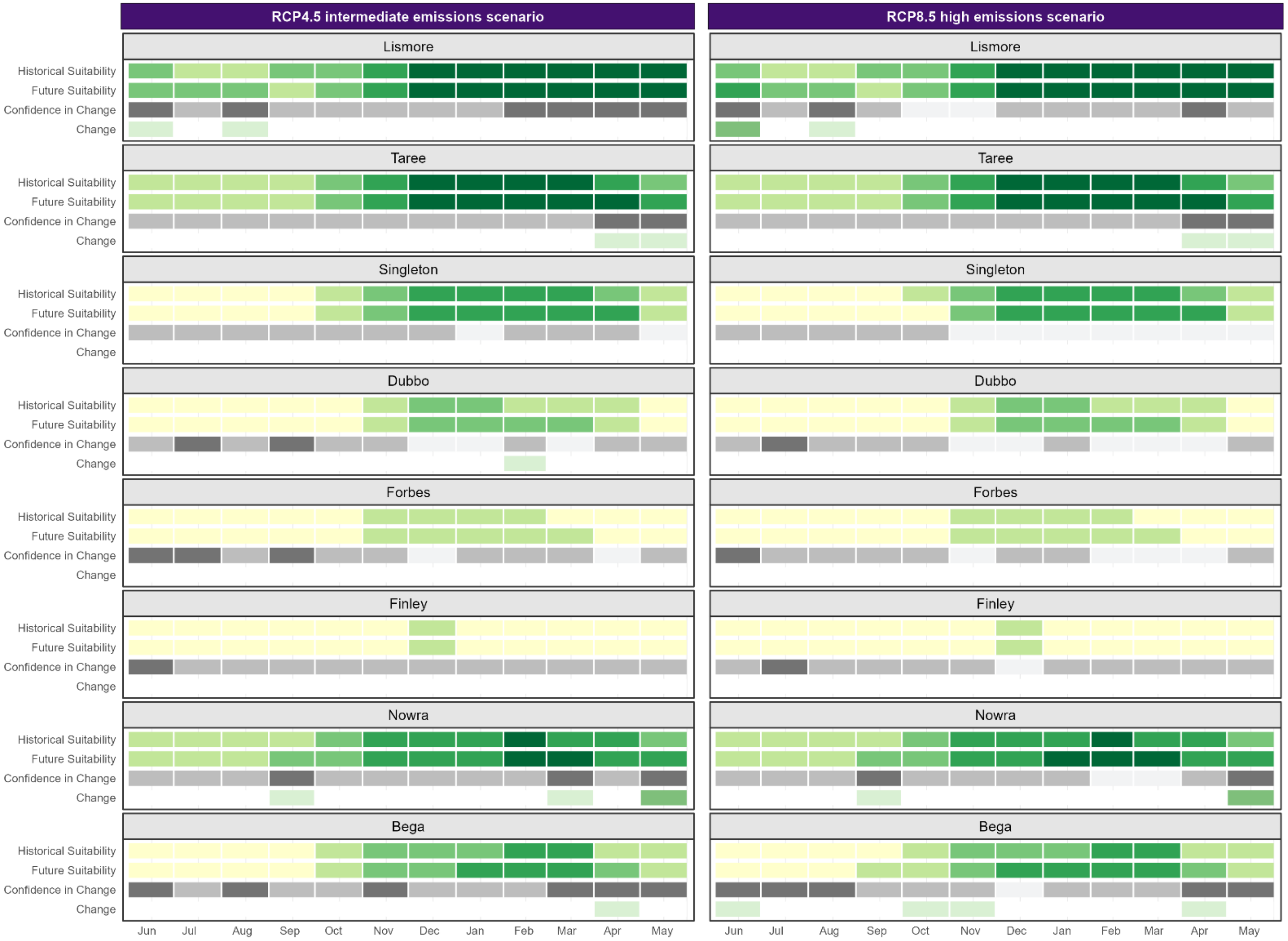
- **Minimal increases in climate suitability** are likely to occur in late summer for kikuyu under both emissions scenarios in the Inland dairy region (*low to high confidence*).
- **Historical climate suitability is likely to be maintained** at very low during late autumn, winter and early spring for Dubbo and Forbes, while Finley is projected to maintain very low suitability throughout all months except December under both future emissions scenarios (*low to high confidence*). Dubbo and Forbes in late spring, summer and early autumn are likely to maintain a very low climate suitability under both emissions scenarios (*low to moderate confidence*).

South Coast dairy region climate suitability

- **Minimal to moderate increases in climate suitability** are likely to occur in autumn and early spring in Nowra under the high emissions scenario (*high confidence*) and in spring and early autumn around Bega under the high emissions scenario (*moderate to high confidence*).
- **Historical climate suitability is likely to remain** moderate to very high from late spring, summer and early autumn under both future emissions scenarios (*low to high confidence*). During the winter months, climate suitability is expected to remain low around Nowra and very low around Bega (*moderate to high confidence*).

The analysis above describes climate suitability trends across key dairy production sites throughout the year. While this summary provides a simplified overview, it may overlook important spatial trends not captured by the individual locations. Monthly climate suitability map panels for all months have been included in the Appendix (Figures A2 to A13), allowing for the examination of spatial trends throughout the year.

Kikuyu: climate suitability calendar



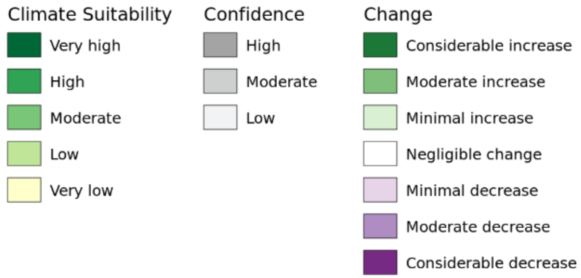


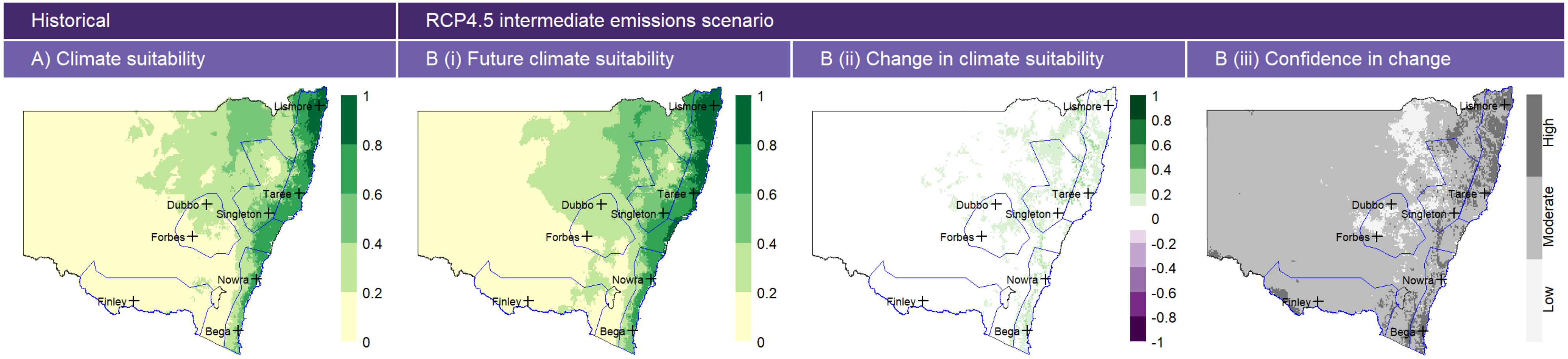
Figure 11: Climate suitability calendar for kikuyu, displaying the monthly climate suitability value for historical climate and future climate scenarios (RCP4.5 and RCP8.5) for sites in each dairy region. The climate suitability values shown are the median of a 10km radius surrounding each site of interest.

Findings: From late spring through summer and into early autumn, climate suitability is generally high along the coast and low to high in other dairy regions, with lower suitability during the cooler months.

In the northern coastal sites, Lismore and Taree, climate suitability is expected to remain moderate to very high for most of the year but typically drops to low during winter. Similarly, the southern coastal sites, Nowra and Bega, are likely to maintain moderate to very high suitability during the warmer months, with a similar drop in winter. A minimal to moderate increase in climate suitability is likely to occur at all coastal dairy sites during some autumn, spring and winter months. This presents a potential opportunity for these dairy regions: these areas may have an extended growing season for kikuyu by 2050.

In contrast, climate suitability in the remaining dairy regions is expected to remain very low to moderate throughout the year. These dairy regions have historically not relied on kikuyu. They are unlikely to do so in the future due to their low climate suitability. Dairy farmers in these areas will need to maintain their reliance on other pastures.

Kikuyu: climate suitability in April



Findings: Coastal dairy regions and areas along the Great Dividing Range may experience minimal to moderate increases in climate suitability in April, under both emissions scenarios. These changes are expected across the North Coast, Hunter, and South Coast dairy regions and in western parts of the Inland and Riverina Murray dairy regions in April, and represent a potential opportunity, suggesting more suitable conditions for the growth of kikuyu in autumn in the future.

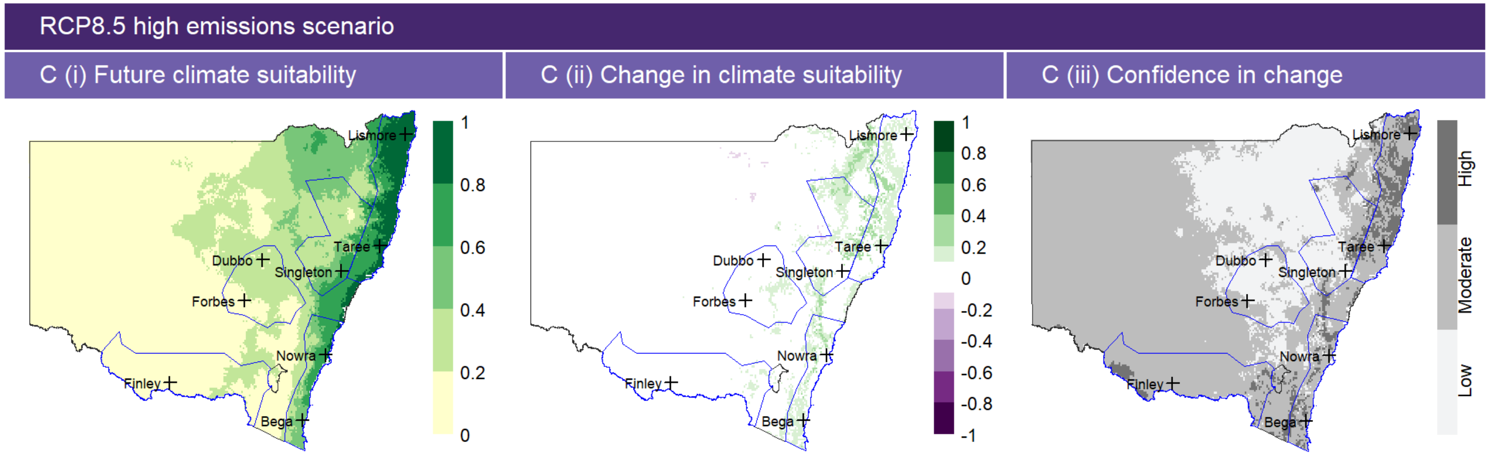


Figure 12: Overall climate suitability for kikuyu in NSW in April. A) shows the historical climate suitability; B) and C) show future climate suitability for the intermediate and high emissions scenarios, respectively; (i) shows future climate suitability, (ii) shows the projected future change in climate suitability as negligible (white), positive (green) or negative (purple) change, and (iii) shows the level of model confidence associated with this change (low, moderate or high).

Key insights for kikuyu

Historical and future trends

Climate suitability for kikuyu in the Riverina Murray and Inland dairy regions is expected to remain similar to what has been historically experienced.

Future climate vulnerabilities

There is likely to be a minimal decrease in climate suitability around Lismore in the North Coast dairy region during September and October (*low to moderate confidence*) (see Appendix Figures A10 and A11). In other dairy regions, no other decreases in climate suitability are expected under either emissions scenario, and no additional climate vulnerabilities for kikuyu have been identified.

Future climate opportunities

Due to higher temperatures, changes in rainfall and a reduction in the number of cold days, there is likely to be a minimal to moderate increase in climate suitability for kikuyu during some months in autumn, winter and spring. Such change is expected in the North Coast, South Coast and certain parts of the Hunter, Inland and Riverina Murray dairy regions. These minimal to moderate increases in climate suitability for April are shown in Figure 12, and these increases are likely to occur under both emissions scenarios (*low to high confidence*). These trends can be further observed in each month from September to May (Appendix Figures A2 to A6 and A10 to A13) and are more prominent under the high emissions scenario. Notably, increases in climate suitability during winter are confined to the North Coast and South Coast dairy regions (see Appendix Figures A7 to A9).

Implications for kikuyu pastures

The North and South Coast dairy regions are likely to become more suitable for the growth of kikuyu by 2050. Increased climate suitability during early autumn, winter and late spring is expected to extend the growing season for this pasture, which could help to bridge gaps in the feed base between cool-season pastures and kikuyu or other summer fodder crops. However, these changes could also shorten the growing season for higher-quality cool-season pastures and make autumn ryegrass establishment more challenging due to increased competition. Kikuyu will also require active management to maintain feed quality throughout the extended growth period. These shifts will require careful feedbase planning.

Historically, parts of the Hunter and Inland dairy regions have not relied upon kikuyu pastures as a significant feed source, due to the limited number of months with favourable conditions for growth. However, with the expected changes, there is a potential for kikuyu to contribute more to the feed base during summer if rainfall is adequate. Further localised studies would need to be undertaken to determine where kikuyu could reliably serve as a feed source during the warmer months in these dairy regions.

In the Riverina Murray and the remaining parts of the Inland and Hunter dairy regions, kikuyu is not utilised as a feed base. It is unlikely to be in the future, as these areas are expected to maintain their very low to moderate suitability for the pasture throughout the year. Dairy businesses in these regions will need to continue relying on other pastures or on summer fodder crops.

Ryegrass

Ryegrass in NSW

Short-term rotational ryegrass (Italian or annual ryegrass) is grown in most major dairying regions of NSW. Typically sown in early autumn, it provides an autumn through spring feed option (both grazed and harvested) for dairy farms. Short-term rotational ryegrass is grown for its nutritional qualities, grazing management options and climatic suitability. In contrast, perennial ryegrass is unable to persist in most NSW dairying regions due to unfavourable hotter conditions in summer and competition from our C4 tropical species.

Final ryegrass MCA model

It was determined that both Italian ryegrass and annual ryegrass share identical climate preferences and tolerances. So a single model was developed to represent both pasture species. The ryegrass model is focused on the vegetative growth stage and the key climate variables that impact its suitability. The climatic conditions considered were the number of hot days and nights, a growing degree day (GDD) threshold of 550 GDD, with a Tbase of 3˚C, and the interaction between mean temperature and rainfall. This GDD threshold was implemented to replicate the vegetative state process that occurs due to the phenology of the plant, imposing realistic limitations on climate suitability during summer. The final MCA model structure for ryegrass can be found in the Appendix (Figure A14). Note: The following climate suitability maps do not consider soil properties, and ryegrass was modelled as a rain-fed system, rather than irrigated. See page 8 for all model assumptions and exclusions.

Overall climate impacts

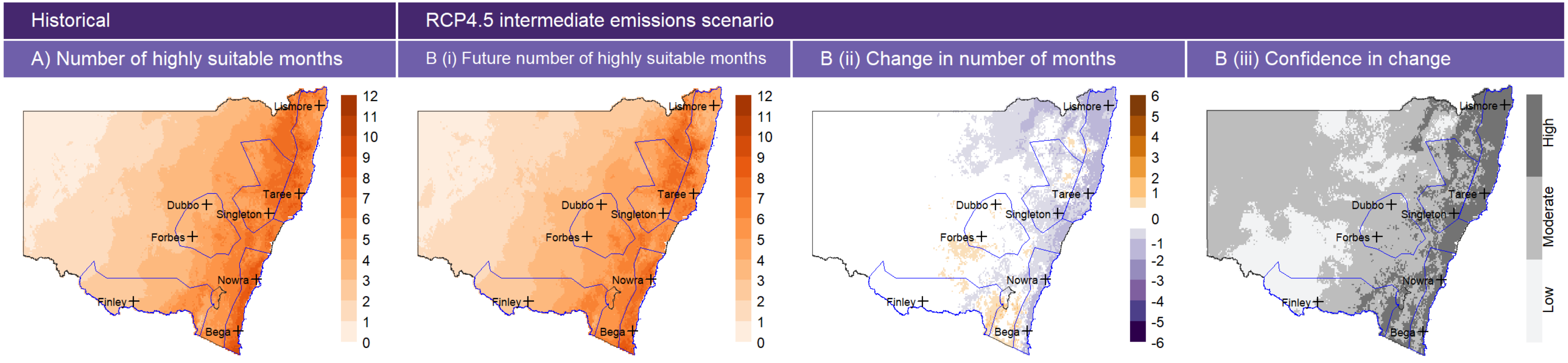
Under both future emissions scenarios, climate suitability for ryegrass is likely to experience a minimal to considerable decrease in some key dairy regions for some months, as well as minimal to moderate increases in some dairy regions in other months.

The mean number of highly suitable months each year, in which the climate suitability is classified as ‘high’ or ‘very high’, is used as a measure of overall climate suitability for pastures, and it varies across the state.

By 2050, the number of highly suitable months for ryegrass (Figure 13) is likely to decrease across much of the Hunter, North Coast and South Coast dairy regions by up to 2 months per year under both emissions scenarios (*low to high confidence*). Areas to the south of Forbes, inland of Bega and in some parts of the Riverina Murray dairy region are likely to experience up to 2 months increase in the number of highly suitable months under both emissions scenarios (*low to high confidence*). There is likely to be negligible change in the number of highly suitable months in the western half of the Riverina Murray and Inland dairy regions.

These projected decreases in the number of highly suitable months for ryegrass in the coastal dairy regions of NSW present potential vulnerabilities for the dairy industry. Results indicate that by 2050, some dairy regions may have a shorter growing season for ryegrass.

Ryegrass: number of highly suitable months



Findings: Under both scenarios, there is likely to be a decrease in the number of highly suitable months across parts of all dairy regions. The western parts of the Inland and Riverina Murray dairy regions are expected to maintain their historical number of highly suitable months. Some areas of the South Coast and Riverina Murray dairy regions are likely to experience increases in the number of highly suitable months.

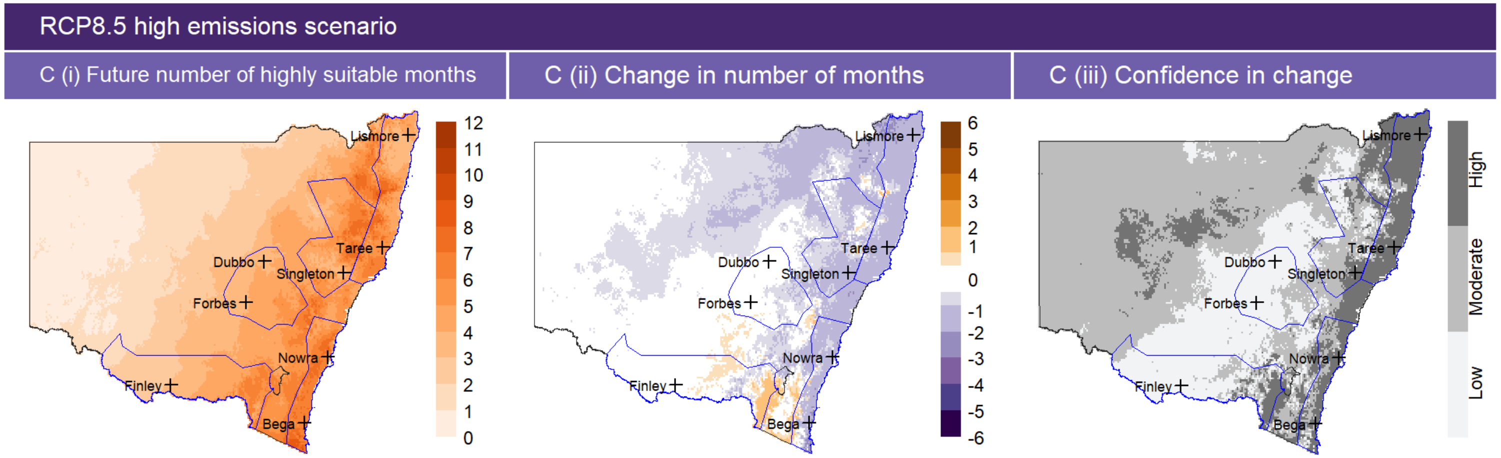


Figure 13: Number of highly suitable months for ryegrass in NSW. The number of highly suitable months measures the months in which climate suitability is 'high' or 'very high'. A) shows the historical number of highly suitable months; B) and C) show the future number of highly suitable months for the intermediate and high emissions scenarios, respectively; (i) shows future number of highly suitable months, (ii) shows the projected change in number of months as negligible (white), increasing (orange) or decreasing (purple) change and (iii) shows the level of confidence in this change (low, moderate or high).

Regional climate impacts on ryegrass

The ryegrass climate suitability calendar (Figure 14) shows the expected change in monthly climate suitability throughout the year at key dairy production sites. These changes in climate suitability vary by region.

North Coast dairy region climate suitability

- **Minimal to considerable decreases in climate suitability** are likely to occur across the North Coast dairy region in spring and the middle of autumn, with greater changes under the high emissions scenario (*low to high confidence)*.
- **Historical climate suitability is likely to be maintained in the future** as very low in the summer months for the North Coast and high in winter, early spring and late autumn (*moderate to high confidence*).

Hunter dairy region climate suitability

- **Minimal to considerable decreases in climate suitability** are likely to occur around Singleton in late spring and early autumn, with greater changes under the high emissions scenario (*low to high confidence)*.
- **Historical climate suitability is likely to be maintained in the future** as very low in the summer months for the Hunter and moderate to high from late autumn through winter and into early spring (*moderate to high confidence*).

Inland dairy region climate suitability

- **Minimal increases in climate suitability** are likely to occur around Dubbo and Finley during winter, under both emissions scenarios *(moderate confidence*).
- **Minimal to moderate decreases in climate suitability** are likely to occur around Dubbo and Forbes during late spring through to early autumn, under both emissions scenarios (*low to moderate confidence*).

Riverina Murray dairy region climate suitability

- **Minimal increases in climate suitability** are likely to occur in winter around Finley under both emissions scenarios (*moderate to high confidence*).
- **Minimal to moderate decreases in climate suitability** are likely to occur during late spring through to early autumn in Finley, under both emissions scenarios (*low to high confidence)*.

South Coast dairy region climate suitability

- **Minimal increases in climate suitability** are likely to occur in midwinter at Bega under both emissions scenarios and for the middle of spring in Nowra under the intermediate emissions scenario (*moderate to high confidence*).
- **Minimal to considerable decreases in climate suitability** are likely to occur in late spring through to early autumn in Nowra and in summer and early autumn in Bega under both emissions scenarios (*low to high confidence)*.

The analysis above describes the climate suitability trends across key dairy production sites throughout the year. While this summary provides a simplified overview, it may overlook important spatial trends not captured by the individual locations. Monthly climate suitability map panels for all months have been included in the Appendix (Figure A15 to A26), allowing for the examination of spatial trends throughout the year.

Ryegrass: climate suitability calendar

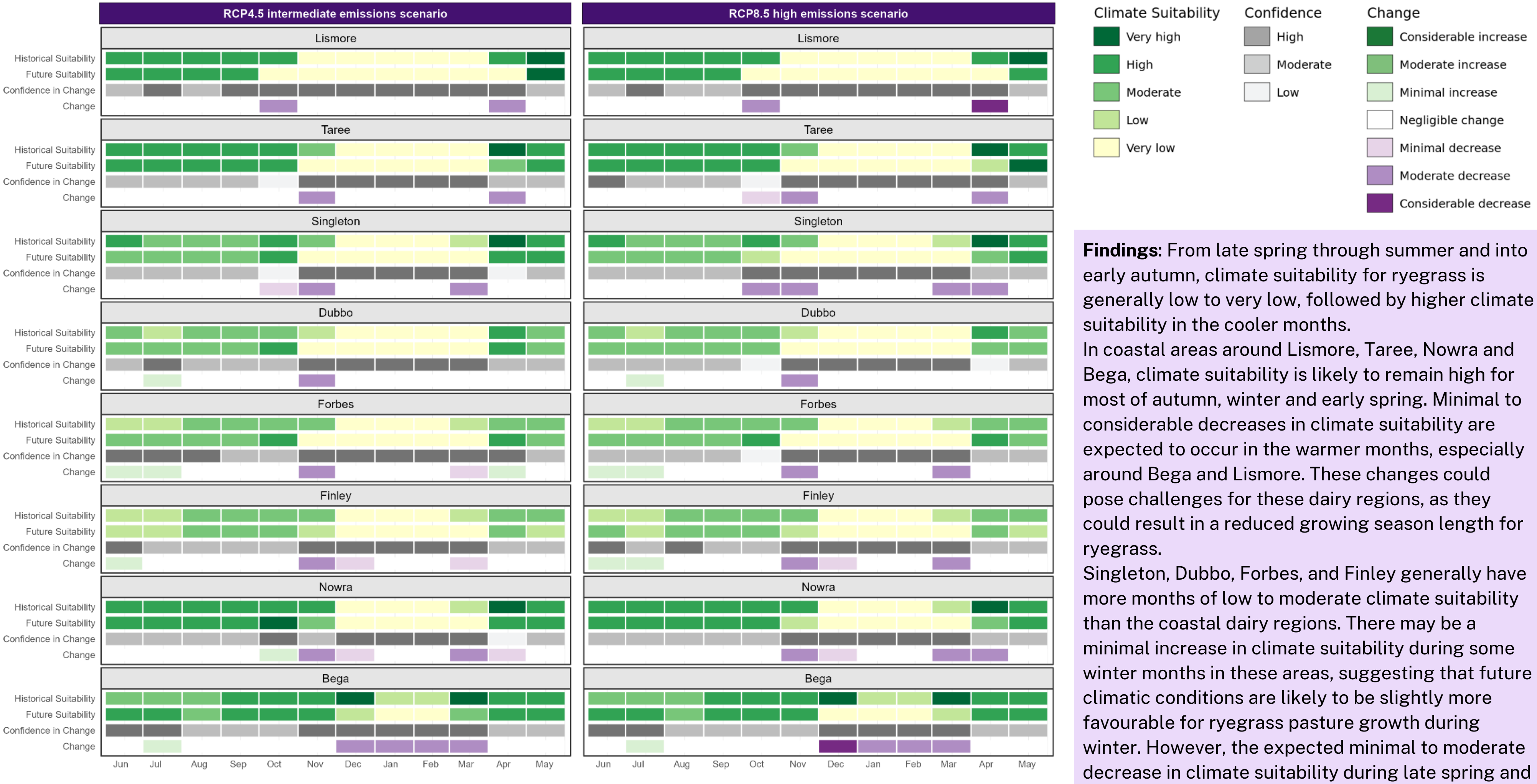


Figure 14: Climate suitability calendar for ryegrass, displaying the monthly climate suitability value for historical climate and future climate scenarios (RCP4.5 and RCP8.5) for sites in each dairy region. The climate suitability values shown are the median of a 10km radius surrounding each site of interest.

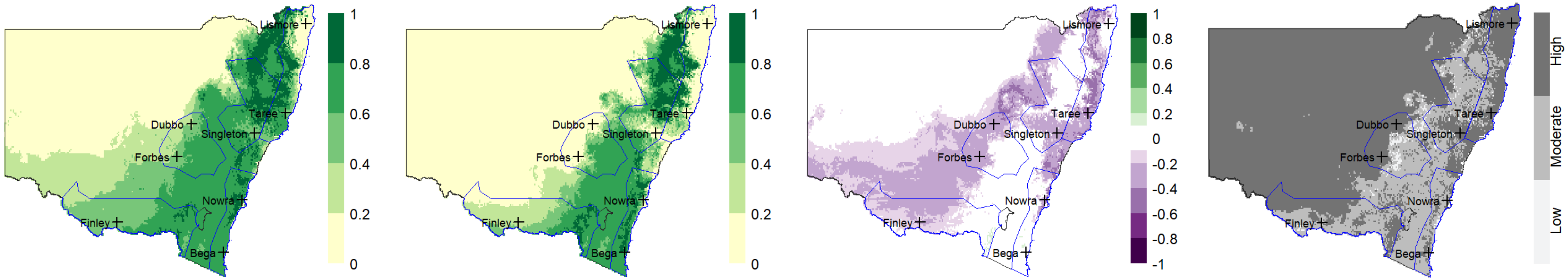
Findings: From late spring through summer and into early autumn, climate suitability for ryegrass is generally low to very low, followed by higher climate suitability in the cooler months.

In coastal areas around Lismore, Taree, Nowra and Bega, climate suitability is likely to remain high for most of autumn, winter and early spring. Minimal to considerable decreases in climate suitability are expected to occur in the warmer months, especially around Bega and Lismore. These changes could pose challenges for these dairy regions, as they could result in a reduced growing season length for ryegrass.

Singleton, Dubbo, Forbes, and Finley generally have more months of low to moderate climate suitability than the coastal dairy regions. There may be a minimal increase in climate suitability during some winter months in these areas, suggesting that future climatic conditions are likely to be slightly more favourable for ryegrass pasture growth during winter. However, the expected minimal to moderate decrease in climate suitability during late spring and autumn could reduce the growing season length for ryegrass and impact pasture establishment in autumn.

Ryegrass: climate suitability for November

Historical	RCP4.5 intermediate emissions scenario		
A) Climate suitability	B (i) Future climate suitability	B (ii) Change in climate suitability	B (iii) Confidence in change



Findings: Under both emissions scenarios, there is likely to be minimal to considerable decreases in climate suitability for ryegrass across the North Coast and parts of the Hunter, South Coast, Inland, and Riverina Murray dairy regions in November. These changes may pose challenges, as the climate is likely to become less favourable for ryegrass growth, resulting in very low suitability in parts of these regions. The growing season for ryegrass is expected to shorten, leading to feed gaps if these changes are not managed.

RCP8.5 high emissions scenario		
C (i) Future climate suitability	C (ii) Change in climate suitability	C (iii) Confidence in change

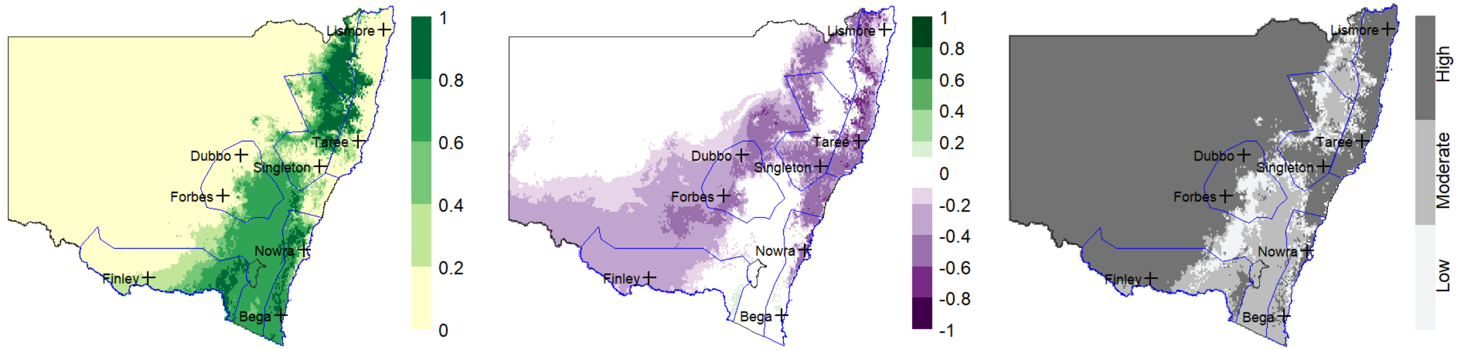


Figure 15: Overall climate suitability for ryegrass in NSW in November. A) shows the historical climate suitability; B) and C) show future climate suitability for the intermediate and high emissions scenarios, respectively; (i) shows future climate suitability, (ii) shows the projected future change in climate suitability as negligible (white), positive (green) or negative (purple) change, and (iii) shows the level of model confidence associated with this change (low, moderate or high).

Key insights for ryegrass

Historical and future trends

Some parts of all dairy regions in NSW are likely to experience minimal increases in climate suitability for ryegrass between late autumn and early spring. During the warmer months, the climate is expected to generally become less suitable for ryegrass growth in a rain-fed system, as indicated by the very low climate suitability across most dairy regions in Figure 14.

Future climate vulnerabilities

Due to higher temperatures, greater numbers of hot days and nights, changes in rainfall and GDD, there is likely to be a minimal to considerable decrease in climate suitability for ryegrass over the months from November to March (see Appendix Figures A25 to A26 and A15 to A17), with greater decreases under the high emissions scenario. These changes are likely to affect all dairy regions. However, decreases in climate suitability in October and April are only observed within the North Coast dairy region around Lismore (see Appendix Figures A24 and A18). Minimal to considerable decreases in climate suitability are shown in Figure 15 for November, and these decreases are expected to occur under both intermediate and high emissions scenarios (*low to high confidence*).

Future climate opportunities

Some parts of all dairy regions in NSW are likely to experience minimal increases in climate suitability between March and October (*low to moderate confidence*) (see Appendix Figures A17 to A24). During winter, these increases in climate suitability are more widespread under both emissions scenarios. They are due to increased mean temperature and changes in rainfall, which make climatic conditions more favourable for ryegrass growth during these months.

Implications for ryegrass pastures

By 2050, during autumn and spring, all dairy regions in NSW are likely to become less suitable for ryegrass growth. The decreased climate suitability during these seasons is expected to affect establishment success and shorten the growing season. Reduced autumn climate suitability may therefore necessitate adjustments to sowing times and increased attention to kikuyu suppression. Spring conditions also pose challenges, as a drier spring compresses the grazing year and shortens the window for high-quality pasture, creating a gap in the feed base. Future research should focus on this potential feed gap and whether the decreased suitability in autumn will impact establishment and necessitate changes in sowing timing.

Ryegrass is widely used across all dairy regions from autumn to spring. The climate suitability during some of these seasons, particularly winter, is likely to increase due to changes in mean temperature and rainfall in most dairy regions. Improved climatic conditions for winter growth could lead to greater pasture availability during these months. More growth during this period may also shorten grazing rotations and create opportunities to conserve surplus feed, helping buffer emerging spring feed gaps. This strategy, however, is dependent on whether farms have sufficient storage and feed-out infrastructure, such as feed pads or total mixed-ration systems, to utilise the conserved feed. Further localised studies are needed to determine whether the increased climate suitability translates into greater pasture availability and higher-quality feed during winter across all dairy regions.

Ryegrass is not utilised as a feed source during summer since it is a temperate pasture that is susceptible to hot conditions and does not persist. All dairy regions are expected to maintain the historically very low climate suitability for this pasture throughout this period. Dairy businesses will need to continue to rely on other pastures or summer fodder crops adapted to warmer conditions during this season.

White clover

White clover in NSW

White clover is a perennial legume able to grow in NSW dairy regions in high rainfall areas, and in low rainfall areas with irrigation. It has high nutritional quality and, as a legume, is able to fix atmospheric nitrogen into the soil, which can provide nutrients for other pasture types. Often grown alongside ryegrass and forage oats, white clover serves as a companion species, enhancing the pasture base's overall productivity and health.

Final white clover MCA model

The white clover model is focused on the vegetative growth stage and the key climate variables that impact its suitability. The key climatic conditions were the interaction of mean temperature and rainfall and the number of hot days. The final MCA model structure for white clover can be found in the Appendix (Figure A27). Note: The following climate suitability maps do not consider soil properties, and white clover was modelled as a rain-fed system, rather than irrigated. See page 8 for all model assumptions and exclusions.

Overall climate impacts

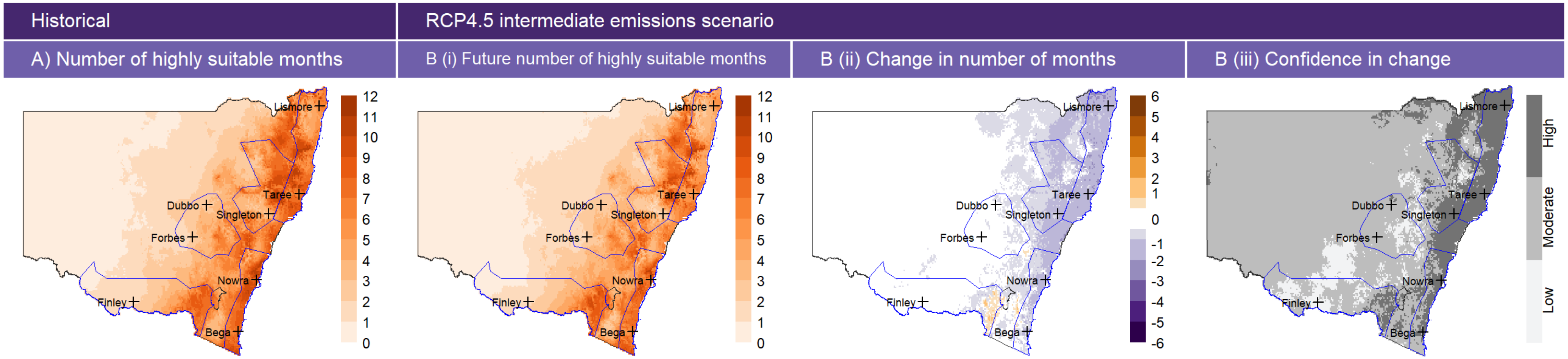
Under both future emissions scenarios, climate suitability for white clover is likely to experience a minimal to moderate decrease in some key dairy regions for some months.

The mean number of highly suitable months each year, in which the climate suitability is classified as 'high' or 'very high', is used as a measure of overall climate suitability for pastures, and it varies across the state.

By 2050, the number of highly suitable months for white clover (Figure 16) is likely to decrease across much of the coastal and inland dairy regions by up to 2 months per year under the intermediate emissions scenarios, and by up to 3 months per year under the high emissions scenario (*low to high confidence*). The eastern end of the Riverina Murray dairy region, however, is likely to experience up to 2 months' increase in the number of highly suitable months under both emissions scenarios (*low to high confidence*).

These projected decreases in the number of highly suitable months for white clover across the dairy regions present potential vulnerabilities for the dairy industry, indicating that there may be a reduced growing season length for white clover in some dairy regions by 2050.

White clover: number of highly suitable months



Findings: Under both scenarios, there is likely to be a decrease in the number of highly suitable months in parts of all dairy regions. The western Inland and central Riverina Murray dairy regions are expected to maintain their historical number of highly suitable months. The easternmost part of the Riverina Murray dairy region is likely to see up to 2 extra highly suitable months per year.

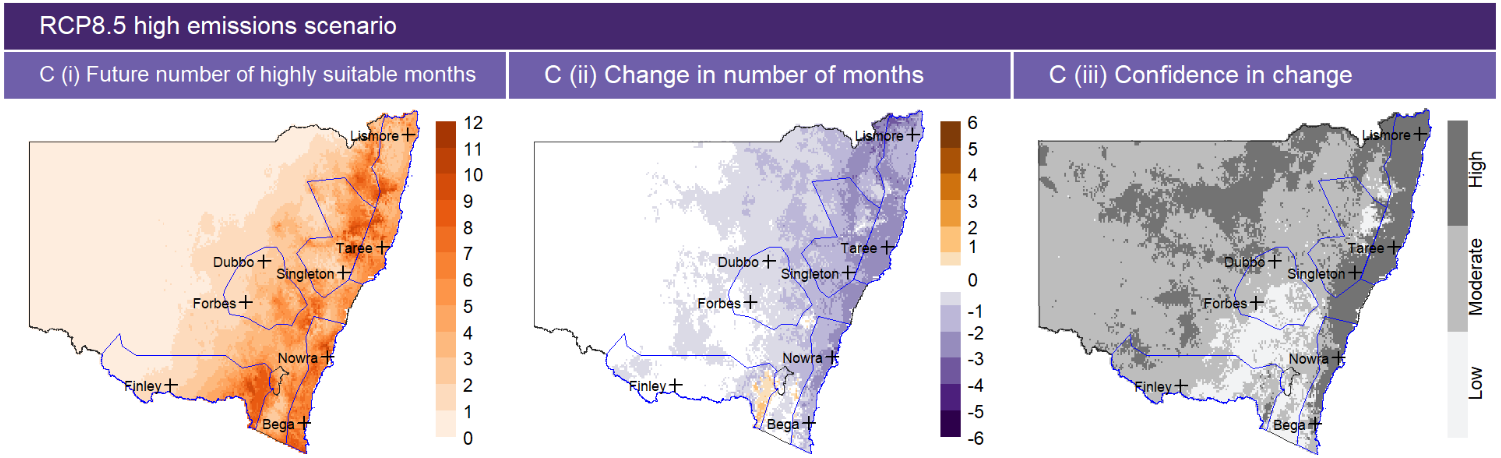


Figure 16: Number of highly suitable months for white clover in NSW. The number of highly suitable months measures the months in which climate suitability is 'high' or 'very high'. A) shows the historical number of highly suitable months; B) and C) show the future number of highly suitable months for the intermediate and high emissions scenarios, respectively; (i) shows future number of highly suitable months, (ii) shows the projected change in number of months as negligible (white), increasing (orange) or decreasing (purple) change and (iii) shows the level of confidence in this change (low, moderate or high).

Regional climate impacts on white clover

The white clover climate suitability calendar (Figure 17) shows the expected change in monthly climate suitability throughout the year at key dairy production sites. These changes in climate suitability vary by region.

North Coast dairy region climate suitability

- **Minimal to moderate decreases in climate suitability** are likely under both scenarios from spring through to autumn for Lismore and Taree (*low to high confidence*).
- **Historical climate suitability is likely to be maintained** as moderate to very high for all remaining months under both emissions scenarios (*moderate to high confidence*).

Hunter dairy region climate suitability

- **Minimal to moderate decreases in climate suitability** are likely to occur in Singleton from late spring through to early winter under both emissions scenarios (*low to high confidence*).
- **Historical climate suitability is likely to be maintained** as very low to moderate for the remaining months under both emissions scenarios (*moderate to high confidence*).

Inland dairy region climate suitability

- **Minimal decreases in climate suitability** are likely to occur in Dubbo during late spring through to early autumn and in Forbes from late winter and throughout spring under the high emissions scenario (*low to high confidence*).
- **Historical climate suitability is likely to be maintained** as very low to moderate for the remaining months under both emissions scenarios (*moderate to high confidence*).

Riverina Murray dairy region climate suitability

- **Minimal decreases in climate suitability** are likely to occur during spring in Finley in the high emissions scenario (*low to high confidence*).
- **Historical climate suitability is likely to be maintained** as very low to low for the remaining months in Finley under both emissions scenarios (*high confidence*).

South Coast dairy region climate suitability

- **Moderate decreases in climate suitability** are likely to occur through summer and early autumn for Nowra and during summer months for Bega under both emissions scenarios (*low to high confidence*).
- **Minimal increases in climate suitability** are likely to occur around Bega during winter under the high emissions scenario (*high confidence*).
- **Historical climate suitability is likely to be maintained** as high to very high across both sites for the remaining months (*moderate to high confidence*).

The analysis above describes the climate suitability trends across key dairy production sites throughout the year. While this summary provides a simplified overview, it may overlook important spatial trends not captured by the individual locations. Monthly climate suitability map panels for all months have been included in the Appendix (Figures A28 to A39), allowing for the examination of spatial trends throughout the year.

White clover: climate suitability calendar

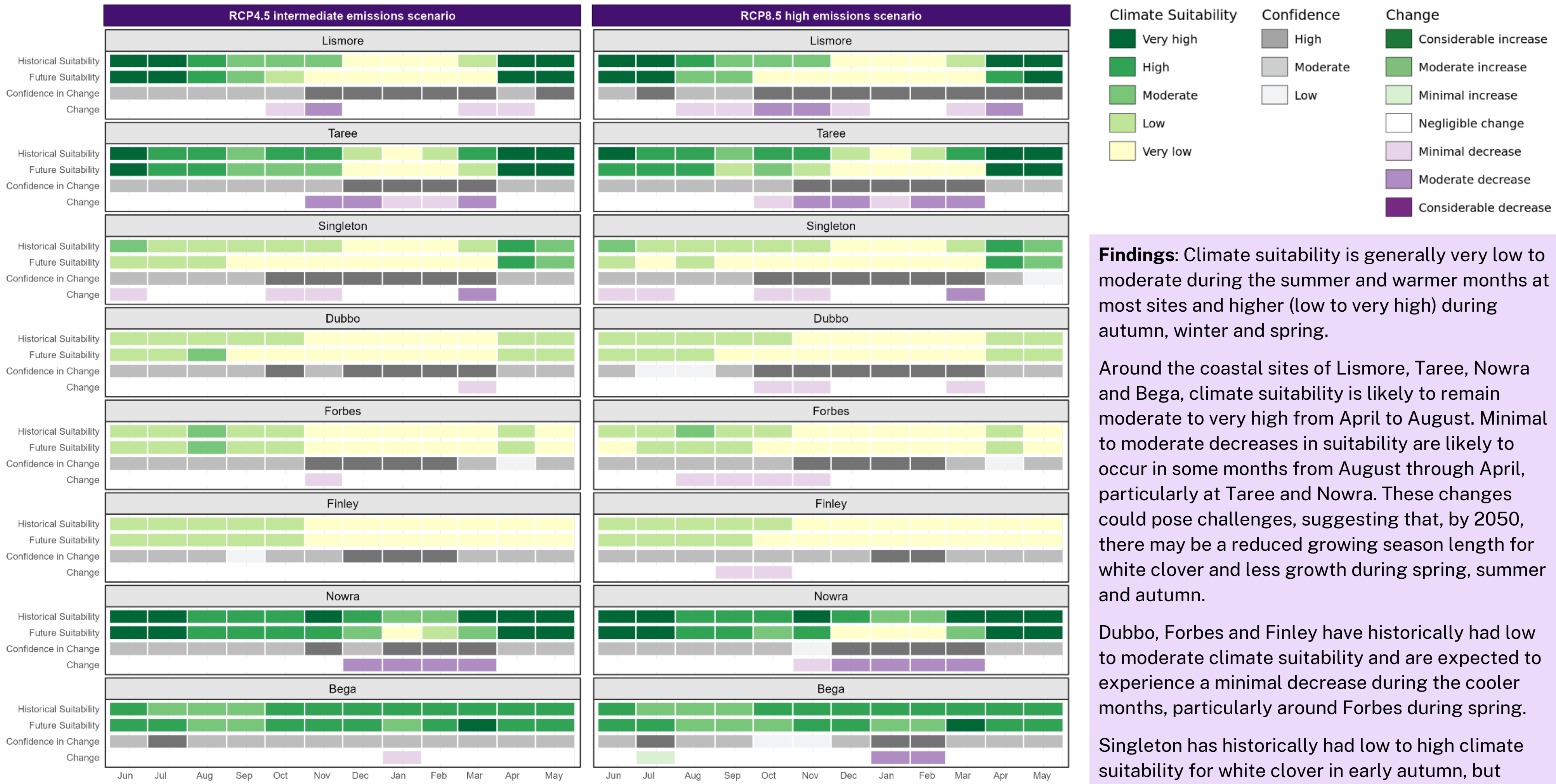


Figure 17: Climate suitability calendar for white clover, displaying the monthly climate suitability value for historical climate and future climate scenarios (RCP4.5 and RCP8.5) for sites in each dairy region. The climate suitability values shown are the median of a 10km radius surrounding each site of interest.

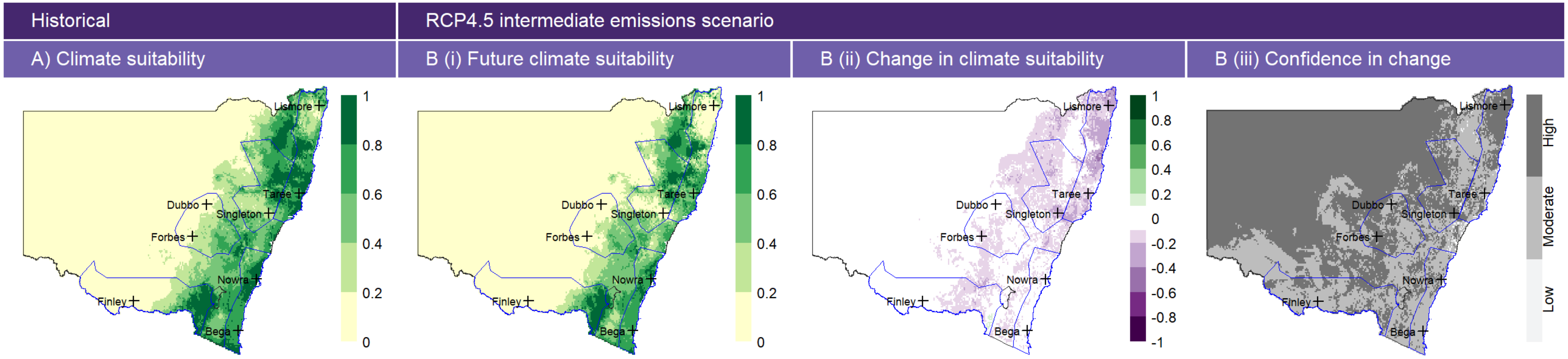
Findings: Climate suitability is generally very low to moderate during the summer and warmer months at most sites and higher (low to very high) during autumn, winter and spring.

Around the coastal sites of Lismore, Taree, Nowra and Bega, climate suitability is likely to remain moderate to very high from April to August. Minimal to moderate decreases in suitability are likely to occur in some months from August through April, particularly at Taree and Nowra. These changes could pose challenges, suggesting that, by 2050, there may be a reduced growing season length for white clover and less growth during spring, summer and autumn.

Dubbo, Forbes and Finley have historically had low to moderate climate suitability and are expected to experience a minimal decrease during the cooler months, particularly around Forbes during spring.

Singleton has historically had low to high climate suitability for white clover in early autumn, but minimal to moderate decreases are likely to occur in winter, spring and early autumn by 2050. Consideration should be given to alternative pasture types which could be grown in this region to maintain the pasture base during these seasons.

White clover: climate suitability for November



Findings: There are likely to be minimal to moderate decreases in climate suitability for white clover across parts of all dairy regions in November, under both emissions scenarios. Such reduced climate suitability for white clover growth during spring could create challenges for dairy production, particularly in the North Coast dairy region.

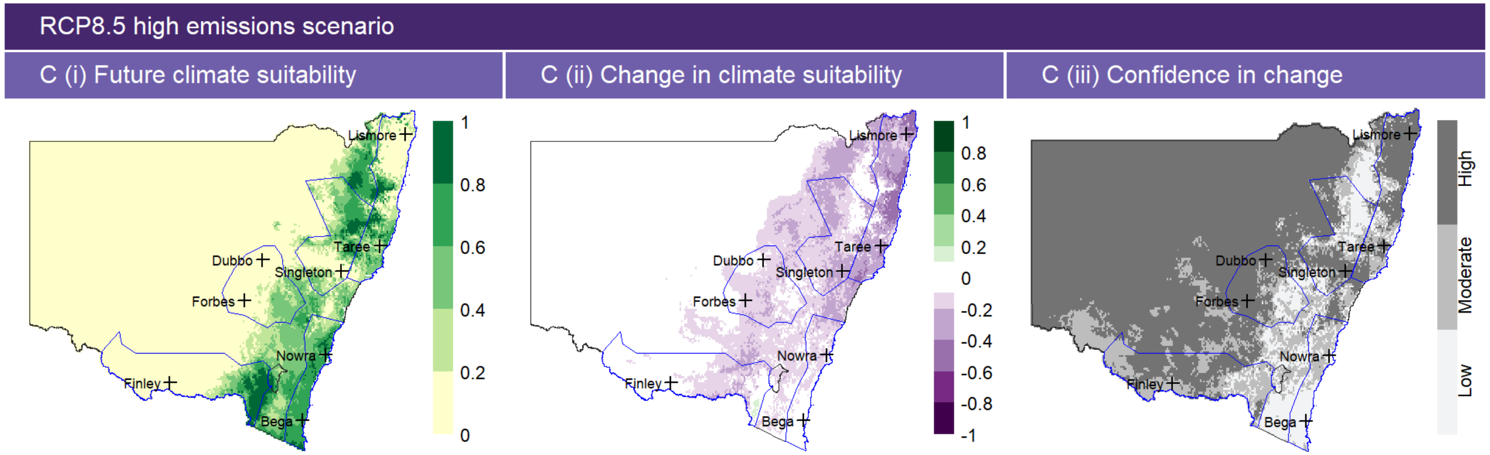


Figure 18: Overall climate suitability for white clover in NSW in November. A) shows the historical climate suitability; B) and C) show future climate suitability for the intermediate and high emissions scenarios, respectively; (i) shows future climate suitability, (ii) shows the projected future change in climate suitability as negligible (white), positive (green) or negative (purple) change, and (iii) shows the level of model confidence associated with this change (low, moderate or high).

Key insights for white clover

Historical and future trends

Some parts of all dairy regions in NSW are likely to experience minimal to considerable decreases in climate suitability for white clover, particularly from spring through autumn. During the warmer months, the climate suitability is expected to generally remain very low to moderate for white clover in rain-fed systems, with the western parts of the Inland and Riverina Murray dairy regions remaining unsuitable year-round (Figure 17).

Future climate vulnerabilities

Due to higher temperatures and changes in rainfall, there is likely to be a minimal to considerable decrease in climate suitability during spring, summer and early autumn, as well as in late winter (see Appendix Figures A31 to A35). The changes are more prominent under high emissions scenarios and affect all dairy regions during these seasons. The minimal to moderate decreases in climate suitability are shown in Figure 18 for November, and these decreases are expected to occur in both emissions scenarios (*low to high confidence*).

Future climate opportunities

There are likely to be scattered areas of minimal increases in climate suitability in the easternmost part of the Riverina Murray dairy region from May to October (*low to moderate confidence*) (see Appendix Figures A32 to A36). A small area of increased climate suitability is expected to occur in the north of the South Coast dairy region in June through winter in the intermediate emissions scenario and during June in the high emissions scenario (*moderate to high confidence*). These increases are due to changes in mean temperature and rainfall, creating climatic conditions which could be more favourable for white clover growth during these months.

Implications for white clover pastures

By 2050, all dairy regions are likely to become less suitable for the growth of white clover from late spring through to early autumn. The decreased climate suitability during these seasons is expected to shorten the growing season. It may impact the persistence of plants in summer, which could affect autumn regrowth. This presents challenges, particularly in spring, when growth is essential to maintain high-quality feed availability for grazing cows and to provide nitrogen to support the growth of other pastures. Losing even one to two highly suitable months of clover growth is especially significant in clover-reliant dairy regions, compounding not just a quantitative but also a qualitative feed gap, impacting the end of spring and early autumn. Future research should address challenges arising from reduced climate suitability and its possible flow-on effects for dairy production.

In the Hunter dairy region, a decrease in climate suitability is expected in all seasons apart from winter, with similar changes expected in the North Coast dairy region. As a result, the Hunter and North Coast dairy regions may need to adapt by reducing their reliance on white clover and by considering pastures for which future climatic conditions are more suitable.

From autumn through winter and into spring, white clover is relied on for feed in the South Coast dairy region. The climate suitability during some winter months is likely to increase due to changes in mean temperature and rainfall in a small northern area of this dairy region as well as in the easternmost part of the Riverina Murray dairy region. Further localised studies are needed to determine whether this increased climate suitability translates to greater pasture availability and higher-quality feed during winter.

Lucerne

Lucerne in NSW

Lucerne is widely grown across NSW. On dairy farms, it is typically not grazed but grown to be harvested and fed back to cows as hay. Lucerne provides a high-quality, high-yield crop that can be fed to cows as required during the cows' lactation and dry periods and in unfavourable seasonal conditions such as drought. A perennial crop, persisting for 3–5 years if managed appropriately, lucerne can often be cut 4–6 times in a growing season. Like white clover, lucerne is a legume with nitrogen-fixing properties, providing nutrients for other pasture types.

Final lucerne MCA model

The lucerne MCA model focused on the establishment and vegetative growth stages. For the establishment growth stage, the key climate variables were mean temperatures, cold days and hot days. In contrast, the key climate variable for vegetative growth was the interaction between mean temperature and rainfall. The final MCA model structure for lucerne can be found in the Appendix (Figure A40). **Note**: The following climate suitability maps do not consider soil properties, and lucerne was modelled as a rain-fed system, rather than irrigated. See page 8 for all model assumptions and exclusions.

Successful lucerne establishment is essential for long-term productivity, as it promotes strong root development, persistence under grazing, and resilience to hotter and drier conditions. In NSW, lucerne is typically sown in early autumn (March and April) or late winter to early spring (August and September), when conditions are most favourable for germination and early growth.

Overall climate impacts

Climate suitability for lucerne is likely to experience a minimal to moderate decrease in most dairy regions across spring and summer and minimal to moderate increases throughout winter.

The mean number of highly suitable months each year, in which the climate suitability is classified as 'high' or 'very high', is used as a measure of overall climate suitability for pastures, and it varies across the state.

By 2050, the number of highly suitable months for lucerne (Figure 19) is likely to decrease by up to 2 months per year in the North Coast and Hunter dairy regions under both emissions scenarios, and small areas of the Inland and South Coast dairy regions under the high emissions scenario (*low to high confidence*). However, much of the South Coast dairy region is expected to experience one additional month per year of 'high' or 'very high' climate suitability (*low to high confidence*). Parts of the other dairy regions may also experience increases of up to 2 months per year, with a greater increase in the high emissions scenario (*low to high confidence*).

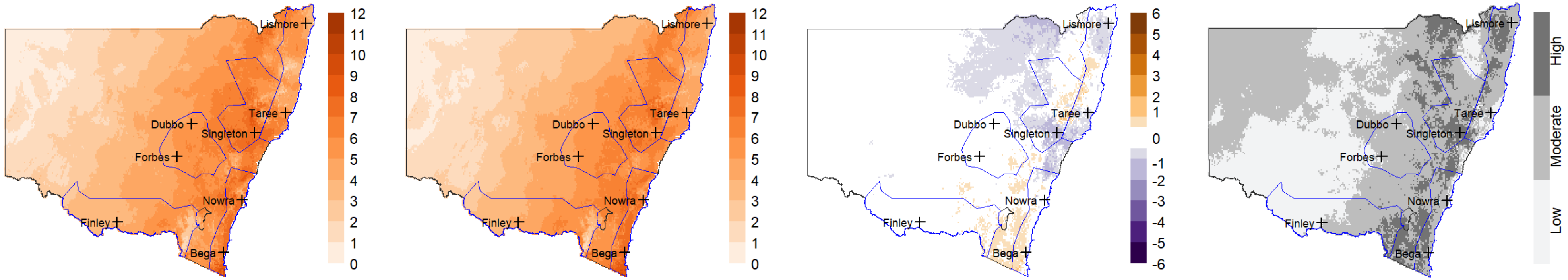
These projected changes present both potential vulnerabilities and potential opportunities for the dairy industry, indicating that there may be a shortened growing season for lucerne in some areas but that other areas are likely to see an extended growing season by 2050.

Lucerne establishment

The climate suitability for establishment during March is expected to decline in the western parts of the Hunter, Inland and Riverina Murray dairy regions. This could result in a minimal to moderate reduction in establishment success (*low to moderate confidence*). In contrast, April, August and September are likely to maintain historical levels of climate suitability. Consideration should be given to shifting establishment to later in autumn or early spring to align with the more favourable climatic conditions in those months.

Lucerne: number of highly suitable months

Historical	RCP4.5 intermediate emissions scenario		
A) Number of highly suitable months	B (i) Future number of highly suitable months	B (ii) Change in number of months	B (iii) Confidence in change



Findings: a minimal to moderate decrease in the number of highly suitable months is expected in parts of the North Coast and Hunter dairy regions in the intermediate emissions scenario and in parts of all dairy regions in the high emissions scenario. However, other parts of the dairy regions are likely to experience increases in the number of highly suitable months.

RCP8.5 high emissions scenario		
C (i) Future number of highly suitable months	C (ii) Change in number of months	C (iii) Confidence in change

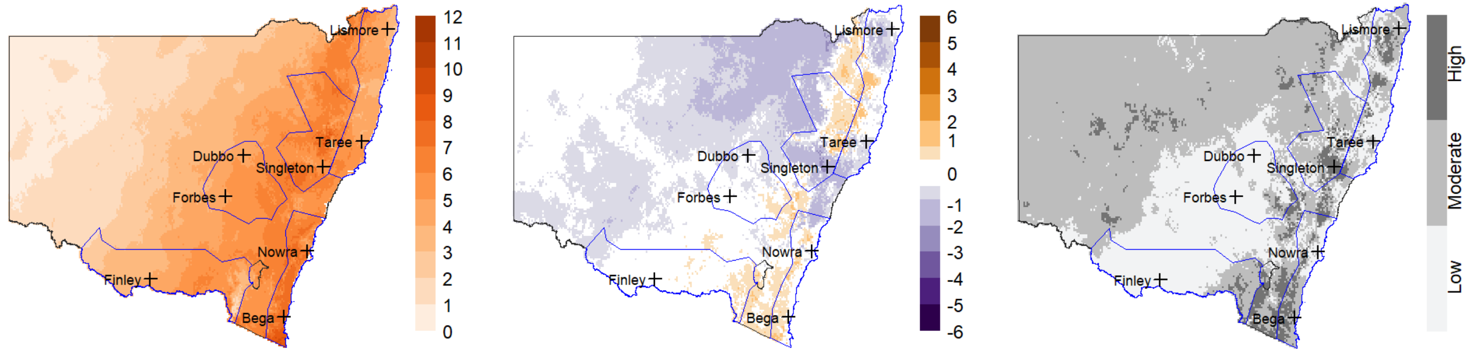


Figure 19: Number of highly suitable months for lucerne in NSW. The number of highly suitable months measures the months in which climate suitability is 'high' or 'very high'. A) shows the historical number of highly suitable months; B) and C) show the future number of highly suitable months for the intermediate and high emissions scenarios, respectively; (i) shows future number of highly suitable months, (ii) shows the projected change in number of months as negligible (white), increasing (orange) or decreasing (purple) change and (iii) shows the level of confidence in this change (low, moderate or high).

Regional climate impacts on lucerne

The lucerne climate suitability calendar (Figure 20) shows the expected change in monthly climate suitability throughout the year at key dairy production sites. These changes in climate suitability vary by region and are summarised as follows:

North Coast dairy region climate suitability

- **Minimal to moderate decreases in climate suitability** are likely to occur in the middle of spring and in summer at Taree and during the summer months at Lismore under both emissions scenarios (*moderate to high confidence).*
- **Historical climate suitability is likely to be maintained** as low to very high for remaining months at Lismore and Taree under both emissions scenarios (*low to high confidence*).

Hunter dairy region climate suitability

- **Minimal to moderate decreases in climate suitability** are likely to occur in Singleton from the middle of spring to the middle of autumn under both emissions scenarios (*moderate to high confidence*).
- **Historical climate suitability is likely to be maintained** as high to very high in Singleton for the remaining months under both emissions scenarios (*moderate to high confidence*).

Inland dairy region climate suitability

- **Minimal to moderate increases in climate suitability** are likely to occur during the winter months at both Dubbo and Forbes under both emissions scenarios (*high confidence*).
- **Minimal to moderate decreases in climate suitability** are likely to occur from the middle of spring to the middle of autumn in Dubbo and Forbes under both emissions scenarios (*low to high confidence*).
- **Historical climate suitability is likely to be maintained** as high to very high in Dubbo and Forbes for the remaining months under both emissions scenarios (*moderate to high confidence*).

Riverina Murray dairy region climate suitability

- **Minimal increases in climate suitability** are likely to occur during winter at Finley under both emissions scenarios (*high confidence*).
- **Minimal to moderate decreases in climate suitability** are likely to occur from late spring until early autumn in Finley under both emissions scenarios (*moderate to high confidence*).

South Coast dairy region climate suitability

- **Minimal to moderate increases in climate suitability** are likely to occur during the winter months at Bega under both emissions scenarios (*high confidence*).
- **Minimal decreases in climate suitability** are likely to occur in late spring in Nowra under both emissions scenarios and also in the middle of autumn in the high emissions scenario, and in the middle of summer and in early autumn in Bega under both emissions scenarios (*moderate to high confidence*).
- **Historical climate suitability is likely to be maintained** as high to very high in Bega and Nowra for the remaining months under both emissions scenarios (*moderate to high confidence*).

The analysis above describes climate suitability trends across key dairy production sites throughout the year. While this summary provides a simplified overview, it may overlook important spatial trends not captured by the individual locations. Monthly climate suitability map panels for all months have been included in the Appendix (Figure A41 to A52), allowing for the examination of spatial trends throughout the year.

Lucerne: climate suitability calendar

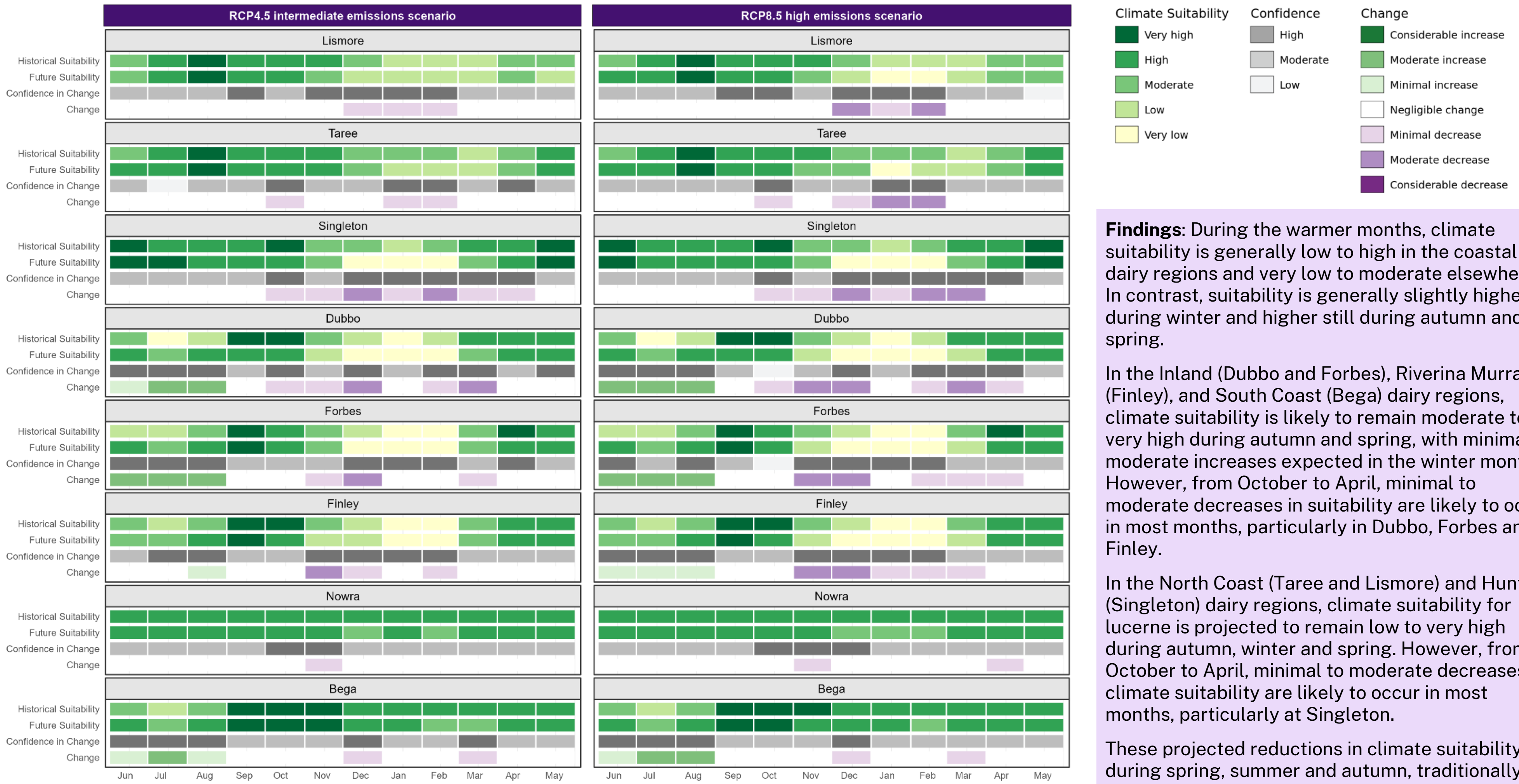


Figure 20: Climate suitability calendar for lucerne, displaying the monthly climate suitability value for historical climate and future climate scenarios (RCP4.5 and RCP8.5) for sites in each dairy region. The climate suitability values shown are the median of a 10km radius surrounding each site of interest.

Findings: During the warmer months, climate suitability is generally low to high in the coastal dairy regions and very low to moderate elsewhere. In contrast, suitability is generally slightly higher during winter and higher still during autumn and spring.

In the Inland (Dubbo and Forbes), Riverina Murray (Finley), and South Coast (Bega) dairy regions, climate suitability is likely to remain moderate to very high during autumn and spring, with minimal to moderate increases expected in the winter months. However, from October to April, minimal to moderate decreases in suitability are likely to occur in most months, particularly in Dubbo, Forbes and Finley.

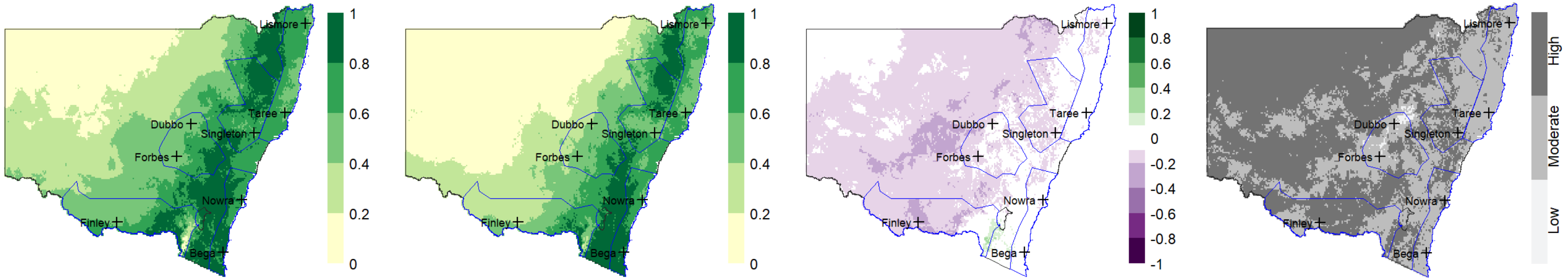
In the North Coast (Taree and Lismore) and Hunter (Singleton) dairy regions, climate suitability for lucerne is projected to remain low to very high during autumn, winter and spring. However, from October to April, minimal to moderate decreases in climate suitability are likely to occur in most months, particularly at Singleton.

These projected reductions in climate suitability during spring, summer and autumn, traditionally the most productive periods for growth, may present challenges for dairying, with the growing season for lucerne expected to shorten. In areas likely to experience summer declines, these reductions may necessitate a shift in pasture management strategies or the introduction of alternative pasture species to maintain a stable feed base throughout the warmer months.

Lucerne: climate suitability for November

Historical | RCP4.5 intermediate emissions scenario

A) Climate suitability | B (i) Future climate suitability | B (ii) Change in climate suitability | B (iii) Confidence in change



Findings: during November, minimal to moderate decreases in climate suitability are expected in the Hunter, Inland and Riverina Murray dairy regions, as well as parts of the North Coast and South Coast dairy regions, in both emissions scenarios. Spring is a key growth period for lucerne, and these changes may present challenges for dairying. Greater changes are expected to occur under the high emissions scenario.

RCP8.5 high emissions scenario

C (i) Future climate suitability | C (ii) Change in climate suitability | C (iii) Confidence in change

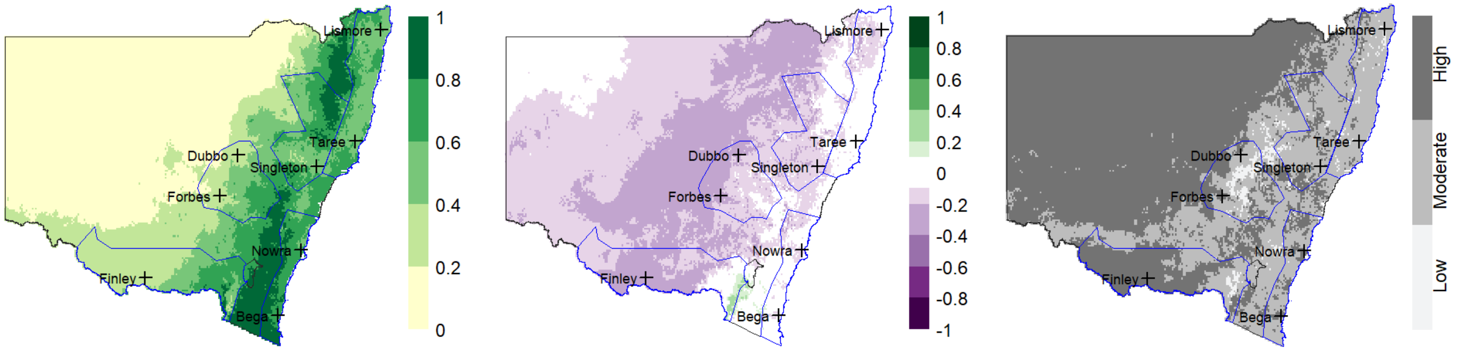


Figure 21: Overall climate suitability for lucerne in NSW in November. A) shows the historical climate suitability; B) and C) show future climate suitability for the intermediate and high emissions scenarios, respectively; (i) shows future climate suitability, (ii) shows the projected future change in climate suitability as negligible (white), positive (green) or negative (purple) change, and (iii) shows the level of model confidence associated with this change (low, moderate or high).

Key insights for lucerne

Historical and future trends

Climate suitability for lucerne is expected to maintain historical levels for growth during late autumn and through winter at most sites. However, climate suitability for lucerne growth is likely to decrease in all dairy regions in some months from October to April. In contrast, an increase in climate suitability is expected in the Inland, Riverina Murray and South Coast dairy regions during winter months (see Figure 20).

Future climate vulnerabilities

Due to higher temperatures, an increase in the number of hot days and changes in rainfall, there is likely to be a minimal to moderate decrease in climate suitability for lucerne in all dairy regions during late spring, summer and early autumn (*moderate to high confidence*) (see Appendix Figures A51 to A52 and A41 to A44). These changes are likely to be more prominent under high emissions scenarios. They are more widespread across the Hunter, Inland, and Riverina Murray dairy regions. Future climatic conditions are therefore expected to be less suitable for lucerne during these months, under the assumption of rain-fed lucerne production with no supplementary irrigation.

Future climate opportunities

There are likely to be minimal to moderate increases in climate suitability across all dairy regions from over winter and from late autumn to early spring, with increases in smaller areas in April (*moderate to high confidence*) (see Appendix Figures A45 to A40). During winter, the increases in climate suitability are more widespread under the high emissions scenario, extending across much of NSW. These changes are attributed to higher minimum temperatures and changes in mean temperature and rainfall, with climatic conditions expected to become more suitable for lucerne growth during these months.

Implications for lucerne pastures

By 2050, the climate during the warmer months is likely to be less suitable for lucerne growth in all dairy regions in NSW. In contrast, winter conditions are likely to become more suitable, which may bring opportunities for lucerne production during the cooler months.

Lucerne growth may benefit from increased winter climate suitability, particularly in the Inland, Riverina Murray, and South Coast dairy regions. To maximise these benefits, producers may need to shift production to late winter and early spring and adjust dormancy ratings of sown varieties to suit warmer winters. This model considered moderately dormant varieties (Dormant 7). In these dairy regions, utilising more lucerne as conserved fodder will depend on farm infrastructure. Further local studies are needed to determine whether these changes improve winter growth and will therefore be able to help producers balance increased winter activity against a projected decrease in climate suitability in other seasons.

The projected decline in lucerne suitability during late spring, summer, and early autumn could present challenges for NSW dairy systems, as rain-fed lucerne is likely to experience reduced productivity in this warmer part of the year. These projected changes highlight the need for NSW dairy farmers to review their lucerne management strategies and consider shifting the seasonal focus of lucerne use toward winter and spring, selecting varieties with different dormancy ratings to better match changing climatic conditions. As a result of these changes, fodder availability may be reduced in the future due to spring and summer declines, potentially affecting the supply of lucerne across NSW. Establishment will require more attention under a changing climate, with hotter, drier conditions in autumn increasing sowing risks in the western Hunter, Inland, and Riverina Murray dairy regions. Research is needed to assess dormancy types across the state, to understand how irrigation could offset some climate impacts, and to develop practical guidance for managing lucerne on NSW dairy farms.

Forage oats

Forage oats in NSW

Forage oats are grown in all NSW dairying regions. They are commonly used as an early winter feed source for dairying. Forage oats are characterised by their 'quick' establishment in winter months, compared to annual ryegrass. Generally sown as individual crops or in combination with ryegrass, forage oats fill a feed gap usually seen in winter, before annual ryegrass has become established and suitable for grazing.

Final forage oats MCA model

The forage oats MCA model focuses on the establishment and vegetative growth stages. For the establishment growth stage, the key climate variables are the number of cold days and hot days. In contrast, the key climate driver for vegetative growth is the interaction between mean temperature and rainfall.

A growing degree day (GDD) threshold of 590 GDD, with a Tbase of 3°C, was implemented to replicate the vegetative state process that occurs due to the phenology of the plant, imposing limitations on climate suitability during summer. The final MCA model structure for forage oats can be found in the Appendix (Figure A53). **Note**: The following climate suitability maps do not consider soil properties, and forage oats were modelled as a rain-fed system, rather than irrigated. See page 8 for all model assumptions and exclusions.

Successful forage oats establishment is essential for high productivity, as it promotes strong root development and persistence under grazing. In NSW, forage oats are typically sown in autumn (March to May), when conditions are most favourable for germination and early growth.

Overall climate impacts

Climate suitability for forage oats is likely to experience a minimal to moderate decrease in all key dairy regions throughout the year, but particularly in summer.

The mean number of highly suitable months each year, in which the climate suitability is classified as 'high' or 'very high', is used as a measure of overall climate suitability for pastures, and it varies across the state.

By 2050, the number of highly suitable months for forage oats (Figure 22) is likely to decrease by up to 3 months per year under both emissions scenarios for all key dairy regions (*moderate to high confidence*) except the easternmost part of the Riverina Murray dairy region, which is expected to experience an increase in the number of highly suitable months of up to 2 months per year under both emissions scenarios (*low to high confidence*).

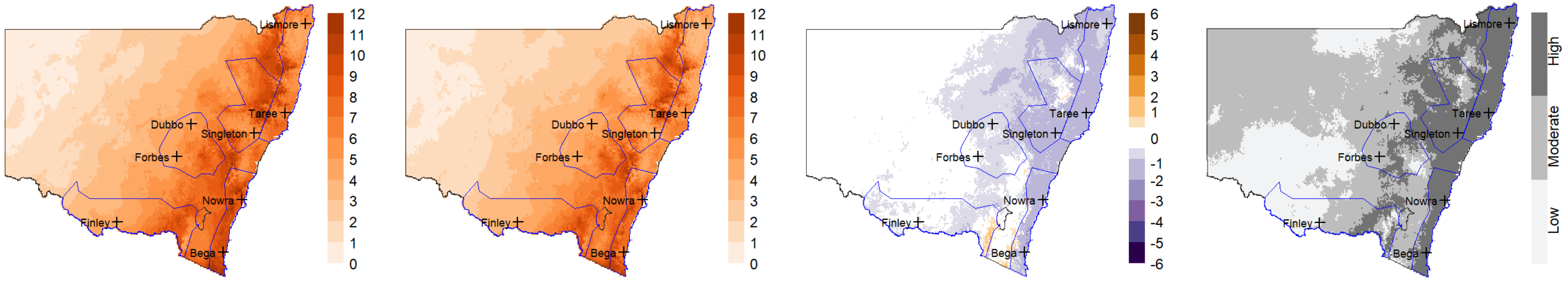
The projected decrease in the number of highly suitable months presents a potential challenge for the dairy industry. Results indicate that by 2050, there may be reduced growing season length for forage oats in all NSW dairy regions.

Forage Oats Establishment

The climate suitability for forage oats establishment in March is likely to decrease in all NSW dairy regions and in the North Coast and parts of the Inland dairy region in April, due to an increase in daily maximum temperatures (*moderate to high confidence*). These changes could result in a reduction in establishment success. In contrast, scattered areas in most dairy regions are likely to experience minimal increases in climate suitability between May and August (*moderate to high confidence*). These findings indicate that March and April may become less reliable for the establishment of forage oats in the future, and consideration should be given to shifting establishment timing to better align with more favourable climatic conditions.

Forage oats: number of highly suitable months

Historical	RCP4.5 intermediate emissions scenario		
A) Number of highly suitable months	B (i) Future number of highly suitable months	B (ii) Change in number of months	B (iii) Confidence in change



Findings: most dairy regions are expected to see a decrease in the number of highly suitable months each year, under both emissions scenarios, with a greater and more widespread decrease in the high emissions scenario. Only the easternmost part of the Riverina Murray dairy region is likely to experience an increase in the number of highly suitable months.

RCP8.5 high emissions scenario		
C (i) Future number of highly suitable months	C (ii) Change in number of months	C (iii) Confidence in change

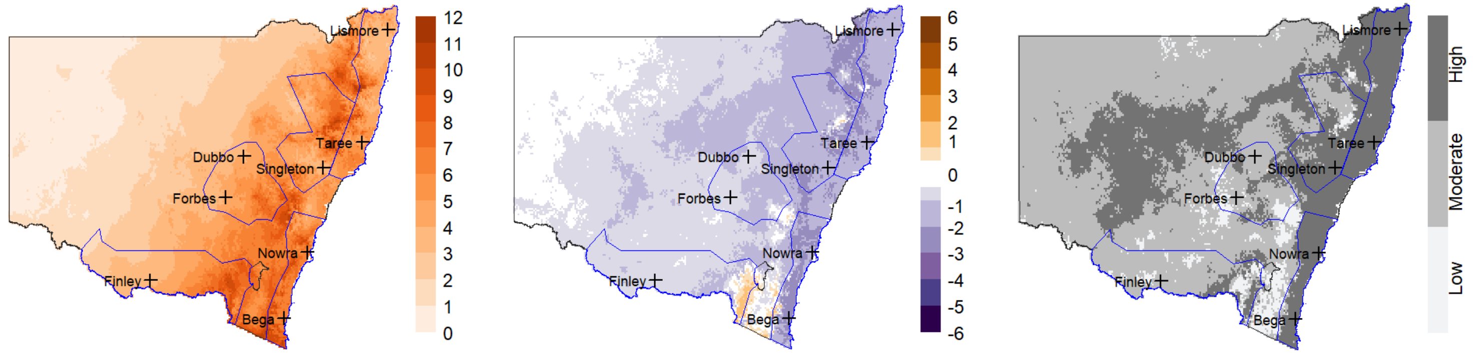


Figure 22: Number of highly suitable months for forage oats in NSW. The number of highly suitable months measures the months in which climate suitability is 'high' or 'very high'. A) shows the historical number of highly suitable months; B) and C) show the future number of highly suitable months for the intermediate and high emissions scenarios, respectively; (i) shows future number of highly suitable months, (ii) shows the projected change in number of months as negligible (white), increasing (orange) or decreasing (purple) change and (iii) shows the level of confidence in this change (low, moderate or high).

Regional climate impacts on forage oats

The climate suitability calendar for forage oats (Figure 23) shows the expected change in monthly climate suitability through the year at key dairy production sites. These changes in climate suitability vary by region and are as follows:

North Coast dairy region climate suitability

- **Minimal increases in climate suitability** are likely to occur in Taree in midwinter under both emissions scenarios (*high confidence*).
- **Minimal to moderate decreases in climate suitability** are likely in Lismore and in Taree during some months in spring, summer and autumn under both emissions scenarios (*moderate to high confidence*).
- **Historical climate suitability in other months is likely to be maintained** in Taree and Lismore, remaining very low in mid-summer and moderate to very high at other times, under both emissions scenarios (*moderate to high confidence*).

Hunter dairy region climate suitability

- **Minimal to moderate decreases in climate suitability** in autumn and spring months in Singleton under both emissions scenarios, extending into summer in this high emissions scenario (*moderate to high confidence*).
- **Historical climate suitability in other months is likely to be maintained** in Singleton, remaining very low in the warmer months and moderate to very high in the cooler months under both emissions scenarios (*moderate to very high confidence*).

Inland dairy region climate suitability

- **Minimal to moderate decreases in climate suitability** are likely in late spring and in autumn in Dubbo and Forbes under both emissions scenarios (*moderate to high confidence*).
- **Historical climate suitability in other months is likely to be maintained** in Dubbo and Forbes, remaining very low in the warmer months and moderate to high in the colder months under both emissions scenarios (*moderate to high confidence*).

Riverina Murray dairy region climate suitability

- **Minimal to moderate decreases in climate suitability** are likely in the late spring/early summer months and in early to mid-autumn months in Finley under both emissions scenarios (*moderate to high confidence*).
- **Historical climate suitability in other months is likely to be maintained** in Finley**,** remaining very low in the warmer months and low to high in the cooler months under both emissions scenarios (*low to high confidence*).

South Coast dairy region climate suitability

- **Minimal increases in climate suitability** are likely to occur in Nowra in midwinter under both emissions scenarios (*high confidence*).
- **Minimal to moderate decreases in climate suitability** are likely to occur in spring, summer and autumn months in Nowra and summer and autumn in Bega, under both emissions scenarios (*moderate to high confidence*).

The analysis above describes climate suitability trends across key dairy production sites throughout the year. While this summary provides a simplified overview, it may overlook important spatial trends not captured by the individual locations. Monthly climate suitability map panels for all months have been included in the Appendix (Figure A54 to A65), allowing for the examination of spatial trends throughout the year.

Forage oats: climate suitability calendar

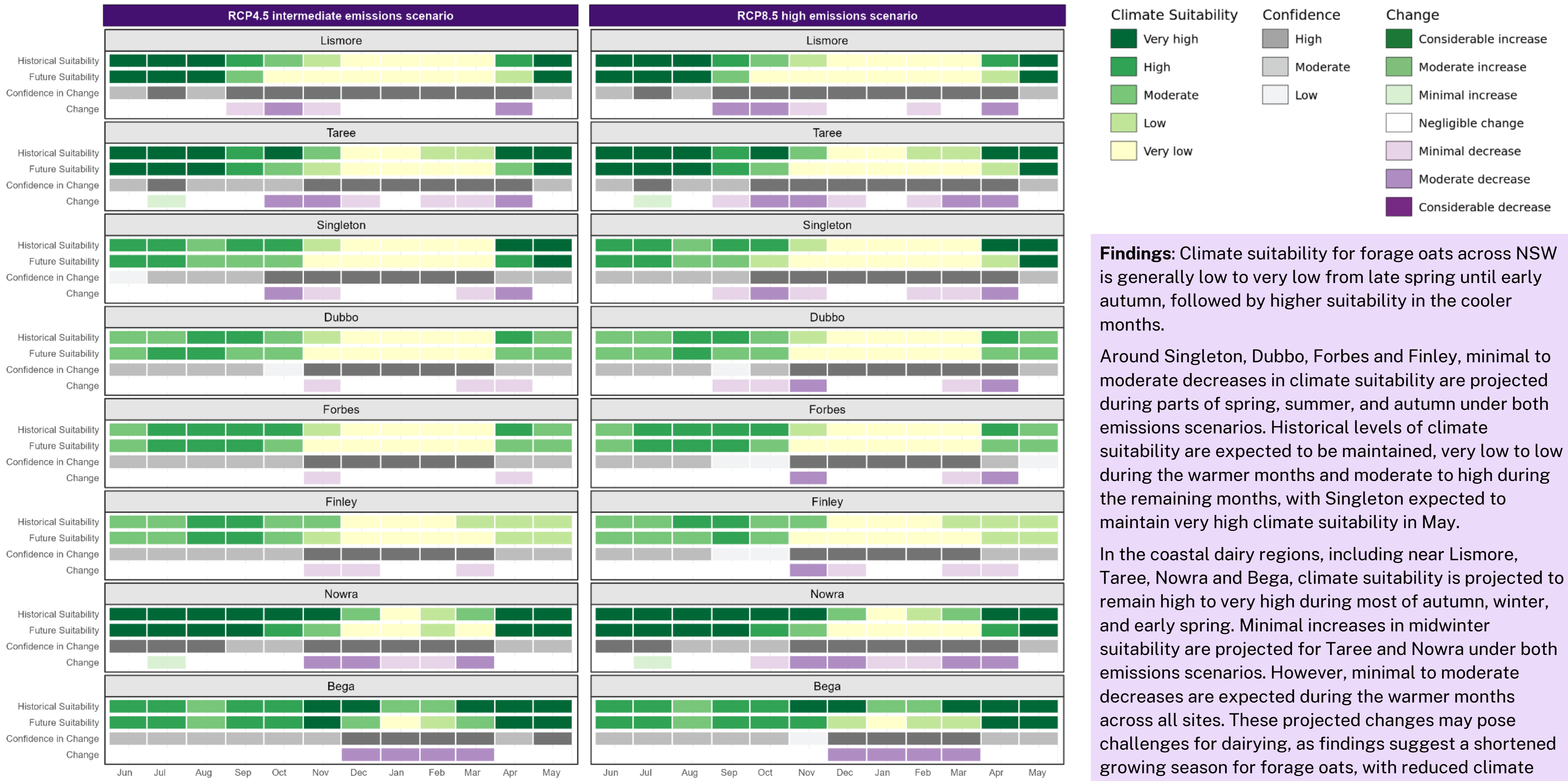


Figure 23: Climate suitability calendar for forage oats, displaying the monthly climate suitability value for historical climate and future climate scenarios (RCP4.5 and RCP8.5) for sites in each dairy region. The climate suitability values shown are the median of a 10km radius surrounding each site of interest.

Findings: Climate suitability for forage oats across NSW is generally low to very low from late spring until early autumn, followed by higher suitability in the cooler months.

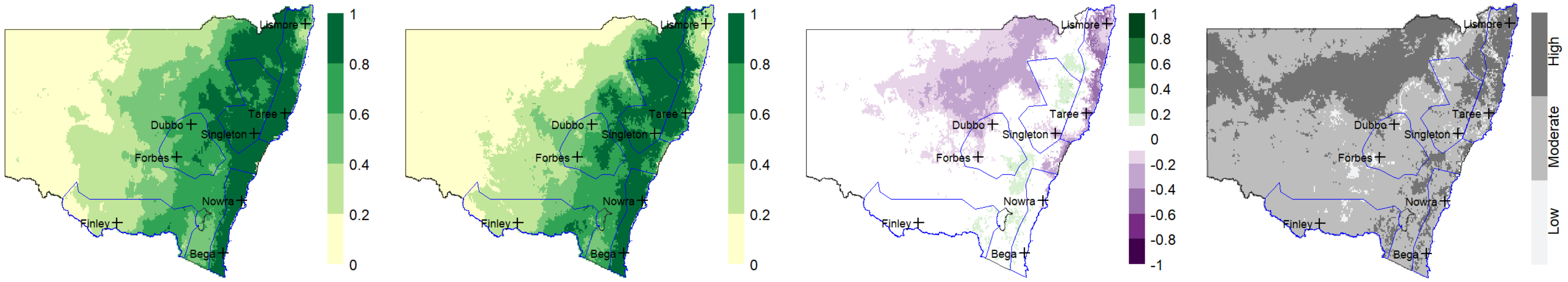
Around Singleton, Dubbo, Forbes and Finley, minimal to moderate decreases in climate suitability are projected during parts of spring, summer, and autumn under both emissions scenarios. Historical levels of climate suitability are expected to be maintained, very low to low during the warmer months and moderate to high during the remaining months, with Singleton expected to maintain very high climate suitability in May.

In the coastal dairy regions, including near Lismore, Taree, Nowra and Bega, climate suitability is projected to remain high to very high during most of autumn, winter, and early spring. Minimal increases in midwinter suitability are projected for Taree and Nowra under both emissions scenarios. However, minimal to moderate decreases are expected during the warmer months across all sites. These projected changes may pose challenges for dairying, as findings suggest a shortened growing season for forage oats, with reduced climate suitability during key growth periods.

The decrease in climate suitability during summer should not be a major concern, as forage oats are not typically used during this season, with dairy producers relying on pasture types better suited to warmer conditions.

Forage oats: climate suitability for April

Historical	RCP4.5 intermediate emissions scenario		
A) Climate suitability	B (i) Future climate suitability	B (ii) Change in climate suitability	B (iii) Confidence in change



Findings: minimal to moderate decreases in climate suitability are projected across parts of all dairy regions during April, under both emissions scenarios. The changes may present challenges for NSW dairy regions. April is a key establishment month for forage oats, and warming autumn conditions could reduce establishment success and early growth, potentially limiting early-winter feed supply.

RCP8.5 high emissions scenario		
C (i) Future climate suitability	C (ii) Change in climate suitability	C (iii) Confidence in change

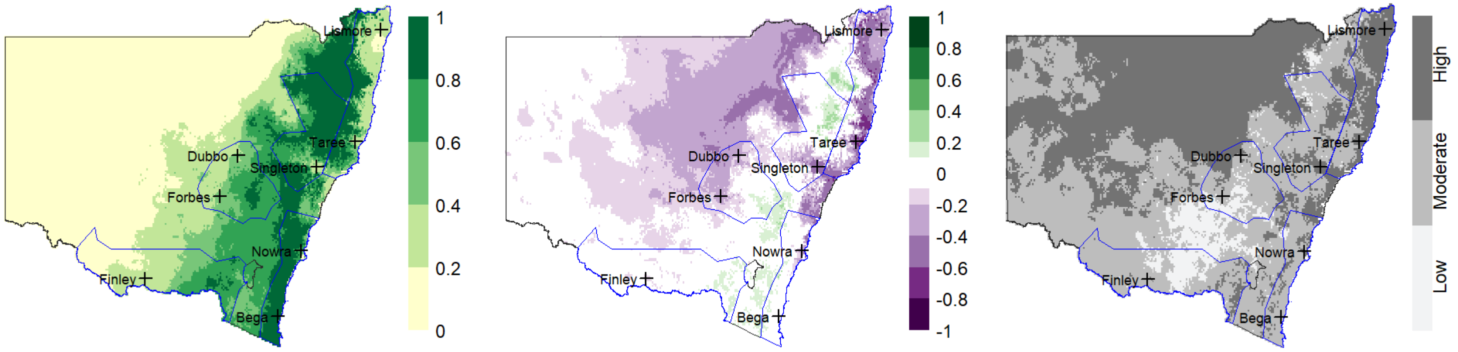


Figure 24: Overall climate suitability for forage oats in NSW in April. A) shows the historical climate suitability; B) and C) show future climate suitability for the intermediate and high emissions scenarios, respectively; (i) shows future climate suitability, (ii) shows the projected future change in climate suitability as negligible (white), positive (green) or negative (purple) change, and (iii) shows the level of model confidence associated with this change (low, moderate or high).

Key insights for forage oats

Historical and future trends

Climate suitability for forage oats is expected to maintain historical levels of climate suitability for growth during late-autumn, winter and in early spring, at most sites. At other times, however, climate suitability for forage oats growth is projected to experience minimal to moderate decreases at all sites. In midwinter, some areas like Taree and Nowra may see a minimal increase in climate suitability, while other dairy regions are expected to maintain historical levels of climate suitability at this time of year (see Figure 23).

Future climate vulnerabilities

Due to higher temperatures, an increase in the number of hot days and changes in rainfall, there is likely to be a minimal to moderate decrease in climate suitability for forage oats during spring, summer, and autumn (*low to high confidence*) (see Appendix Figures A54 to A58 and A62 to A65). These changes are greater under the high emissions scenario and affect all dairy regions during these months. However, the decreases are expected to be more widespread in the North Coast, Hunter, Inland and Riverina Murray dairy regions. These changes indicate that future climatic conditions could become less suitable for forage oats during these months, assuming rain-fed forage oats production with no supplementary irrigation. The decreases for April (Figure 24) are expected to occur under both emissions scenarios (*low to high confidence*).

Future climate opportunities

There are likely to be scattered areas of minimal increase in climate suitability in the North Coast and South Coast dairy regions during winter (*low to high confidence*) (see Appendix Figures A59 to A61). These increases are expected to be more widespread under the high emissions scenario. They are due to higher minimum and mean temperatures and changes in rainfall. They indicate that climatic conditions could become more suitable for forage oats during these months.

Implications for forage oats pastures

All dairy regions in NSW are likely to become less suitable for growing forage oats by 2050, due to higher temperatures in key establishment and growth months. Climate suitability during midwinter is projected to increase in some coastal areas, potentially creating opportunities for winter forage oat growth.

The growth of forage oats could benefit from improved winter climate suitability. In places such as Taree and Nowra, projections show minimal increases in climate suitability during midwinter, which may allow shorter rotations, earlier first grazing, or occasional winter silage. However, further localised studies are needed to determine whether these changes will lead to increased pasture growth, as it's also strongly influenced by soil moisture and rainfall timing.

Conversely, the anticipated decline in climate suitability during late spring and especially early autumn presents challenges for the NSW dairy industry. April is a key month for establishing forage oats, and projected warming during this period could reduce establishment success and possibly impact early growth and have a flow-on impact to early-winter feed. Higher spring temperatures may reduce grazing or conserved-fodder opportunities. While these changes are also observed in summer, they are not particularly relevant to dairying because this pasture species is not typically grown during this season.

These projected changes highlight the need for NSW dairy farmers to examine their forage oat management strategies and consider adopting adaptations, such as shifting sowing times and incorporating other pasture or oat varieties that may perform better under future climatic conditions.

Chicory

Chicory in NSW

Chicory is gaining popularity as a grazing option for pastoral dairy farms in NSW due to its deep-rooted, summer-active properties. It has high nutritional value and can be grazed by dairy cows. Commonly grown in mixed-sward paddocks alongside species such as kikuyu and annual ryegrass, chicory can persist longer than its shallow-rooted counterparts.

Final chicory MCA model

The chicory MCA model focused on the vegetative growth stage climatic conditions, considering the number of cold days and the interaction between mean temperature and rainfall. The final MCA model structure for chicory can be found in the Appendix (Figure A66). **Note**: The following climate suitability maps do not consider soil properties, and chicory was modelled as a rain-fed system, rather than irrigated. See page 8 for all model assumptions and exclusions.

Overall climate impacts

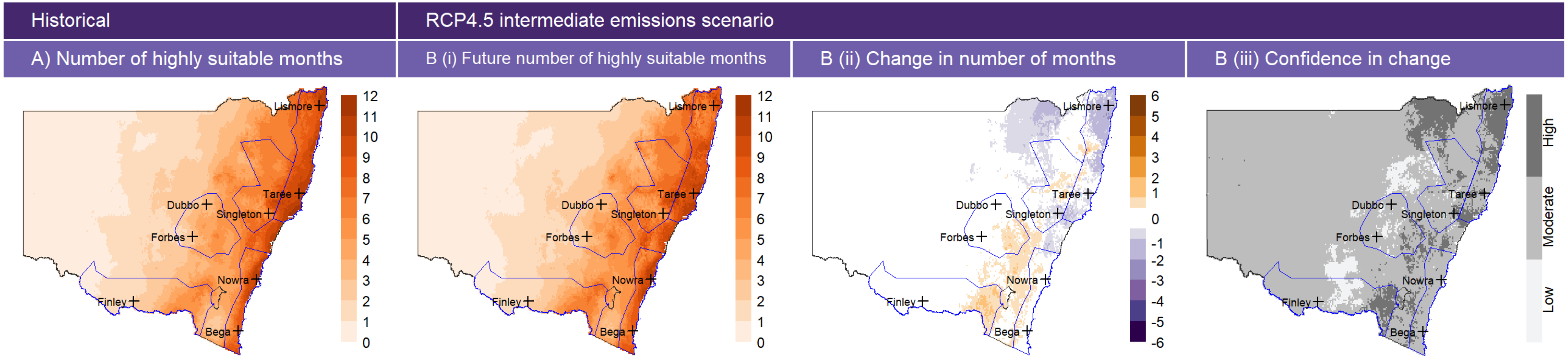
Under both future emissions scenarios, climate suitability for chicory is likely to experience a minimal to moderate decrease in some key dairy regions in the summer months, but a minimal to moderate increase in some dairy regions in other seasons.

The mean number of highly suitable months each year, in which the climate suitability is classified as 'high' or 'very high', is used as a measure of overall climate suitability for pastures, and it varies across the state.

By 2050, the number of highly suitable months for chicory (Figure 25) in the northern part of the North Coast dairy region is likely to decrease by up to 2 months per year under the intermediate emissions scenario and by up to 3 months per year in the high emissions scenario (*low to high confidence*). The south of the Hunter and the west of the Inland dairy regions are also expected to see a decrease of 1 or 2 highly suitable months per year (*low to moderate confidence*). However, the east of the Inland and Riverina Murray dairy regions, as well as scattered areas in other dairy regions, are likely to see an increase in the number of highly suitable months under both emissions scenarios or 1 or 2 months per year (*low to high confidence*).

These projected changes present potential vulnerabilities and opportunities for the dairy industry, indicating that the length of the chicory growing season in NSW dairy regions by 2050 is likely to decrease in some areas and increase in others.

Chicory: number of highly suitable months



Findings: There is likely to be a decrease in the number of highly suitable months across parts of the Hunter, North Coast, and Inland dairy regions under both emissions scenarios. The easternmost part of the Riverina Murray dairy region and parts of the other dairy regions are likely to see increases in the number of highly suitable months.

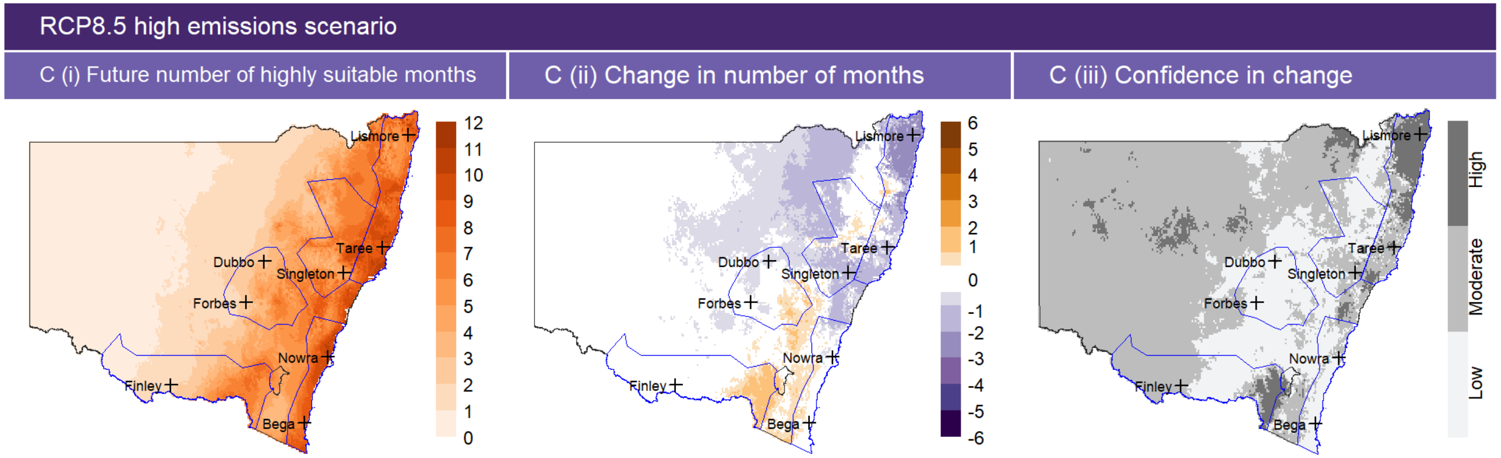


Figure 25: Number of highly suitable months for chicory in NSW. The number of highly suitable months measures the months in which climate suitability is 'high' or 'very high'. A) shows the historical number of highly suitable months; B) and C) show the future number of highly suitable months for the intermediate and high emissions scenarios, respectively; (i) shows future number of highly suitable months, (ii) shows the projected change in number of months as negligible (white), increasing (orange) or decreasing (purple) change and (iii) shows the level of confidence in this change (low, moderate or high).

Regional climate impacts on chicory

The chicory climate suitability calendar (Figure 26) shows the expected change in monthly climate suitability throughout the year at key dairy production sites. These changes in climate suitability vary by region:

North Coast dairy region climate suitability

- **Minimal increases in climate suitability** are likely to occur during the winter months for Lismore under both emissions scenarios and Taree in the intermediate emissions scenario (*moderate to high confidence*).
- **Minimal to moderate decreases in climate suitability** are likely in summer under the intermediate emissions scenario and from early spring through summer under the high emissions scenario (*moderate to high confidence*).
- **Historical climate suitability is likely to be maintained** as moderate to very high across Lismore and Taree in the remaining months under both emissions scenarios (*moderate to high confidence*).

Hunter dairy region climate suitability

- **Minimal to moderate decreases in climate suitability** are likely around Singleton in the summer months under both emissions scenarios (*low to high confidence*).
- **Historical climate suitability is likely to be maintained** as very low to very high around Singleton in the remaining months under both emissions scenarios (*moderate to high confidence*).

Inland dairy region climate suitability

- **Minimal decreases in climate suitability** in December are expected around Dubbo under the intermediate emissions scenario and **minimal to moderate decreases** around both Dubbo and Forbes in summer under the high emissions scenario (*moderate to high confidence*).
- **Historical climate suitability is likely to be maintained** as very low to high around Dubbo and Forbes for all remaining months under both emissions scenarios (*moderate to high confidence*).

Riverina Murray dairy region climate suitability

- **Historical climate suitability is likely to be maintained** as low to very low around Finley for all months under both emissions scenarios (*low to moderate confidence*).

South Coast dairy region climate suitability

- **Minimal to moderate increases in climate suitability** are likely around Bega during July under the intermediate emissions scenario and July and October under the high emissions scenario (*moderate to high confidence*).
- **Historical climate suitability is likely to be maintained** as moderate to very high year-round around Nowra and Bega in the remaining months under both emissions scenarios (*moderate to high confidence*).

The analysis above describes climate suitability trends across key dairy production sites throughout the year. While this summary provides a simplified overview, it may overlook important spatial trends not captured by the individual locations. Monthly climate suitability map panels for all months have been included in the Appendix (Figure A67 to A78), allowing for the examination of spatial trends throughout the year.

Chicory: climate suitability calendar

Figure 26: Climate suitability calendar for chicory, displaying the monthly climate suitability value for historical climate and future climate scenarios (RCP4.5 and RCP8.5) for sites in each dairy region. The climate suitability values shown are the median of a 10km radius surrounding each site of interest.

Findings: Climate suitability for chicory is at its highest from spring through to early autumn, followed by lower suitability during cooler months.

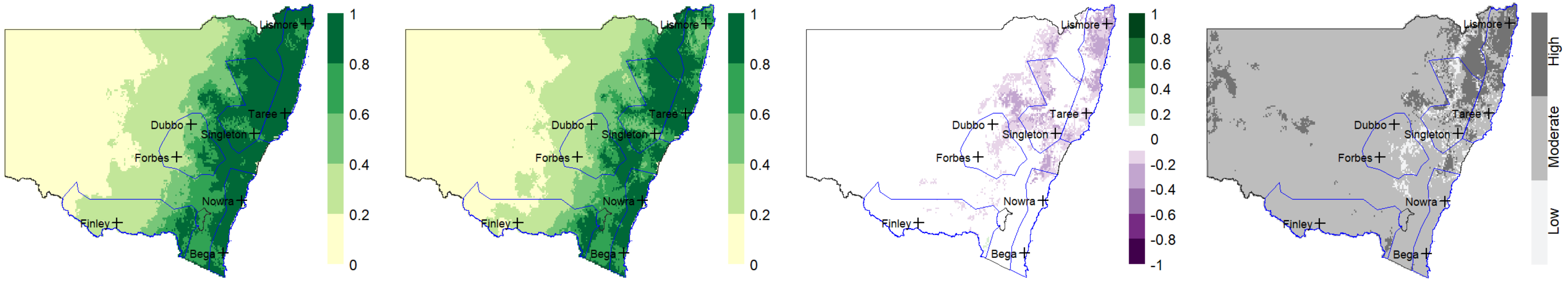
In Lismore, Taree, Nowra and Bega, climate suitability is expected to be moderate to very high from November to April, aligning with the peak growth for chicory. By 2050, increases in climate suitability in some months during winter and spring may support persistence and earlier spring activation at Bega, Taree and Lismore, under the high emissions scenario. However, minimal to moderate decreases in suitability during spring and summer near Lismore and Taree could impact chicory establishment and growth. Singleton follows a similar pattern, although its climate suitability for chicory is lower than on the coast.

Changes in suitability suggest that chicory is likely to be still used as a summer-active forage in these regions. However, careful consideration of sowing times and management will be necessary to adapt to changing conditions and maintain productivity.

For Dubbo, Forbes and Finley, climate suitability is expected to remain very low to moderate year-round. Historically, these areas have been less reliant on chicory, and this is unlikely to change, with minimal to moderate decreases in climate suitability during December and February. Dairy farmers in these areas are likely to continue dependence on other pastures.

Chicory: climate suitability for January

Historical	RCP4.5 intermediate emissions scenario		
A) Climate suitability	B (i) Future climate suitability	B (ii) Change in climate suitability	B (iii) Confidence in change



Findings: minimal to moderate decreases in climate suitability are expected in the North Coast, Hunter and Inland regions in January, under both emissions scenarios. This may pose challenges for the North Coast and Hunter regions, as chicory is most productive during spring and summer. With climate conditions for chicory growth in January expected to become less favourable in the future, careful management will be necessary to adapt.

RCP8.5 high emissions scenario		
C (i) Future climate suitability	C (ii) Change in climate suitability	C (iii) Confidence in change

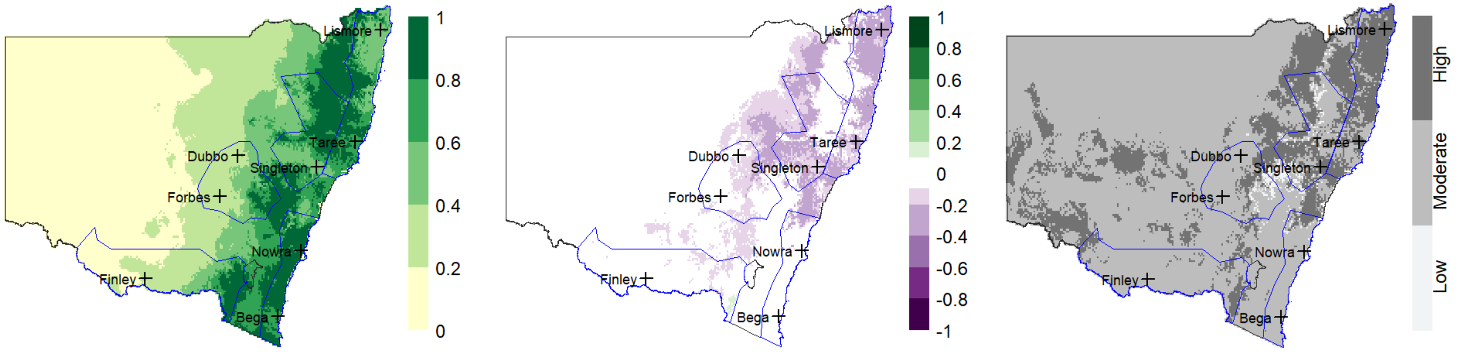


Figure 27: Overall climate suitability for chicory in NSW in January. A) shows the historical climate suitability; B) and C) show future climate suitability for the intermediate and high emissions scenarios, respectively; (i) shows future climate suitability, (ii) shows the projected future change in climate suitability as negligible (white), positive (green) or negative (purple) change, and (iii) shows the level of model confidence associated with this change (low, moderate or high).

Key insights for chicory

Historical and future trends

Climate suitability for chicory is expected to maintain historical levels of climate suitability for growth during autumn and spring in most dairy regions (although the North Coast could see decreases in spring in the high emissions scenario). However, climatic conditions for chicory growth are projected to experience minimal to moderate decreases in climate suitability, particularly during summer around most key sites. In winter, areas around Lismore, Taree and Bega may see minimal increases in climate suitability (and in October near Bega), while the remaining dairy regions should maintain their historical levels of climate suitability during these months (Figure 26).

Future climate vulnerabilities

Due to higher mean temperatures and changes in rainfall, there is likely to be a minimal to moderate decrease in climate suitability for chicory in the North Coast region from September (December in the intermediate emissions scenario), and in the Inland and Hunter regions over summer (*low to high confidence*) (see Appendix Figures A67 to A70). These changes are more prominent and widespread in the high emissions scenario. Minimal to moderate decreases in climate suitability in January are shown in Figure 27 and are expected under both emissions scenarios (*low to high confidence*). These changes indicate that future climatic conditions could become less suitable for chicory growth during these months, assuming rain-fed chicory production with no supplementary irrigation.

Future climate opportunities

There are likely to be scattered areas of minimal to moderate increases in climate suitability in most dairy regions during autumn, winter and spring (*low to high confidence*) (see Appendix Figures A69 to A77). From May to September, these increases in climate suitability are more widespread under the high emissions scenario. They are attributed to higher minimum temperatures, indicating that climatic conditions could become more suitable for chicory during these months.

Implications for chicory pastures

By 2050, the climate in most dairy regions is likely to become more suitable for growing chicory during winter and spring. This change in winter could improve over-winter persistence and earlier spring activation, particularly in areas where chicory was previously semi-dormant in these months and could allow some additional growth, helping to bridge gaps in feed supplies between cool-season pastures and kikuyu or other summer fodder crops.

There may be a minimal to moderate decline in suitability in the late spring and summer months in the North Coast, Hunter and Inland regions. Although chicory can still be utilised as part of the feed base, careful grazing management may be necessary during hotter periods in these regions.

Historically, chicory pastures have not been heavily relied upon in the Riverina Murray and Inland dairy regions due to the limited months with favourable growth conditions. These areas are expected to continue to have only very low to moderate suitability for chicory, with declines projected during summer months for the Inland region. Dairy businesses in these regions will need to rely on other pastures or summer fodder crops to sustain their feed base.

The projected changes in climate suitability for chicory highlight the need for dairy farmers in NSW to examine their chicory management and to consider adopting adaptations including sowing timing to ensure strong establishment, optimising rotational grazing to maintain plant longevity and prevent overgrazing as chicory foliage is often preferentially grazed by stock, and mixing chicory with legumes or other perennials to improve resilience and reduce input costs.

Irrigation water requirements of pastures

Determining irrigation water requirements

Pasture production for dairy systems is predominantly rainfed. However, there are several NSW regions which use irrigation to maintain year-round production. The MCA model assessed climate suitability for pasture based on the assumption of a rainfed system. However, irrigation water requirements were also assessed, in order to understand how future water requirements may change. To gain insights into future needs, irrigation water requirement maps were produced using the method outlined below.

Assessment of the future availability of water is outside the scope of this assessment. See the *Regional Water Strategies* (page 58), which provides more information on estimates of future water availability.

Calculation of irrigation water requirements

The globally accepted FAO56[10] crop coefficient method was used to assess changes in irrigation water requirements by 2050. The approach uses crop coefficient values (Kc) to calculate crop evapotranspiration (ETc), which represents the amount of water used by a crop at a given growth stage. The Kc value varies by month (Table 1), reflecting the changing requirements during the plant's lifecycle.

In NSW, dairy pastures typically comprise a mixture of different grass species, operated under rotational grazing. To assess future irrigation water requirements while reflecting current dairy-farming methods, we adopted a set of Kc values which represent the rotationally grazed pasture as a complete system, instead of modelling the water requirements of each pasture species individually. Our approach is intended to align with current farming practices and the way in which the modelled pastures are incorporated into dairy production.

Irrigation water requirements were calculated as the difference between crop evapotranspiration and total effective rainfall across the growing season. These results were then used to estimate the change between historical and future irrigation water requirements over an entire growing season (one annual crop cycle).

Climate variables used to calculate irrigation water requirement

- **Effective rainfall** is the amount of rainfall (mm per day) that enters the soil after considering interception by the crop/plant canopy and the capacity of the soil to hold water.
- **Potential evapotranspiration** (ETo) refers to the transfer of water vapour (mm per day) to the atmosphere from vegetated and unvegetated land surfaces across the planted area (that is, crop transpiration plus soil evaporation). A model which predicts ETo from solar radiation and mean daily temperature has been used[11].
- **Crop evapotranspiration** (ETc) is calculated as ETo * Kc.

For further details, refer to the Climate Vulnerability Assessment Methodology Report.

Table 1: Crop coefficient (Kc) values for rotational grazed pastures. Values were derived using FAO56.

Month	Kc Value	Month	Kc Value
January	0.85	July	0.4
February	0.85	August	0.64
March	0.85	September	0.85
April	0.85	October	0.85
May	0.75	November	0.85
June	0.75	December	0.85

[10] Allen, Richard G., Luis S. Pereira, Dirk Raes, and Martin Smith. 'FAO Irrigation and drainage paper No. 56.' Rome: Food and Agriculture Organization of the United Nations 56, no. 97 (1998).

[11] Hargreaves, G.H. and Samani, Z.A. (1982) Estimating Potential Evapotranspiration, Journal of the Irrigation and Drainage Division, 108(3). https://doi.org/10.1061/JRCEA4.0001390

Interpreting the irrigation water requirements maps

The results are presented as panels of 7 maps, comparing historical irrigation water requirements, in megalitres per hectare (ML ha^{-1}), with irrigation water requirements under two future emissions scenarios. Maps of change and confidence in that change are also presented. Key dairy regions in NSW are displayed on each map to indicate areas where these pastures are grown.

The historical climate suitability map shows the mean suitability for 30 years (1981 to 2010). For future projections, the mean suitability for 30 years (2036 to 2065) was calculated for 8 global climate models11 (GCMs), and the median of these models was used to produce future projection climate suitability maps.

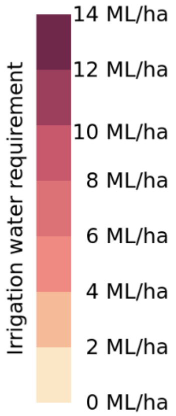


Figure 28 Colour scheme for the irrigation water requirement maps; the range varies by commodity

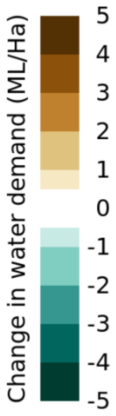


Figure 29 Colour scheme for the change in irrigation water requirements maps

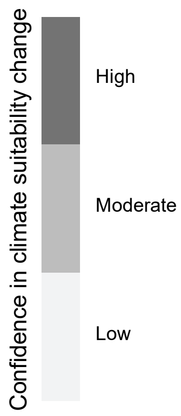


Figure 30 Colour scheme for the confidence in the change in the irrigation water requirements maps

Irrigation water requirements maps

The 'irrigation water requirements' maps show the water requirements on a scale of 0 to 14 ML h^{-1}. Pale yellow corresponds to very low irrigation water requirements, and dark burgundy corresponds to very high irrigation water requirements. The maximum value shown on the map varies for each commodity.

Change in irrigation water requirements maps

The 'change in irrigation water requirements' maps use a turquoise-white-brown colour scheme with 11 categories: positive change, where the future irrigation water requirements become higher, is shown in shades of brown; negative change is shown in shades of turquoise. Negligible change is represented by white and occurs for values between –5 and 5ML ha^{-1}; in these areas, the future irrigation water requirements are expected to be very similar to the historical.

Confidence in the change in irrigation water requirements maps

The 'confidence in change in irrigation water requirements' maps represent the level of agreement on the direction and magnitude of change in irrigation water requirements across the ensemble of 8 GCMs. These maps use a grey colour scheme with three categories: the lightest grey represents low confidence, and the darkest grey represents high confidence.

Climate impacts on irrigation water requirements

The irrigation water requirements of pastures are likely to change in the future.

Pastures are likely to use more water due to higher temperatures, which influence the total amount of irrigation water required to maintain pasture growth.

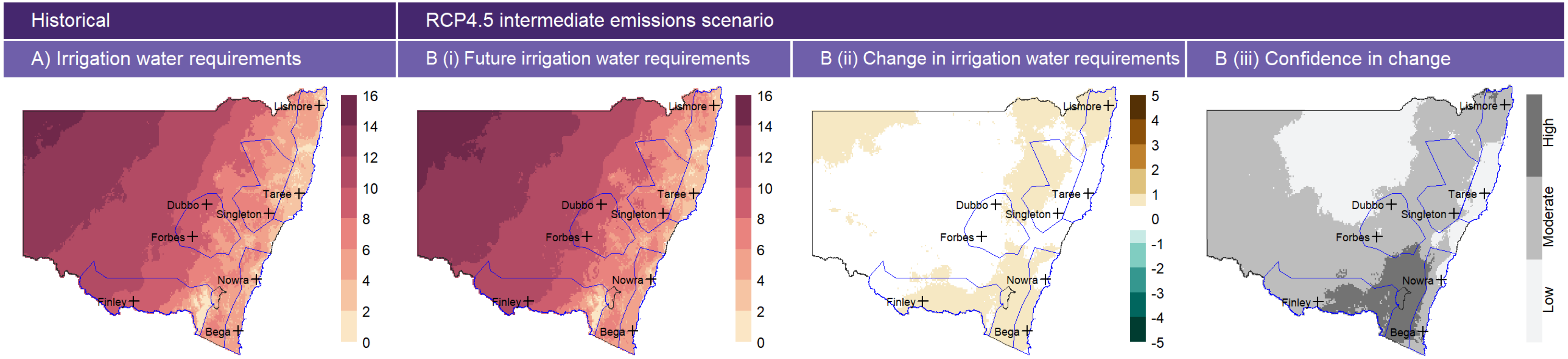
Under the high emissions scenario, irrigation water requirements are likely to increase in most dairy regions by 0.5 to 1 ML ha^{-1} (*moderate confidence*) (Figure 31); the remainder of the dairy regions are expected to retain their historical levels of irrigation water requirements (*low confidence*). Across the dairy regions, future requirements under both emissions scenarios range from 4 to 6 ML ha^{-1} at Lismore, to 10 to 12 ML ha^{-1} at Finley. Modelling confidence varies substantially across the state, as indicated by the range of confidence from low to high (Figure 28). This varying level of confidence indicates disagreement between projections made by the individual GCMs, and deeper examination of individual GCM projections (Figure 29) is warranted.

Note that changes in irrigation water requirements presented here are based on a 30-year average. Year-on-year climatic variability could mean that even greater amounts of water are required for irrigation during hot or dry years in the future.

Adapting to changing irrigation water requirements

The dairy industry in many areas may need to improve water storage and water use by adopting more efficient irrigation practices or new technologies to maintain pasture growth. Enhancing on-farm irrigation efficiency, such as using soil moisture monitoring, irrigation scheduling tools and timely grazing, could help manage hotter conditions. These changes may help to build resilience against water availability challenges. Future assessments should integrate soil constraints, irrigation access, and supply to provide more accurate guidance on irrigation demand and, therefore, adaptation needs.

Pastures: irrigation water requirements



Findings: Under the intermediate emissions scenario, irrigation water requirements are projected to increase by 0.5 to 1ML ha^{-1} in parts of all dairy regions. Under the high emissions scenario, statewide irrigation water requirements could increase by between 0.5 and 1ML ha^{-1}, with some areas increasing by up to 2ML ha^{-1}. In the dairy regions, requirements range from 2 to 6ML ha^{-1} around Lismore to 10 to 12ML ha^{-1} around Finley under the high emissions scenario. Confidence in climate projections is low across much of the state, due to disagreement between the underlying GCMs (see Figure 32).

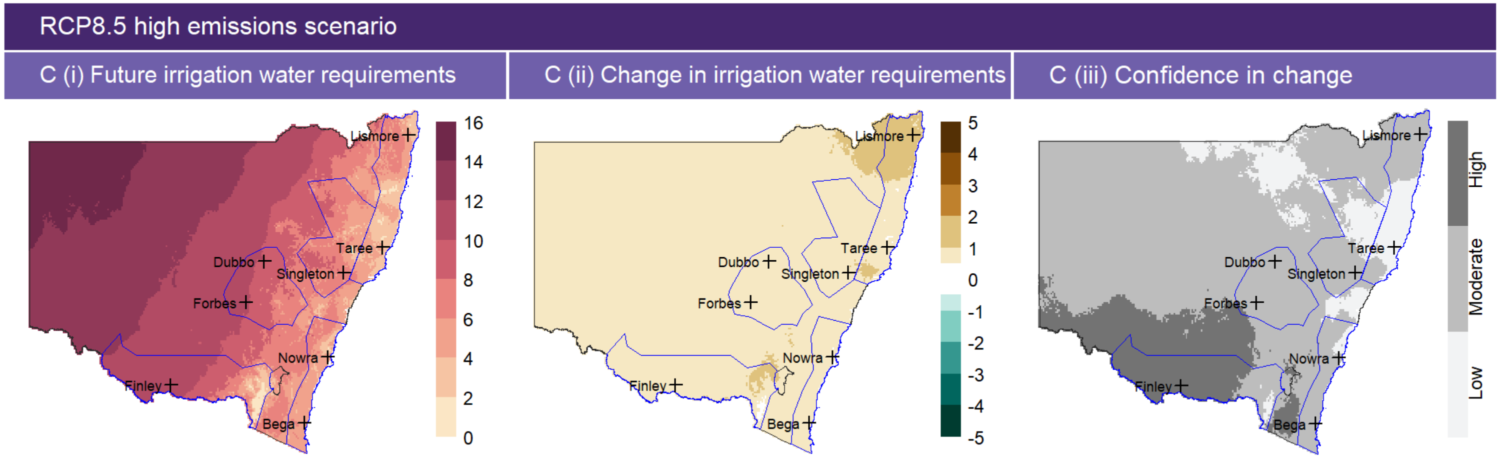
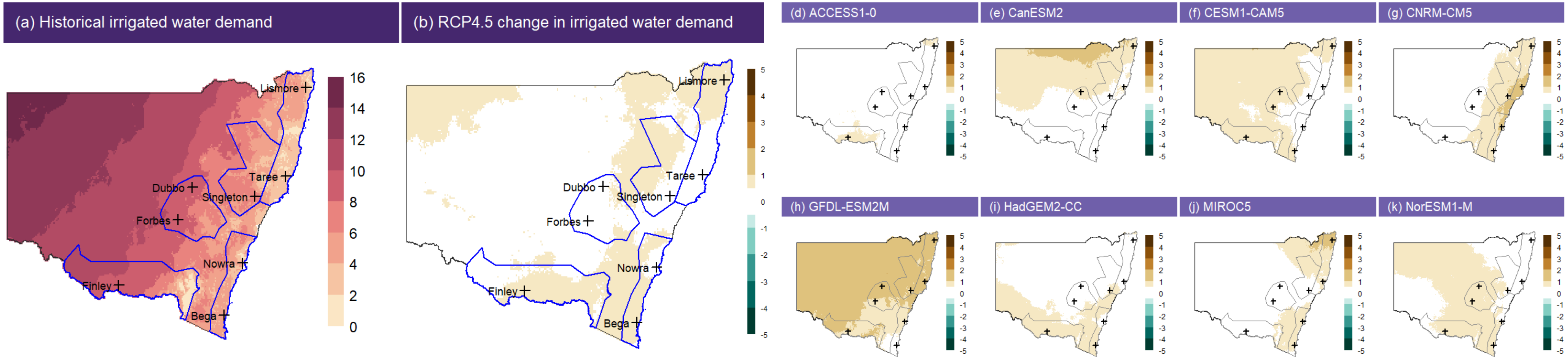


Figure 31: Overall irrigation water requirements for pastures. The figure is comprised of 7 maps: A) shows historical irrigation water requirements; B) and C) show future irrigation water requirements for the intermediate and high emissions scenarios, respectively; (i) shows future irrigation water requirements, (ii) shows projected future change in irrigation water requirements as negligible (white), positive (green) or negative (purple) change, and (iii) shows the level of model confidence associated with this change (low, moderate or high). Blue polygons and black crosses show key dairy production regions and sites.

Pastures: change in irrigation water requirements for each GCM



Findings: The individual GCMs show a range of projected changes in irrigation water requirements by 2050. The median change map (c) shows irrigation water requirements in the high emissions scenario may increase by 0.5 to 1ML ha^{-1} statewide with some areas of increase by up to 2ML ha^{-1}. However, individual GCMs show increases of up to 3 ML ha^{-1} (p) in some dairy regions, with others showing increases of 1 to 2ML ha^{-1} (m, o, q) and still others showing increases of 0.5 to 1ML ha^{-1} (l, n, r, s). This variability reduces confidence in the results, and it is important to consider the full range of change across the GCMs.

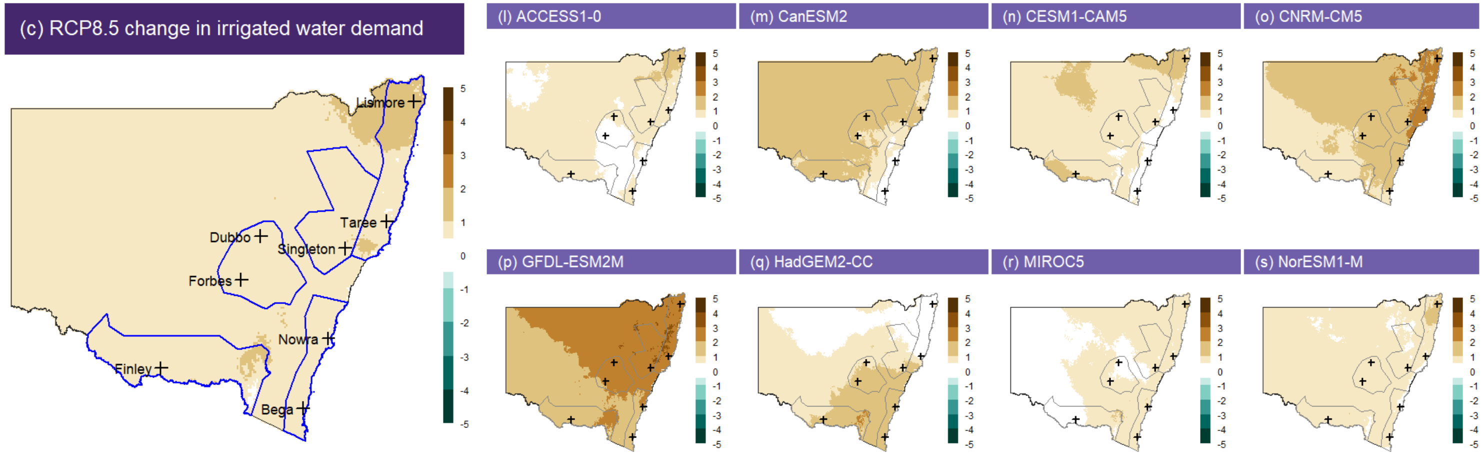


Figure 32: Irrigation water requirement GCMs panel for dairy pastures in NSW. (a) historical irrigation water requirements; (b) and (c) median projected future change in irrigation water requirements for the intermediate and high emissions scenario, respectively; (d) to (k) projected future change in irrigation water requirements for each GCM under the intermediate scenario; (l) to (s) projected future change in irrigation water requirements for each GCM under the high emissions scenario. Blue polygons and black crosses show key dairy production regions and sites.

Regional water strategies

The assessment of future water availability for irrigation was not within the scope of the Climate Vulnerability Assessments. However, insights into changing water availability can be gained from the work of the NSW Department of Climate Change, Energy, the Environment and Water (DCCEEW).

A new approach that aims to improve understanding of past and future climate risk is informing 12 regional water strategies across NSW. Undertaken by the NSW DCCEEW, these strategies form a roadmap for the next 20 years for a more water-secure future.

The regional water strategies look at how much water a region will need to meet future demand. Regional water strategies determine the actions we need to take to manage risks around water availability from our surface water and groundwater systems.

Each strategy is an evidence-based integrated package that balances diverse water objectives and aims to deliver the right amount of water at the right time to people and businesses across NSW.

The regional water strategies modelling approach helps us to understand water security for NSW.

The regional water strategies are underpinned by new climate data and modelling that improve our understanding of past climate conditions and plausible climate futures.

This improved climate data has informed our river system models, enabling a better understanding of the water security and reliability risks faced by water users and the environment in each region. Regional water strategies use these data to investigate the potential benefits and effects of regional water strategy options. Water NSW and other agencies will also use these data to assess the merits of new projects, plans and programs.

If you are interested in learning more about the regional water strategies modelling approach, please refer to the *Regional Water Strategies Guide*.

NSW's water supply is likely to be less secure

Modelling undertaken by the Regional Water Strategies[12] found that winter and spring rain is likely to decrease for southern inland NSW. There is a lower likelihood of significant changes in the average annual rainfall in the northern part of the state. All models in the ensemble predict increases in evaporation rates across the state, leading to drier conditions, and NSW's surface water supplies are likely to be less secure. More work is required to apply this new climate data to our understanding of groundwater systems and the security of groundwater supplies.

Find out more about projected changes for your region on DCCEEW's Regional Water Strategies website:

- Border Rivers
- Far North Coast
- Fish River–Wywandy*
- Greater Hunter
- Gwydir
- Lachlan
- Macquarie-Castlereagh
- Murrumbidgee
- Namoi
- North Coast
- NSW Murray
- South Coast
- Western

*under development at the time of writing (July 2026)

[12] Regional Water Strategies, 2020. Fact Sheet - New climate analysis informs New South Wales regional water strategies. Department of Planning, Industry and Environment.

Key regional findings and insights from the changing climate

The results of this study provide valuable insights into the historical and potential future climate suitability of dairy pastures, with implications for the dairy industry.

Purpose of this section

This section provides a regional assessment of how the six pasture species, kikuyu, ryegrass, white clover, lucerne, forage oats and chicory, may be impacted by future climatic conditions for each dairy region. The analysis focuses on the five key dairy-farming regions in NSW: North Coast, South Coast, Inland, Hunter and Riverina Murray.

How the analysis was conducted

To assess how suitable the future climate is for the different pasture species, three representative sites were selected for each dairy region. These sites were used to develop regional pasture climate suitability calendars (Appendix Figures A70 to A83), which show how the climate suitability of each species in each dairy region changes throughout the year.

These climate suitability calendars highlight both opportunities, such as increases in climate suitability that could lead to longer growing seasons, and vulnerabilities, like reduced climate suitability during hotter or drier conditions in summer, which impact pasture growth.

Understanding pasture importance

The types of pasture used on dairy farms can vary depending on the region. Different pasture species play more important roles in different areas, depending on local conditions and dairy systems. The table below shows which pasture types are most commonly used and more important in each dairy region.

Table 2: List of pasture species for each dairy-farming region, informed by the expert focus group, from most important to least important for the region.

Dairy region	Important pastures (most important first)
Inland	Lucerne, ryegrass, forage oats, white clover and kikuyu
North Coast	Kikuyu, ryegrass, white clover, lucerne and forage oats
South Coast	Ryegrass, lucerne, forage oats, white clover and kikuyu
Riverina Murray	Lucerne, ryegrass, forage oats, white clover and kikuyu
Hunter	Kikuyu, ryegrass, white clover, lucerne and forage oats

It is important to note that chicory has not been included in Table 2, as it was a later addition to the list of species studied in this project. Experts identified it as an alternative pasture species with potential to perform well under hotter climatic conditions. Although not part of the original species list, chicory has been assessed as an adaptation option for its suitability across all NSW dairy regions.

Insights for the Inland dairy region

The Inland dairy region contains around 20 dairy farms, with most stocking larger herds exceeding the state average of 338 cows. This area experiences a more variable climate than the coastal dairy regions, with potentially harsher climate extremes. Farming practices in the region range from pasture-based systems to a more intensive system that utilises total mixed ration (TMR). Due to the climatic conditions, many farms depend on irrigation or TMR systems, or both, to ensure that cows receive a balanced diet of forage and concentrate. As a result, the region is more reliant than the coastal and Hunter dairy regions on irrigation and supplementary feeding to maintain productivity.

Figure 33: The key dairy production regions in NSW, with the Inland dairy region highlighted in purple. Black dots show towns representative of dairy farming in the region.

Historical and future trends

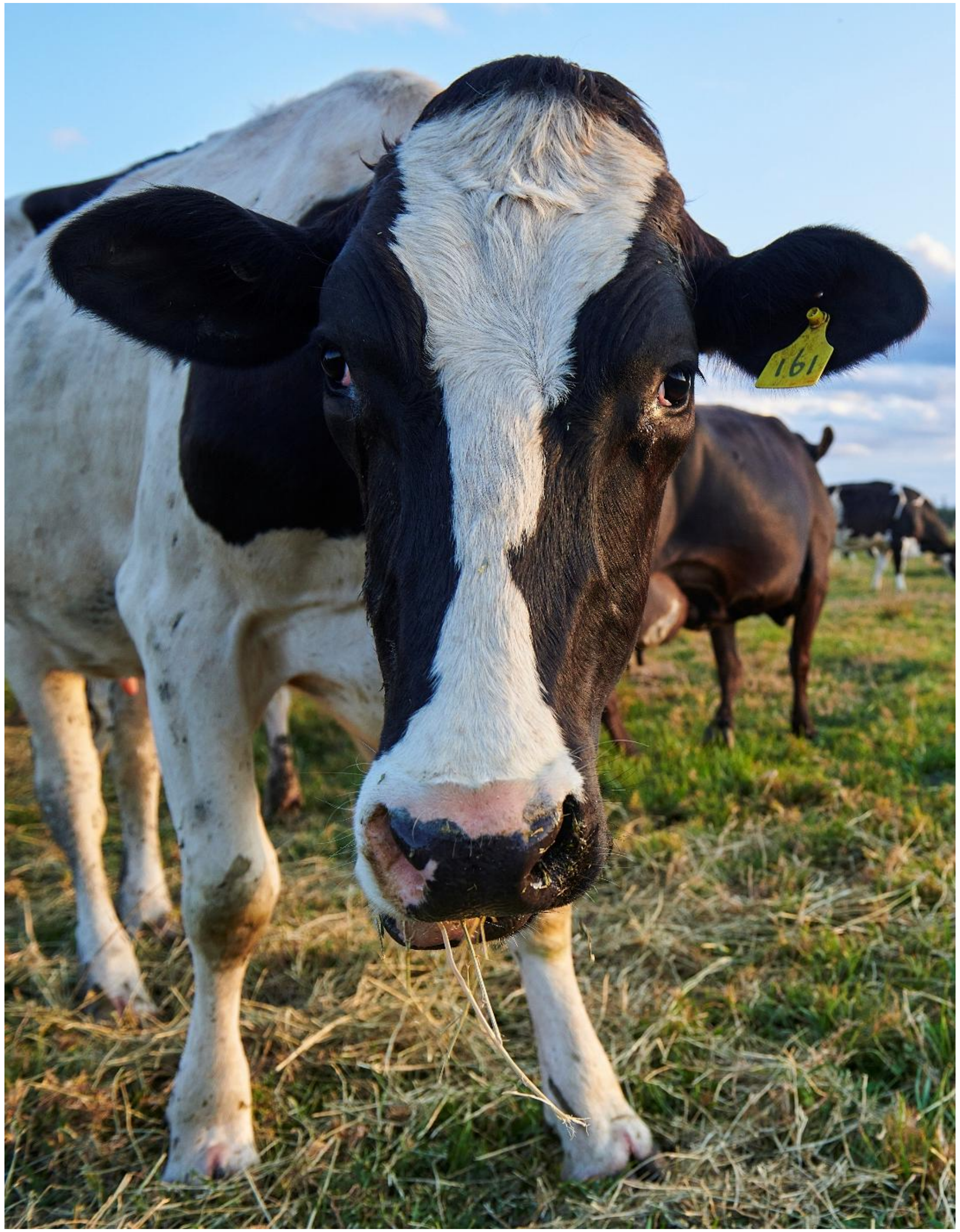
By 2050, the count of pasture species for which the climate suitability is high or very high at Cowra, Dubbo and Forbes is likely to decrease.

Historically, the Inland dairy region shows a seasonal pattern, with climate suitability being high or very high for 3 species in spring. In contrast, during summer and other warmer months there are no species in the high to very-high climate suitable band reflecting strong seasonal limits on rain-fed pastures in this region.

Under the intermediate and high emissions scenarios, this seasonal pattern shifts. The region is likely to experience longer periods with no species reaching the high or very high band and only 2 to 3 months occurring in spring and autumn, where climate suitability reaches this level for up to 2 species. Summer and warmer months continue to show no months in which there is high or very high climate suitability for any pasture species.

These reductions in highly suitable climatic conditions highlight the need for deliberate feed base planning to avoid feed and quality gaps in 2050. Potential strategies to ensure that feed availability and quality are maintained throughout the year include, but are not limited to, adjusting sowing timing, putting greater emphasis on conserving feed, and diversifying pasture swards.

Please refer to Appendix Figure A79, which shows the climate suitability calendars for pasture species in this dairy region.



Future climate vulnerabilities for the Inland dairy region

Climate suitability for all pasture species except for kikuyu is projected to undergo minimal to moderate decreases from late spring through to early autumn. These changes are attributed to higher temperatures and to shifts in rainfall patterns. For lucerne and forage oats, these decreases are likely to happen throughout these seasons, especially in the high emissions scenario. Climate suitability for white clover and ryegrass is expected to decrease during the spring and autumn months, while, in contrast, climate suitability for chicory is projected to decrease during summer across the Inland dairy region.

Future climate opportunities for the Inland dairy region

Due to a reduction in the number of cold days and changes in mean temperature and rainfall, there will likely be a minimal to moderate increase in climate suitability for the growth of lucerne in autumn and ryegrass during winter and autumn. Additionally, chicory may benefit from improved climatic conditions during winter at Cowra, while kikuyu may benefit from improved growth around Cowra during spring and Dubbo during the summer. These increases are more pronounced under the high emissions scenario, particularly for lucerne and ryegrass.

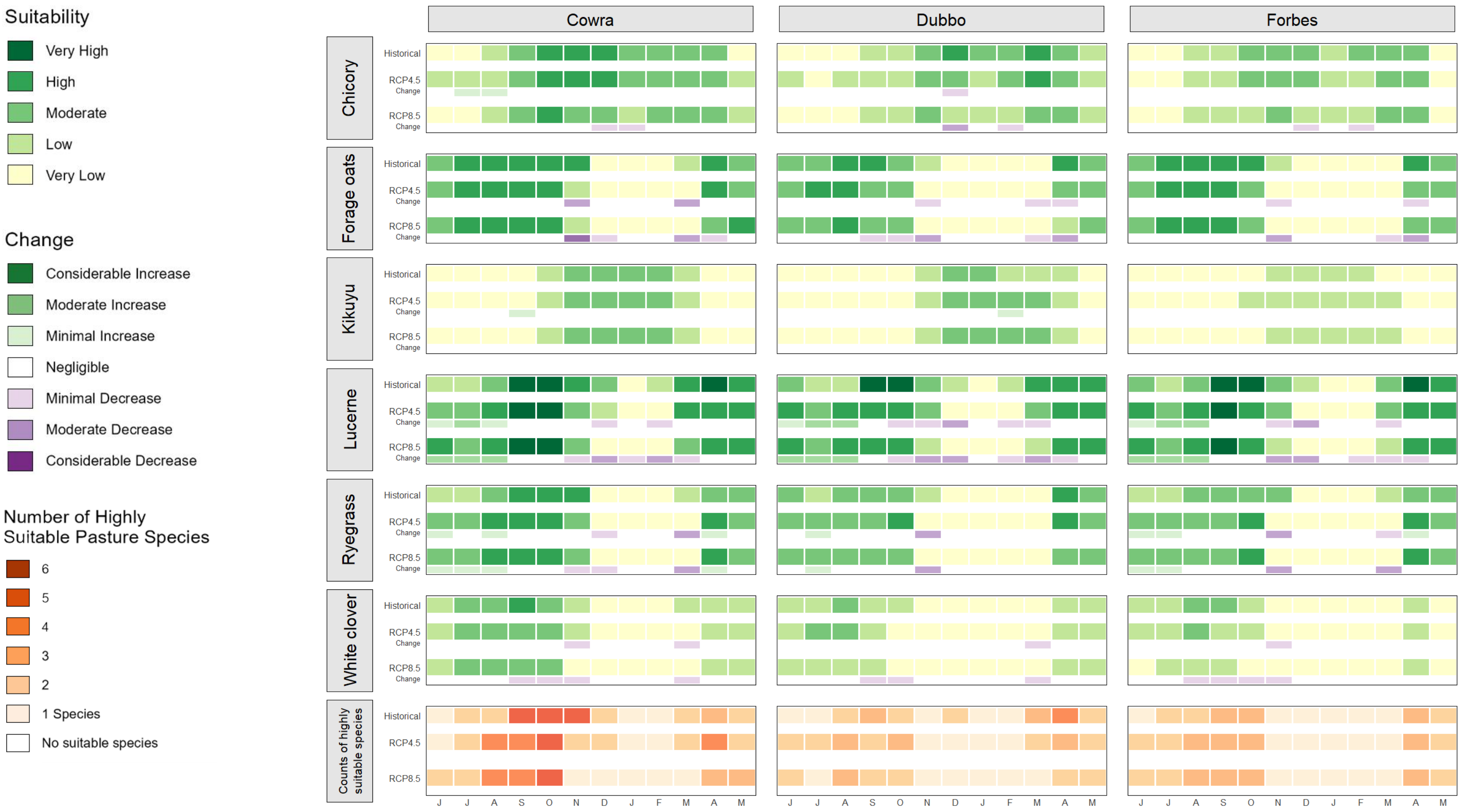


Figure 34: Climate suitability calendar for the Inland dairy region, displaying the monthly climate suitability value for historical climate and future climate scenarios (RCP4.5 and RCP8.5) for 6 pasture species at 3 sites. The climate suitability values shown are the median of a 10km radius surrounding each site of interest.

Insights for the North Coast dairy region

The North Coast dairy region is home to approximately 180 dairy farms, which typically have herds close to the state average of 338 cows or fewer. The region's subtropical climate supports year-round pasture growth, characterised by high rainfall, mild temperatures, and fertile soils. Dairy operations primarily rely on pasture-based systems supplemented with concentrate, silage and hay.

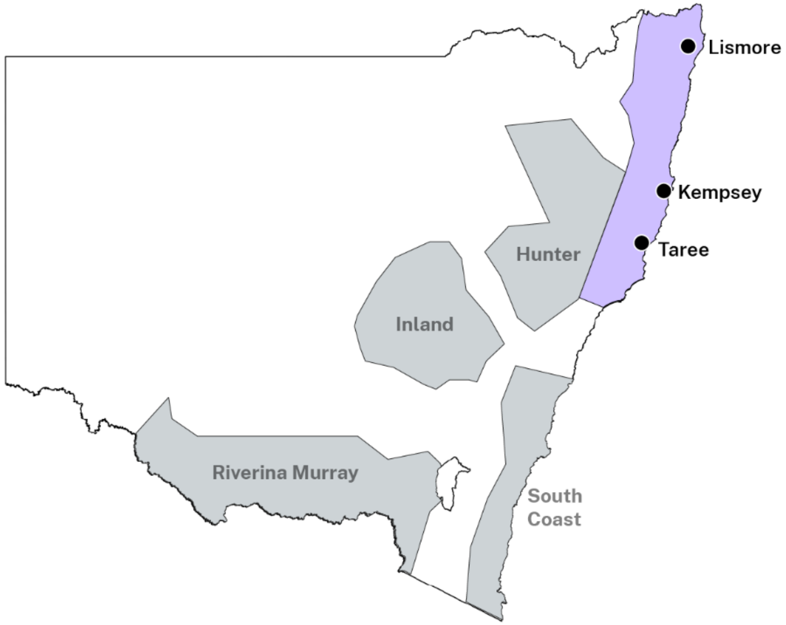


Figure 35: The key dairy production regions in NSW, with the North Coast dairy region highlighted in purple. Black dots show towns representative of dairy farming in the region.

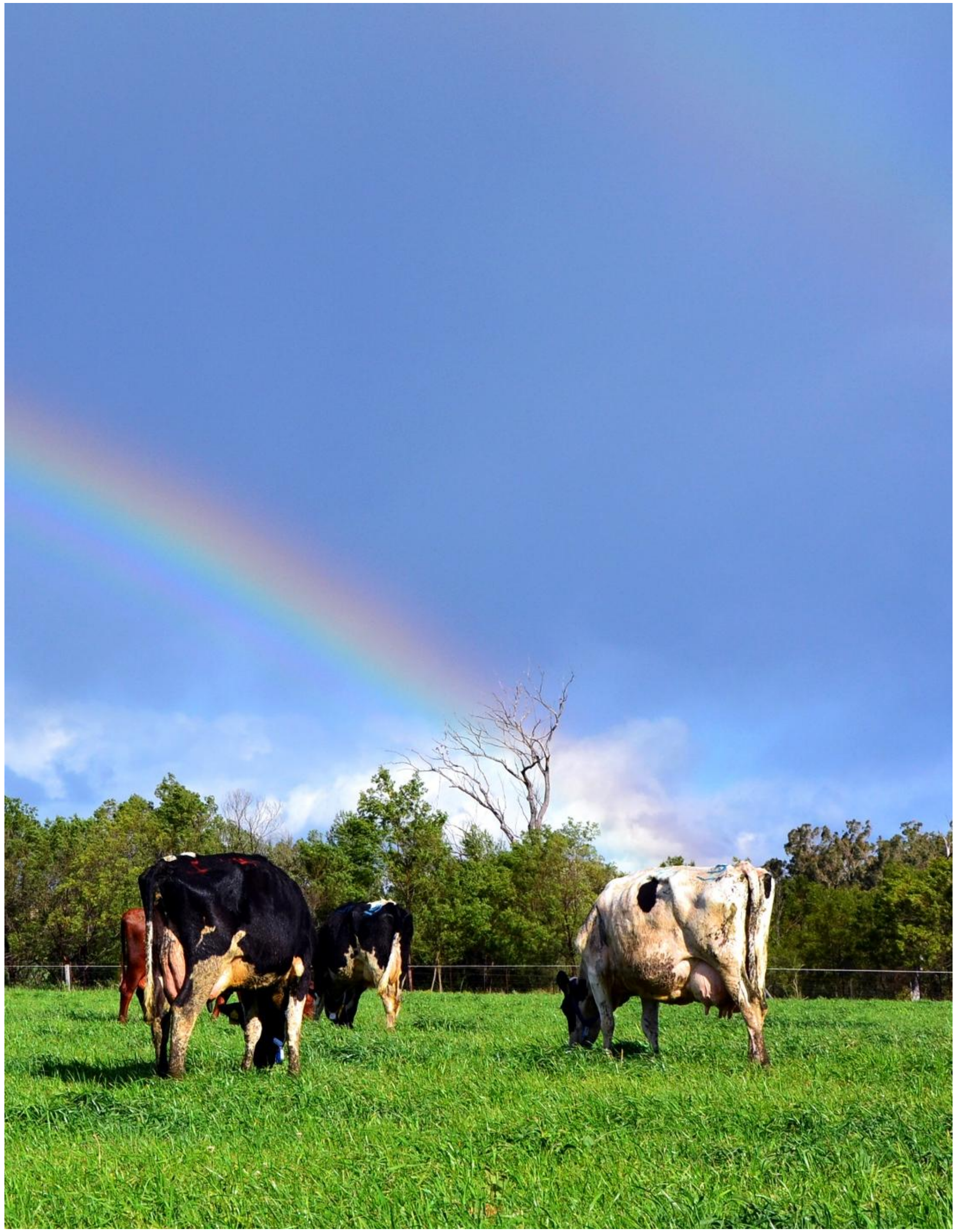
Historical and future trends

By 2050, the monthly count of pasture species with high or very high climate suitability at Kempsey, Lismore, and Taree is likely to decrease. Historically, the North Coast shows a seasonal pattern, with the highest number of highly suitable species in the cooler months (late autumn through winter and into early spring), and at some sites reaching up to six species (all those studied). In contrast, the hottest part of summer has fewer highly suitable species, reflecting seasonal limits on temperate pastures.

Under the intermediate and high emissions scenarios, this seasonal pattern shifts further. The region is likely to experience longer periods with two species reaching the high or very high band, with the changes occurring in spring and early autumn. Summer continues to show that few pasture species reach high or very high suitability at some sites.

These reductions in highly suitable climatic conditions highlight the need for deliberate feed base planning to avoid feed and quality gaps in 2050. Potential strategies to ensure that feed availability and quality are maintained throughout the year include, but are not limited to, adjusting sowing timing, putting greater emphasis on conserving feed, and diversifying pasture swards.

Please refer to Appendix Figure A80, which shows the climate suitability calendars for pasture species in this dairy region.



Future climate vulnerabilities for the North Coast dairy region

All pastures except kikuyu are projected to experience minimal to moderate decreases in climate suitability from spring to autumn due to higher temperatures, an increase in the number of hot days and changes in rainfall. For white clover and forage oats, these decreases are expected in most of these months under the high emissions scenario. In contrast, chicory, lucerne and ryegrass are only likely to see decreases in a few of these months. However, ryegrass around Kempsey and Lismore is expected to experience a considerable decrease in suitability in April under the high emissions scenario.

Future climate opportunities for the North Coast dairy region

Due to a reduction in the number of cold days and changes in mean temperature and rainfall, there is likely to be a minimal to moderate increase in climate suitability for kikuyu and chicory growth during some months of autumn and winter. These increases are more pronounced under the high emissions scenario. Forage oats may also benefit from increased climate suitability in August at Taree, and ryegrass in September at Kempsey.

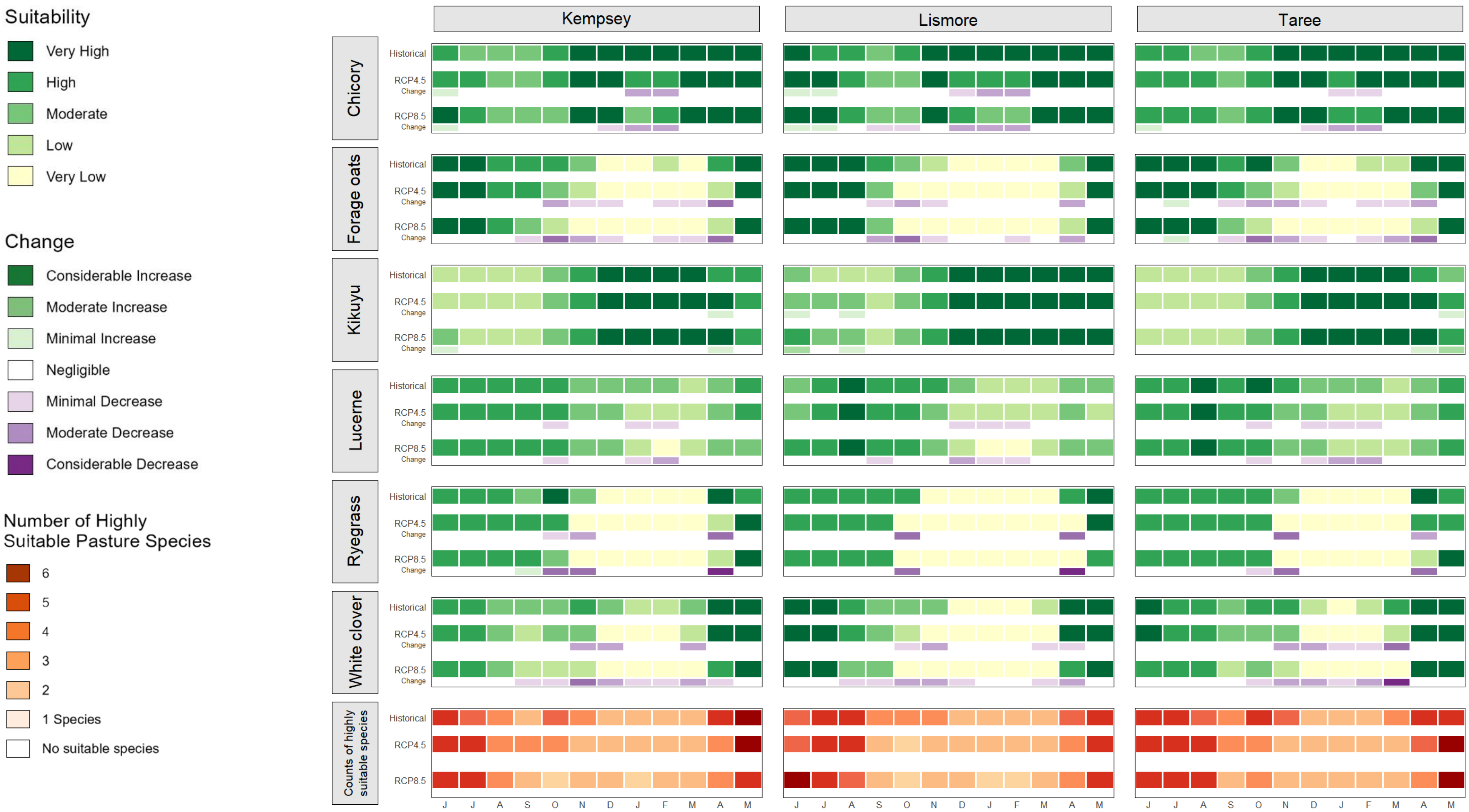


Figure 36: Climate suitability calendar for the North Coast dairy region, displaying the monthly climate suitability value for historical climate and future climate scenarios (RCP4.5 and RCP8.5) for 6 pasture species at 3 sites. The climate suitability values shown are the median of a 10km radius surrounding each site of interest.

Insights for the South Coast dairy region

The South Coast dairy region has approximately 130 dairy farms. Many of these businesses maintain herd sizes close to or below the state average of 338 cows. The temperate climate of the South Coast is ideal for dairy farming. This region predominantly uses pasture-based systems, with some supplement feeding of silage and hay during drier periods. Irrigation is also used in low rainfall areas such as the far south coast.

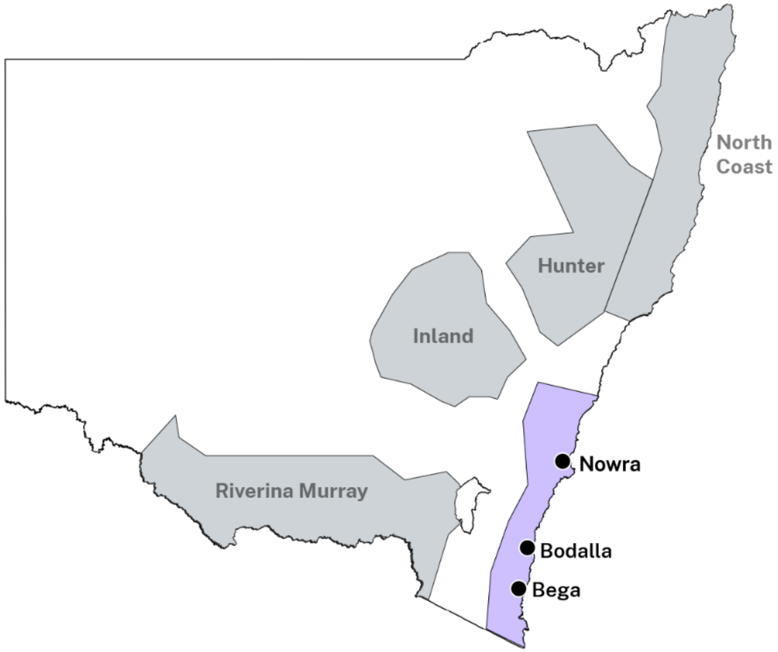


Figure 37: The key dairy production regions in NSW, with the South Coast dairy region highlighted in purple. Black dots show towns representative of dairy farming in the region.

Historical and future trends

By 2050, the monthly count of pasture species with high or very high climate suitability at Bega, Bodalla, and Nowra is likely to decrease. Historically, the South Coast shows a seasonal pattern, with the highest number of highly or very highly suitable species in autumn and spring, up to six pastures (all those studied). In contrast, summer and winter have fewer species with high or very high climate suitability.

Under the intermediate and high emissions scenarios, this seasonal pattern shifts further. The region is likely to experience longer periods during the warmer months when fewer species reach the high or very high band. In contrast, winter and autumn will experience an increase in the number of pasture species with high or very high climate suitability, which means these species could be utilised in the feed base by 2050. Spring is likely to retain historical levels of suitable species.

Strategies could include, but are not limited to, adjusting sowing timing, placing greater emphasis on conserving feed, and diversifying pasture swards by using pasture species that are expected to become more suitable in the future, to ensure feed availability and quality are maintained throughout the year.

Please refer to Appendix Figure A81, which shows the climate suitability calendars for pasture species in this dairy region.

Future climate vulnerabilities for the South Coast dairy region

All pastures, except for kikuyu and chicory, are projected to experience minimal to moderate decreases in climate suitability during the summer months. These decreases are prominent for forage oats, ryegrass, and white clover under the high emissions scenario, with changes extending from the middle of spring until the middle of autumn, especially in the northern part of the region around Nowra. In contrast, changes for lucerne are expected to be limited to some spring or autumn months. These declines in climate suitability are expected due to higher temperatures, an increase in the number of hot days and changes in rainfall patterns.

Future climate opportunities for the South Coast dairy region

Due to reductions in the number of cold days and changes in mean temperature and rainfall, there is likely to be a minimal to moderate increase in climate suitability for chicory, forage oats, kikuyu, lucerne and ryegrass growth during some winter months. These increases are more prominent under high emissions scenarios. Kikuyu may also benefit from increased climate suitability during some autumn and spring months in the South Coast dairy region, potentially extending the growth season for this pasture.

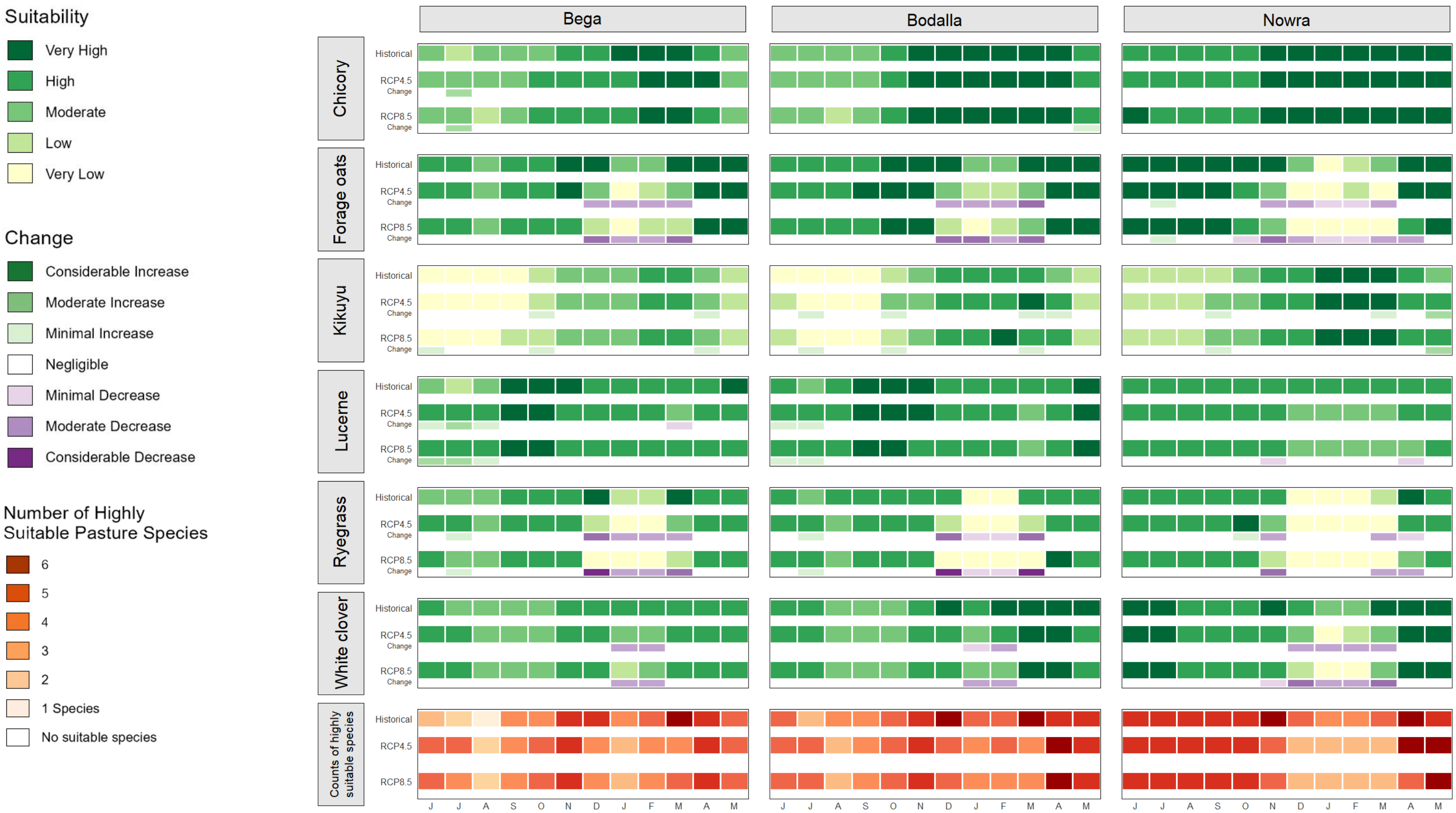


Figure 38: Climate suitability calendar for the South Coast dairy region, displaying the monthly climate suitability value for historical climate and future climate scenarios (RCP4.5 and RCP8.5) for 6 pasture species at 3 sites. The climate suitability values shown are the median of a 10km radius surrounding each site of interest.

Insights for the Riverina Murray dairy region

The Riverina Murray dairy region has approximately 61 dairy farms, with most stocking larger herds exceeding the state average of 338 cows. This area experiences a more variable climate than the coastal dairy regions, with potentially harsher climate extremes. Farming practices in the region range from pasture-based systems to a more intensive total mixed ration (TMR) system. Due to the climate conditions, many farms depend on irrigation or TMR systems, or both, to ensure that cows receive a balanced diet of forage and concentrate. As a result, the region is more reliant than the coastal and Hunter dairy regions on irrigation and supplementary feeding to maintain productivity.

Figure 39: The key dairy production regions in NSW, with the Riverina Murray dairy region highlighted in purple. Black dots show towns representative of dairy farming in the region.

Historical and future trends

Historically, the number of highly suitable species in the Riverina Murray dairy region follows a seasonal pattern, being highest in spring and, to some extent, autumn, reaching up to two pasture species. In contrast, during late spring, summer, early autumn and winter, there are no species in the high to very-high climate suitable band, reflecting strong seasonal limits on rain-fed pastures in this region.

By 2050, the monthly count of pasture species with high or very high climate suitability around Deniliquin, Finley and Wagga Wagga is likely to decrease.

Under the intermediate and high emissions scenarios, the seasonal pattern also shifts. Wagga Wagga is likely to experience longer periods with no high or very high climate suitability for any species in warm months, whereas at Deniliquin and Finley, the climate is likely to maintain historical levels of suitability for pasture species. Wagga Wagga could see the climate suitability becoming ‘high’ or ‘very high’ for one extra species in some months during winter, spring and summer, providing an additional species which could be included in the feed base by 2050.

These reductions in highly suitable climatic conditions highlight the need for deliberate feed base planning to avoid feed and quality gaps in 2050. Potential strategies to ensure that feed availability and quality are maintained throughout the year include, but are not limited to, adjusting sowing timing, putting greater emphasis on conserving feed, and diversifying pasture swards.

Please refer to Appendix Figure 82, which shows the climate suitability calendars for pasture species in this dairy region.

Future climate vulnerabilities for the Riverina Murray dairy region

Climate suitability for lucerne, ryegrass and forage oats are projected to experience minimal to moderate decreases during some months from late spring to early autumn. These changes are attributed to higher temperatures, an increased number of hot days, and changes in rainfall. For lucerne, ryegrass and forage oats, these decreases are likely to occur in most of these months, particularly under the high emissions scenario. In contrast, climate suitability for white clover is expected to decrease during spring at Finley and Wagga Wagga, and Wagga Wagga is also likely to experience a decrease in climate suitability for chicory during summer.

Future climate opportunities for the Riverina Murray dairy region

Due to reductions in the number of cold days and changes in mean temperature and rainfall, there is likely to be a minimal to moderate increase in climate suitability for lucerne and ryegrass growth during winter. These increases are more prominent under the high emissions scenario, particularly for those two species. Chicory could also benefit from improved climatic conditions in July at Wagga Wagga.

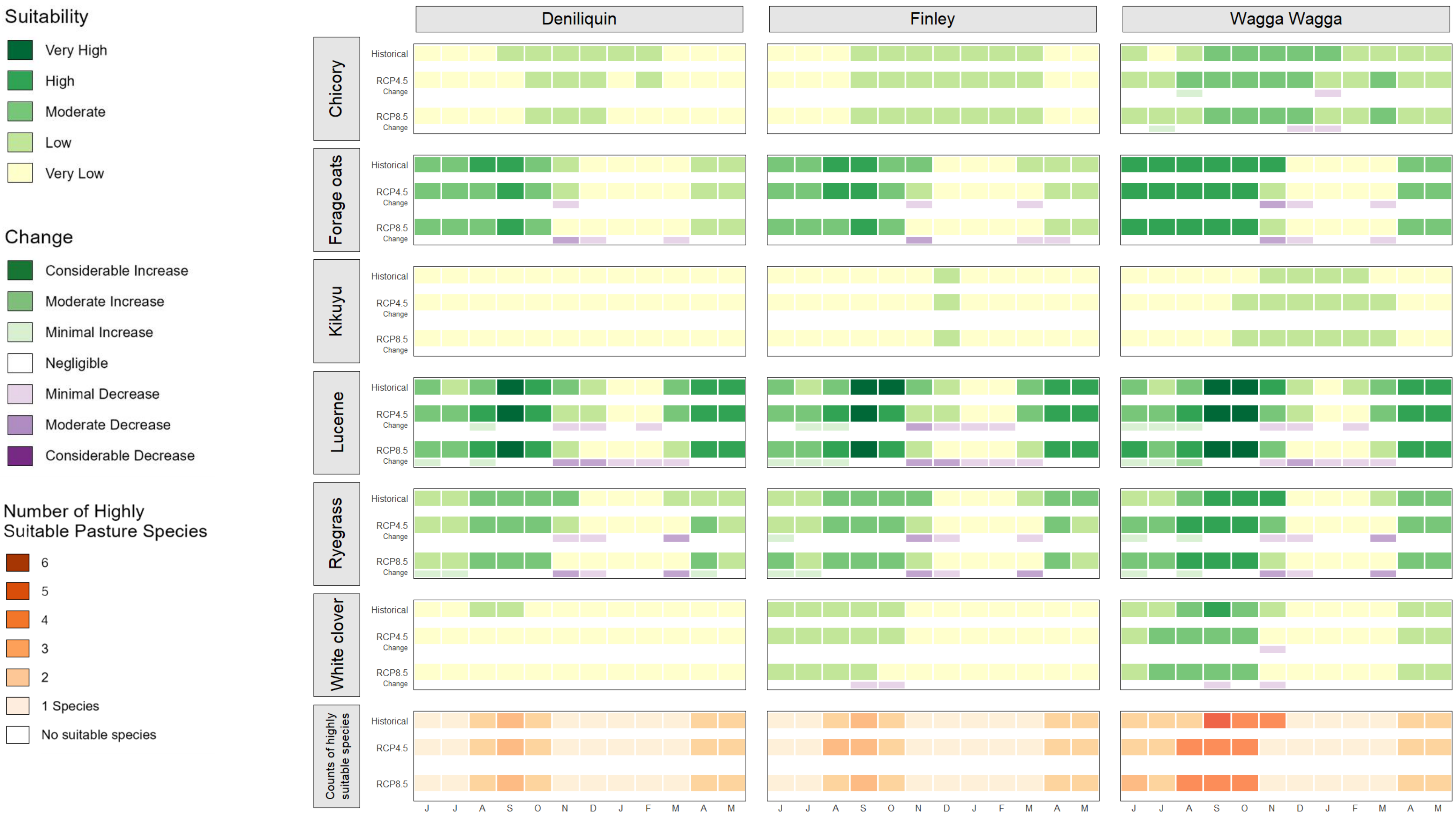


Figure 40: Climate suitability calendar for the Riverina-Murray dairy region, displaying the monthly climate suitability value for historical climate and future climate scenarios (RCP4.5 and RCP8.5) for 6 pasture species at 3 sites. The climate suitability values shown are the median of a 10km radius surrounding each site of interest.

Insights for the Hunter dairy region

The Hunter dairy region, containing approximately 40 dairy farms, has a temperate climate, with reliable water sources and fertile soils supporting productive pastures and fodder crops. The region primarily operates pasture-based systems, and some irrigation is used to maintain pasture quality. Supplementary feeding with concentrates, hay and silage is common to ensure consistent milk production and manage drier conditions.

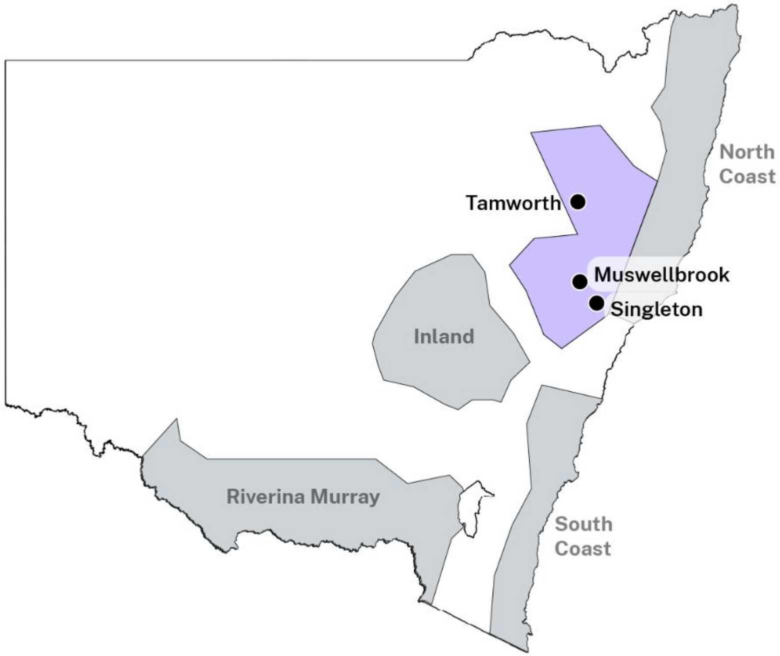


Figure 41: The key dairy production regions in NSW, with the Hunter dairy region highlighted in purple. Black dots show towns representative of dairy farming in the region.

Historical and future trends

Historically, the Hunter shows a seasonal pattern, with climate suitability being high or very high for the greatest number of species in autumn, up to six (all those studied). In contrast, winter, spring and summer contain months with high or very high climate suitability for only a few species.

By 2050, the number of months with high or very high climate suitability for the pasture species around Muswellbrook, Singleton and Tamworth is expected to decrease.

In the intermediate and high emissions scenarios, the seasonal pattern also shifts. The region is likely to experience longer periods during winter, spring and summer with high or very-high climate suitability for very few pasture species; only during autumn is the climate expected to be highly suitable for up to four of the pasture species. By 2050, this trend continues, with Autumn remaining the month with high or very high climate suitability for the most pasture species.

These reductions in highly suitable climatic conditions highlight the need for deliberate feed base planning to avoid feed and quality gaps in 2050. Potential strategies to ensure that feed availability and quality are maintained throughout the year include, but are not limited to, adjusting sowing timing, putting greater emphasis on conserving feed, and diversifying pasture swards.

Please refer to Appendix Figure 83, which shows the climate suitability calendars for pasture species in this dairy region.

Future climate vulnerabilities for the Hunter dairy region

Climate suitability for all pasture species, except kikuyu, is expected to experience minimal to moderate decreases between late spring and early autumn. These changes are attributed to higher temperatures, an increase in the number of hot days, and changes in rainfall patterns. For lucerne and forage oats, climate suitability is likely to decline in most of these months, particularly under the high emissions scenario. In contrast, climate suitability for ryegrass is expected to decrease just before and just after summer. Climate suitability for white clover is projected to decline during winter, spring and early autumn at all sites, while decreased climate suitability for chicory during the summer months could impact growth of that pasture across this region. These declines in climate suitability are more pronounced in the high emissions scenario.

Future climate opportunities in the Hunter dairy region

Due to a reduction in the number of cold days and changes in mean temperature and rainfall, there will likely be a minimal to moderate increase in climate suitability for the vegetative growth life stage of lucerne in winter and for ryegrass during winter at some sites within the Hunter dairy region. These increases are likely to occur under both emissions scenarios. Kikuyu is likely to maintain climate suitability similar to what has been historically experienced.

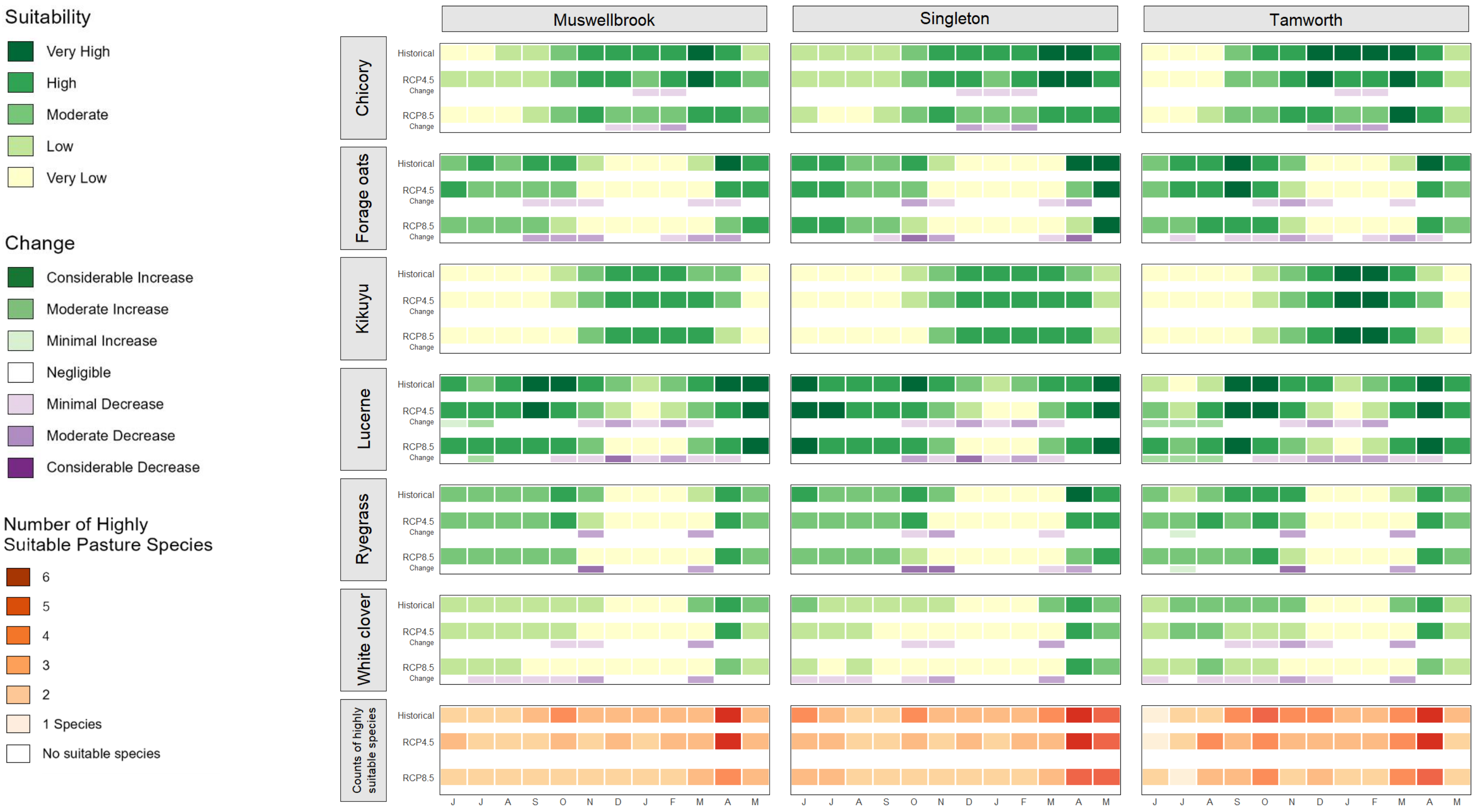


Figure 42: Climate suitability calendar for the Hunter dairy region, displaying the monthly climate suitability value for historical climate and future climate scenarios (RCP4.5 and RCP8.5) for 6 pasture species at 3 sites. The climate suitability values shown are the median of a 10km radius surrounding each site of interest.

Adapting to the changing climate

Assessing future climate suitability is a prerequisite to making effective decisions around planning for primary industries and developing effective adaptation strategies for addressing future climate change.

The dairy industry could investigate strategies such as:

Adapting to changing growth patterns

As climate change alters seasonal conditions and the timing of pasture growth by 2050, strategic adaptations will be necessary. Adjusting sowing times and selecting pasture species with growth patterns that better align with future conditions, such as tropical pastures, summer-active perennials, or heat-tolerant annuals, will help to optimise establishment and productivity. Evaluating alternative species, improved varieties and adopting mixed-sward combinations or cropping systems could also assist in maintaining feed quality and filling gaps in pasture systems.

Shifts in pasture growth patterns may necessitate the realignment of calving and lactation periods with peak pasture availability. Such changes have the potential to improve feed efficiency, reduce reliance on purchased supplements, and better match feed demand with on-farm supply.

Additionally, increasing the use of conserved fodder by aligning peak growth periods with hay and silage production should help buffer feed supply during months with reduced pasture growth. This approach may require investment in on-farm infrastructure and careful planning to optimise feed storage and usage.

Adapting to changing irrigation water requirements

The dairy industry in many areas may need to improve water storage and water use by adopting more efficient irrigation practices or new technologies to maintain pasture growth. Enhancing on-farm irrigation efficiency, such as using soil moisture monitoring, irrigation scheduling tools and timely grazing, could help manage hotter conditions. These changes may help to build resilience against water availability challenges.

Adapting to decreases in climate suitability during establishment

Declining climate suitability during pasture establishment periods will require proactive adaptation across timing, genetics, and soil preparation.

Using seasonal forecasts to identify suitable establishment periods should enable better timing of sowing to coincide with favourable conditions for germination and early pasture growth, reducing the risk of establishment failure.

Complementing this timing approach, selecting pasture varieties with strong early vigour or tolerance to heat and moisture stress should further increase the likelihood of success under variable conditions. Improved soil preparation can also play a critical role in helping to retain moisture, supporting pasture establishment during drier or hotter periods.

Understanding how heat stress, moisture variability and emerging pests, such as fall armyworm, influence establishment success remains a key research priority for the dairy industry.

Dairy pastures: where to from here?

Future priorities

We have assessed the future climate suitability for pastures as a prerequisite for effective planning decisions and the development of adaptation strategies to address future climate change impacts.

The results presented in this report have identified changes in climate suitability for pastures that are likely to impact the industry in NSW. More research and development are needed to best advise the industry on managing pastures, looking forward to 2050.

The next stage of work is to conduct a detailed assessment of adaptation strategies to provide industries with insights into the value of adaptation for reducing the impacts of climate change. Effective management approaches must be carefully planned, evaluated, and deployed to minimise disruptions and costs. The following options may merit initial consideration.

- Assess whether different pasture types or cropping systems could grow more effectively during months currently showing reduced climate suitability, helping to maintain feed availability year-round.
- The Climate Vulnerability Assessment did not consider soil type or conditions, which limits the accuracy of the climate impact assessment. Soils play a critical role in pasture performance, affecting nutrient availability and root development. Without considering soil, the climate suitability results may overestimate or underestimate the viability of certain pasture species in specific regions. Future assessments should integrate climate suitability with soil interactions, irrigation availability and the influence of rainfall and extreme-event variability to more accurately assess viable pasture options.
- Results presented in this report suggest that certain pasture species may struggle to persist under increased heat and variable rainfall. Without a deeper understanding of these persistence challenges, particularly for species like forage oats and lucerne, adaptation strategies may overestimate the resilience of key pastures. Further investigation is needed to assess long-term viability under projected climatic conditions.
- Long-term adaptation planning will benefit from undertaking local varietal trials and multispecies pasture experiments to quantify persistence, feed quality, and guide adaptation in the dairy industry in NSW.
- The Climate Vulnerability Assessment did not assess pasture quality or grazing management. However, climate change may reduce the nutritional value of pastures, particularly during heat stress periods, posing risks to the balanced diet required by high-producing dairy cows. Further work is needed to evaluate whether future pasture systems can meet energy, protein and fibre requirements year-round. This requires region-specific modelling using tools such as APSIM or DairyMod to identify optimal timing and system adjustments.
- Adding cropping systems to pasture systems to fill gaps, by introducing forage-suitable crops such as maize or sorghum.

Addressing the gaps, barriers and challenges

The information generated by this project has helped to identify future climate vulnerabilities for the pasture species presented here. However, knowledge gaps were identified during the development of the MCA model.

A lack of knowledge about a particular organism and its optimal climatic conditions leads to a risk of important climate factors being left out of the model. Additional research may lead to results which improve the pasture models used here. The following areas are deemed key knowledge gaps in need of further research:

- **Unclear growth triggers for key species**: a lack of well-defined GDD thresholds for pasture species made it difficult to reliably model potential changes in growth windows and seasonal productivity under climate change.
- **Limited understanding of seed head development**: a lack of data on how day length and temperature influence seed head development made it difficult to assess their impact on pasture growth, quality and persistence under future climate scenarios.
- **Oversimplified rainfall assumptions**: published research in the literature often relies on static, annual rainfall needs, which do not accurately reflect how changes in rainfall timing and distribution will affect pasture growth and system resilience.

This report highlights these gaps to assist in directing future research and project development. Consideration should be given to modelling other significant or emerging dairy breeds, pasture systems, and intensive dairy industries like dairy, poultry, and pigs, as well as expanding the range of the current modelling Australia-wide to inform future industry planning.

Conclusion

This work provides important baseline information to support state, regional and strategic industry-level planning for climate change, highlighting where adaptation and investment should be prioritised to sustain and enhance dairy industries and limit climate change's impacts on pastures.

The results presented in this report provide a comprehensive assessment of how climate suitability for dairy pastures is likely to shift under climate change in NSW. This research also sets out the challenges ahead, which now require investment in adaptation strategies and education to underpin the dairy industry's future growth and sustainability.

DPIRD will use these findings in partnership with industry to prioritise future efforts, strategic partnerships, and networks across the state to support effective policies and programs that keep primary industries resilient and productive in a changing climate.

For more information

For detailed information on the methodology and data used in this project please see the Climate Vulnerability Assessment Methodology Report.

Results from other commodities and biosecurity risk assessments can be found in the Climate Vulnerability Assessment Summary Report or on the website.

An accompanying report on NSW Drought in a Changing Climate provides a comprehensive understanding of how drought frequency and duration will change as a result of climate change and it is recommended to read this report alongside the results presented for Pastures.

Contact us

For further information, please get in touch with vulnerability.assessment@dpird.nsw.gov.au

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