Department of Primary Industries
and Regional Development

Verticillium

(*Verticillium dahliae*)

Results Report

Climate Vulnerability Assessment

NSW GOVERNMENT

Authors

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Acknowledgement of Country

The 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

Primary industries in New South Wales operate a wide variety of production systems within diverse landscapes, while facing the challenges of a changing and highly variable climate. The Primary Industries Climate Change Research Strategy invested $29.2 million in projects to help the state's primary industries adapt to climate change. As part of this work, the Climate Vulnerability Assessment Project undertook impact assessments for primary industries in the broadacre cropping, marine fisheries, forestry, extensive livestock, and horticulture and viticulture sectors, and key related biosecurity risks, to improve our understanding of the impacts of climate change.

The Climate Vulnerability Assessment has delivered consistent and comparable understandings of potential climate change impacts across the state, providing a deep insight into sectoral impacts. This strategic information is invaluable for policymakers and industry bodies, providing insights into 28 commodities and 14 biosecurity risks considered valuable or important to NSW.

This comprehensive assessment allows primary industries to understand the risks ahead, to prepare for and adapt to identified climate vulnerabilities, and to take advantage of future opportunities to expand in NSW.

Purpose of this report

This report contains the results of the *Verticillium dahliae* model from the Climate Vulnerability Assessment. The report introduces *Verticillium dahliae* (hereafter simply referred to as *Verticillium*) in NSW and provides an overview of the model and its key features, assumptions, and exclusions. The main results and findings provide insights into future increases and decreases in climate suitability for Verticillium.

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.

Verticillium significantly impacts cotton production. The suitability of land for cotton production is determined by climate, topography and water availability. Due to the variety of climate needs of the cotton industry, the majority of this production is found west of the Great Dividing Range.

A 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 NSW $23.1 billion sector supports economic growth and development, contributes to food security at the state and national levels, and plays a vital role in biosecurity management. Biosecurity risks threaten primary industries. Climate change is likely to make their impact worse in NSW by altering their range, distribution, and ability to spread. Industries with permanent plantings or geographic constraints are particularly vulnerable.

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.

Biosecurity risks have been well-researched in Australia. It is, nonetheless, 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[1]. A literature review of research on climate change impacts for primary industries revealed that biosecurity research was dominated by weed and insect threats (41 of 55 papers) whilst overlooking some important biosecurity risks to Australia altogether[1]. The studies we reviewed have revealed significant collective impacts of climate change. As temperatures increase, we can expect species to experience southward range shifts[2,3] and to see those currently restricted by cool temperatures in lower altitudes moving into higher altitude areas[3,4.]. Climate change is likely to expand the range of some biosecurity risks while further constraining others. The literature on this topic has largely overlooked how these changes may impact primary industries, which will be affected by evolving biosecurity risks under climate change[5].

Assessing the impacts of climate change

The Climate Vulnerability Assessment examined the potential impacts of climate change on a wide range of economically important primary industry commodities and biosecurity risks. By applying a standardised approach, the assessments enable an identification of 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] 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.
[2] McFadyen, R. (2007). Invasive plants and climate change. Briefing notes. Cooperative Research Centre for Australian Weed management, Adelaide. 2 pp.
[3] Bellard, C., Jeschke, J.M., Leroy, B., Mace, G.M. (2017). Insights from modelling studies on how climate change affects invasive alien species geography. Ecology and Evolution 8:5688-5700.
[4] Taylor, S., Kumar, L., Reid, N. and Kriticos, D.J. (2012). Climate change and the potential distribution of an invasive shrub, Lantana camara L. PLoS (Public Library of Science) One 7, e35565.
[5] De La Rocque, S., Rioux, J.A. & Slingenbergh, J. 2008. Climate change: effects on animal disease systems and implications for surveillance and control. Rev. sci. tech. Off.int. Epiz. (2) 339-354.

Verticillium in NSW

Verticillium dahliae is a fungal pathogen which lives in the soil and can infect over host 400 plant species in Australia, including many valuable agricultural crops such as cotton. The resulting disease, Verticillium wilt, reduces yield in infected plants, costing Australian primary industries millions of dollars in lost production each year.

Cotton is grown in the Gwydir Valley (Mungindi and Moree), the Namoi Valley (Narrabri, Wee Waa, Bourke, Boggabri and Gunnedah), the Macquarie Valley (Warren, Trangie and Narromine), the Lachlan Valley (Condobolin, Forbes and Hillston) and the Murrumbidgee Valley (Griffith, Hay, Balranald, Narrandera and Jerilderie). In NSW, the *Verticillium* pathogen is present in cotton-producing regions, stretching from the Moree region to Griffith (Figure 1).

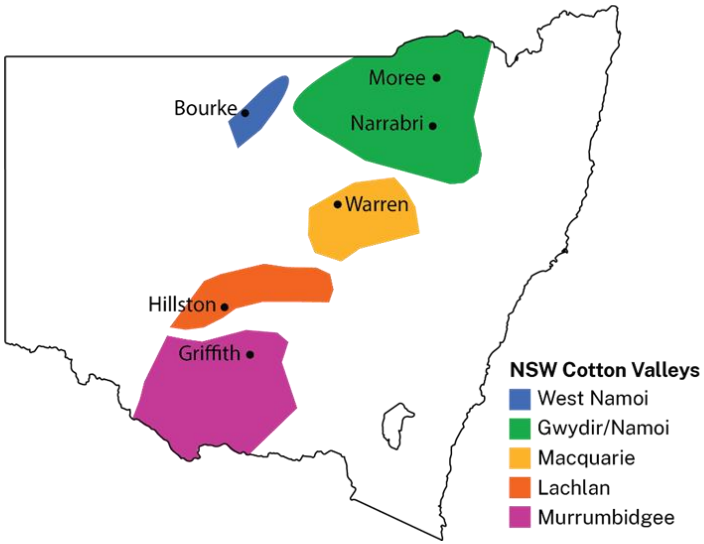


Figure 1: The cotton valleys in NSW, and some key towns within each region, marked by black dots.

Verticillium affects many plants, but this analysis focuses on its impacts on cotton in NSW. This fungal pathogen has two pathotypes (commonly referred to as strains): defoliating and non-defoliating.

Currently in NSW, the non-defoliating pathotype and the defoliating pathotype occur in all NSW cotton growing regions. Both pathotypes cause wilting and yellowing of cotton plants, with the defoliating pathotype generally causing more severe symptoms, leading to complete loss of leaves known as defoliation and plant death.

These two pathotypes respond to different temperature thresholds, which means the future distribution of each is likely to change in varying ways due to climate change.

The pathogen can survive for more than 10 years in a dormant life stage in the soil, from where it can emerge to infect host plants via the roots (Figure 2).

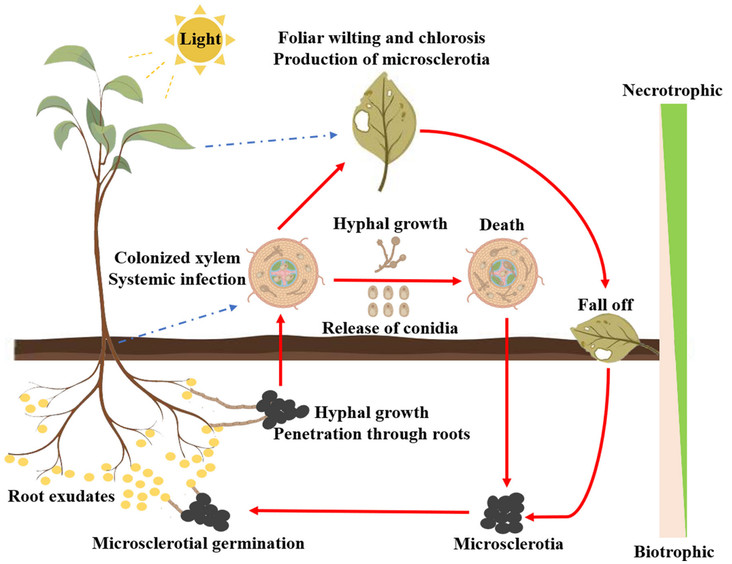


Figure 2: infection lifecycle of Verticillium lifecycle in a host plant[6]

[6] Zhu Y, Zhao M, Li T, Wang L, Liao C, Liu D, Zhang H, Zhao Y, Liu L, Ge X and Li B (2023) Interactions between *Verticillium dahliae* and cotton: pathogenic mechanism and cotton resistance mechanism to Verticillium wilt. *Front. Plant Sci*

Climate Vulnerability Assessment framework

The Climate Vulnerability Assessment was designed 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 comparable way.

Figure 3: Outline of expert engagement for framework developed by the Climate Vulnerability Assessment. Internal and external experts were involved throughout the process, helping to develop and refine the models of primary industry commodities and biosecurity risks in their area of expertise.

The assessment framework, outlined in Figure 3, provides a rigorous, flexible and transparent process for assessing vulnerability to climate change. The first step is a literature review, used to inform an initial 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.

Over 100 Department of Primary Industries and Regional Development staff contributed to this process, and almost 200 additional experts participated in focus groups to support the review and refinement of the models. External experts were drawn from industry bodies, producers, academia and elsewhere.

MCA modelling approach

The steps in the framework developed for the Climate Vulnerability Assessment were 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.

An MCA model with defined assumptions and exclusions was developed for each biosecurity risk, and these models were developed using a combination of published data, empirical evidence and expert judgment. In the hierarchical structure of an MCA model, the biosecurity risk sits at the top level, with the key lifecycle stages forming the level below. The next level of the model then associates one or more climate variables with each of these life stages.

Each life stage was weighted relative to the others, to reflect the importance of its contribution to the overall success in the survival of the biosecurity risk. The weightings were derived using an analytical hierarchy process[7], reflecting the consensus reached by the focus group experts.

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

The MCA model is not designed as a distribution 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[8].

The MCA model provides an assessment of climate suitability (ranging from unsuitable to highly suitable) for each individual climate variable, for each stage of the lifecycle, and for the overall model. Climate suitability is modelled for both historical (recent past) conditions and for projected (near future) climate to understand how the climate suitability for the cotton 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 *Verticillium* and key results showing important changes to future climate suitability for the pathogen, 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 scope and exclusions are briefly summarised to the right, and *Verticillium* model-specific assumptions are summarised on the next page.

Project limitations

The scope was limited to the assessment of vulnerability to future climate change. The assessment captures the response of *Verticillium* 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:

- topography
- other non-climatic biophysical parameters
- socio-economic factors
- 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.

[8] 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 *Verticillium* model

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 this model were mean temperature (Tmean, °C) and rainfall (Rain, mm).

Categorising climate variables

The hierarchical structure of the MCA model (Figure 4) categorises climate variables to assess their impact on cotton. Each category (for example, a temperature between 15 and 20°C) is assigned a rating, R, between 0 and 1 that indicates how well it suits *Verticillium*, from unfavourable (R=0) to optimal (R=1).

Modules used in the *Verticillium* MCA model

The *Verticillium* MCA model uses the following standardised modules to produce ratings from the climate variables:

- **Proportional module**: examines the duration (in days) spent in each climate category during a given month.
- **Matrix module**: Matrices capture the interaction between two climate variables. These were monthly mean temperature and cumulative rainfall. This module was used for stages that are particularly sensitive to the interplay between two climate variables. The matrix categories define different combinations of climate conditions, for example, temperature between 21 and 26°C with cumulative rainfall of between <31mm. 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 *Verticillium*.

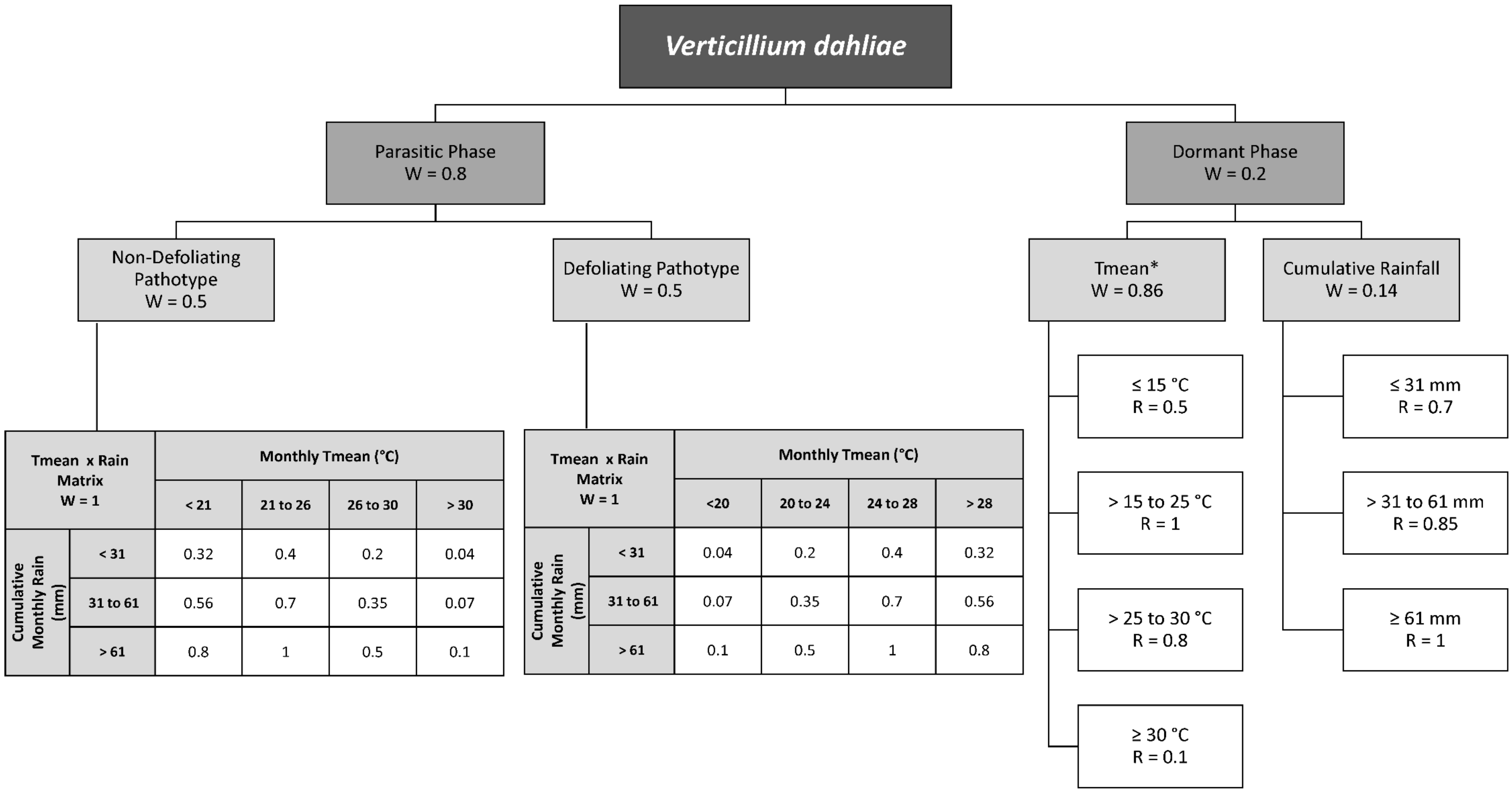
Verticillium model assumptions

In addition to the global assumptions and exclusions, the *Verticillium* model also contains the following:

- A susceptible host is present and viable.
- The host plant is not irrigated.
- No management undertaken to control *Verticillium*.

Final *Verticillium* model

The *Verticillium* model (Figure 4) has been divided into key life stages and has been run monthly, as the pathogen's lifecycle can be a few days to weeks, and so multiple cycles can occur within a single month under ideal conditions. Using model monthly outputs allows for an assessment of the influence of climate during any given month and over the year, and this can be used to explore potential timing changes in the pathogen’s distribution in the future. The life stages used in this modelling were the dormant and parasitic phenophases, and two pathotypes were investigated: non-defoliating and defoliating. Climate conditions were used to calculate climate suitability for each month and phenophase, for both pathotypes.



Tmean x Rain Matrix W = 1		Monthly Tmean (°C)			
		< 21	21 to 26	26 to 30	> 30
Cumulative Monthly Rain (mm)	< 31	0.32	0.4	0.2	0.04
	31 to 61	0.56	0.7	0.35	0.07
	> 61	0.8	1	0.5	0.1

Tmean x Rain Matrix W = 1		Monthly Tmean (°C)			
		<20	20 to 24	24 to 28	> 28
Cumulative Monthly Rain (mm)	< 31	0.04	0.2	0.4	0.32
	31 to 61	0.07	0.35	0.7	0.56
	> 61	0.1	0.5	1	0.8

Figure 4: MCA model hierarchical structure and model components for Verticillium. The top level of the hierarchy is the biosecurity risk. The second level contains the life stages identified as climate-sensitive by the literature review and expert judgment. The third level contains climate variables which affect each life stage.

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[9], and the median of these models was used to produce ensemble future projection climate suitability maps.

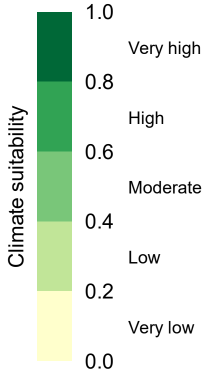


Figure 5: Colour scheme for the climate suitability maps

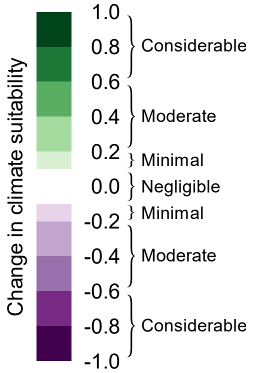


Figure 6: Colour scheme for the change in climate suitability maps

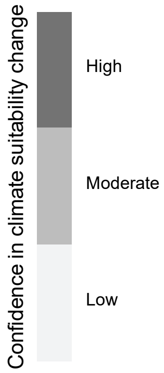


Figure 7: Colour scheme for the confidence in the change in climate suitability maps

Historical and future 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, where the future climate becomes more suitable, is shown in shades of green; negative change is shown in shades of purple. Negligible change is represented by white and occurs for values between −0.1 and 0.1; in these areas, the future climate suitability will be very similar to the historical suitability.

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.

[9]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 each of the two emissions scenarios.

Maps of change in the number of highly suitable months (see colour scheme in Figure 8) and confidence (see colour scheme in Figure 9) in the change are also presented. Polygons and key sites are displayed on each map to indicate the areas where the biosecurity risk is currently found in NSW or is of concern.

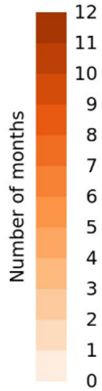


Figure 8: Colour scheme for the number of highly suitable months maps

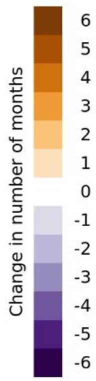


Figure 9: Colour scheme for the change in the number of highly suitable months maps

Figure 10: Colour scheme for confidence in the change in the number of highly suitable months maps

Historical and future number of highly suitable months maps

The 'number of highly suitable months' maps show the mean number of highly suitable months on a scale from 0 to 12. Pale orange corresponds to a low number of highly suitable months, and dark orange to a high number of highly suitable months. The values represent the mean overall years and thus may be any value between 0 and 12.

Change in the number of highly suitable months maps

The 'change in the number of highly suitable months' maps uses a purple-white-orange colour scheme with 11 categories ranging from –6 to 6. Shades of Orange indicate an increase in the number of highly suitable months; shades of purple indicate a decrease in the number of highly suitable months. 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 the calendar plots

Calendars for biosecurity risks were made 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). Calendars are included for the biosecurity risk overall and each life stage.

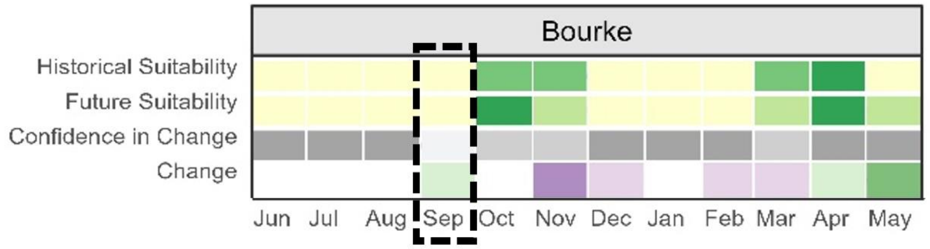
Calendars use the same colour categorisation as the climate suitability panels (see page 9, 'Interpreting the results'), except that the change scale uses 7 colours instead of 11, condensing them into the following categories: negligible, minimal, moderate and considerable.

There are two important points to note when interpreting calendar s:

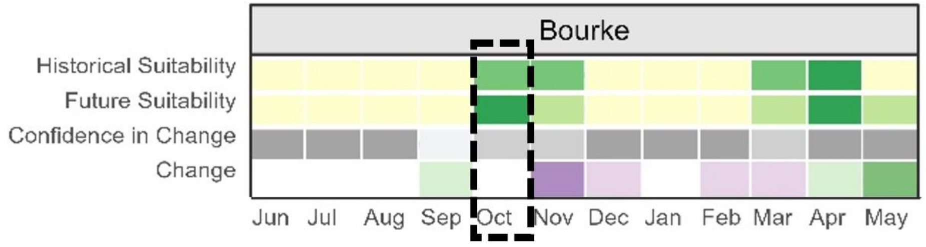
One occurs when the historical and future climate suitability categories are the same, but the 'change in suitability' is non-negligible (green or purple). This situation is shown in **Example 1** and has arisen from a historical September climate suitability of 0.000 and a future climate suitability 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 other occurs when the change from historical to future climate suitability is negligible (white), but the climate suitability is in different categories. This situation is shown in **Example 2** and has arisen from a historical October climate suitability of 0.577 and a future 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 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 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 *Verticillium*

Changes in Verticillium climate suitability are likely to create challenges for the cotton industry.

This section provides a selection of key results for the *Verticillium* climate vulnerability assessment. It begins with an overview of the overall climate impacts and a breakdown of the climate impacts on each life stage, followed by the relevant maps and calendar plots. The interpretation and findings are provided in the text on the bottom left corner of each map panel and on the right side of the calendar plot 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 calendar plots. Each map includes the outline (in blue) of the cotton growing valleys in NSW (as shown in Figure 1). The cotton-growing valleys are used to highlight regions where Verticillium wilt is likely to have an impact on cotton production.

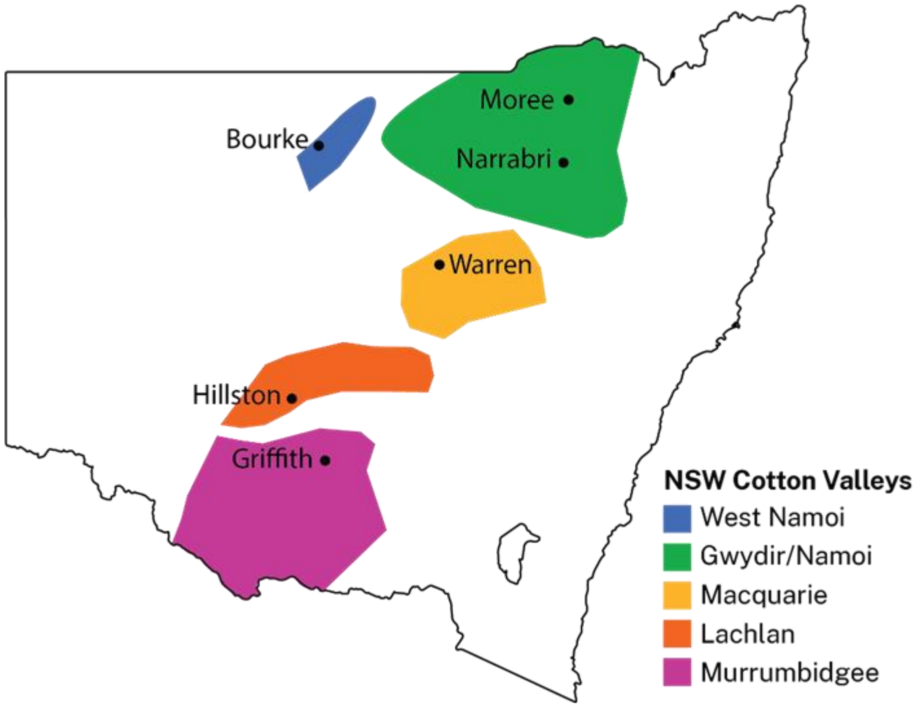


Figure 11: The cotton valleys in NSW, and some key towns within each region, marked by black dots.

Changes in climate suitability for the non-defoliating pathotype

Annual climate suitability trends: impacts on different regions in NSW

The number of months each year for which the climate suitability is classified as ‘highly suitable’ (‘high’ or ‘very high’) is used as a measure of overall climate suitability for the non-defoliating pathotype. This varies across different parts of the state, as shown in Figure 12.

For the non-defoliating pathotype, the number of highly suitable months in the northern cotton-growing valleys (West Namoi, Gwydir/Namoi and Macquarie) by 2050 is likely to decrease by 1 to 2 months per year under both emissions scenarios (*moderate to high confidence*).

Most of the rest of the state, including the southern cotton-growing regions (Lachlan and Murrumbidgee valleys) are likely to experience negligible change in the number of highly suitable months, under both emissions scenarios (*low to high confidence*).

Spatial trends: how climate change will alter the non-defoliating pathotype distribution across NSW

The trends described above address climate suitability across NSW for the whole year. In this section, the spatial distribution of the non-defoliating pathotype is examined for key months of the year. Potential changes for the non-defoliating pathotype include:

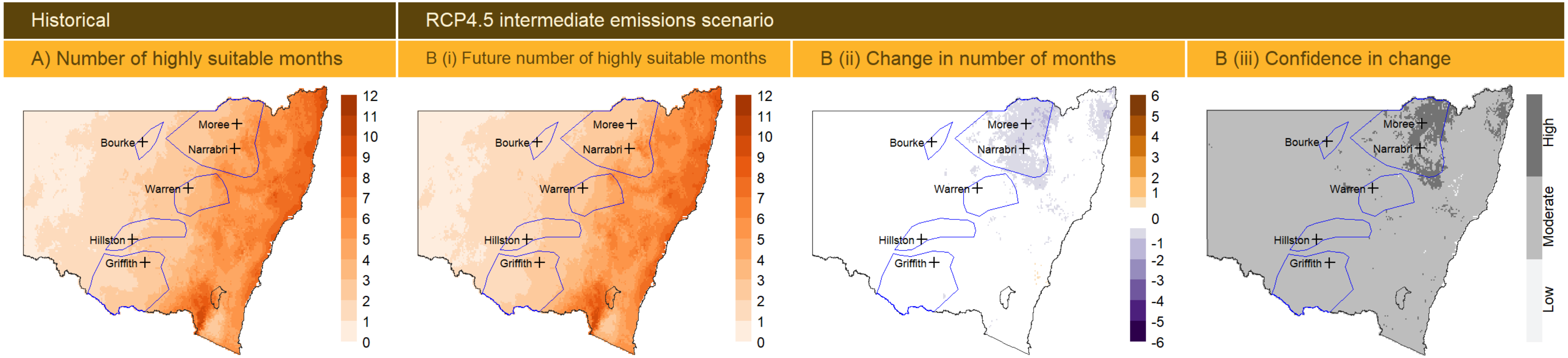
- **December to February***:* there are likely to be minimal to moderate decreases in climate suitability in all cotton valleys. The decreases are likely to be greatest under the high emissions scenario (*moderate to high confidence*) (Figure 13 and Appendix Figure A1 and A2).
- **March***:* there are likely to be minimal to moderate decreases in climate suitability in the West Namoi and Gwydir/Namoi valleys and on the edge of the Macquarie Valley. The decreases are likely to be greatest in the high emissions scenario (*moderate to high confidence*) (Appendix Figure A3).
- **April to October***:* Climate suitability in all cotton valleys is expected to remain similar to historically levels, under both emissions scenarios (*moderate to high confidence*) (Appendix Figure A4 to A10)
- **November***:* there are likely to be minimal to moderate decreases in the West Namoi and Gwydir/Namoi cotton valleys. The decreases are likely to be greatest under the high emissions scenario (*low to high confidence*) (Appendix Figure A11).

Monthly climate suitability trends in cotton valleys

The non-defoliating pathotype climate suitability calendar (Figure 14) shows the expected temporal change in monthly climate suitability throughout the year around sites of importance for the non-defoliating pathotype. An analysis of future climate suitability around these sites provides insights into potential future monthly trends by 2050.

- **Decreased climate suitability** due to changes in mean temperature and rainfall is likely from December to February for all regions; for Narrabri, Bourke and Warren regions in March; and for Narrabri and Warren regions in November (*low to high confidence*).
- **Historical climate suitability is likely to be maintained** for all regions from April to October (*low to high confidence*).

Non-defoliating pathotype: number of highly suitable months



Findings: In cotton-growing regions, particularly under high-emission scenarios, the number of highly suitable months for non-defoliating pathotype is expected to decrease minimally to moderately. This decline in climate suitability is widespread in the northern regions of West Namoi, Gwydir/Namoi, and Macquarie, while changes in the southern regions, like Lachlan and Murrumbidgee, are more localised. This minimal to moderate decrease are likely to lead to the defoliating pathotype dominating in these areas.

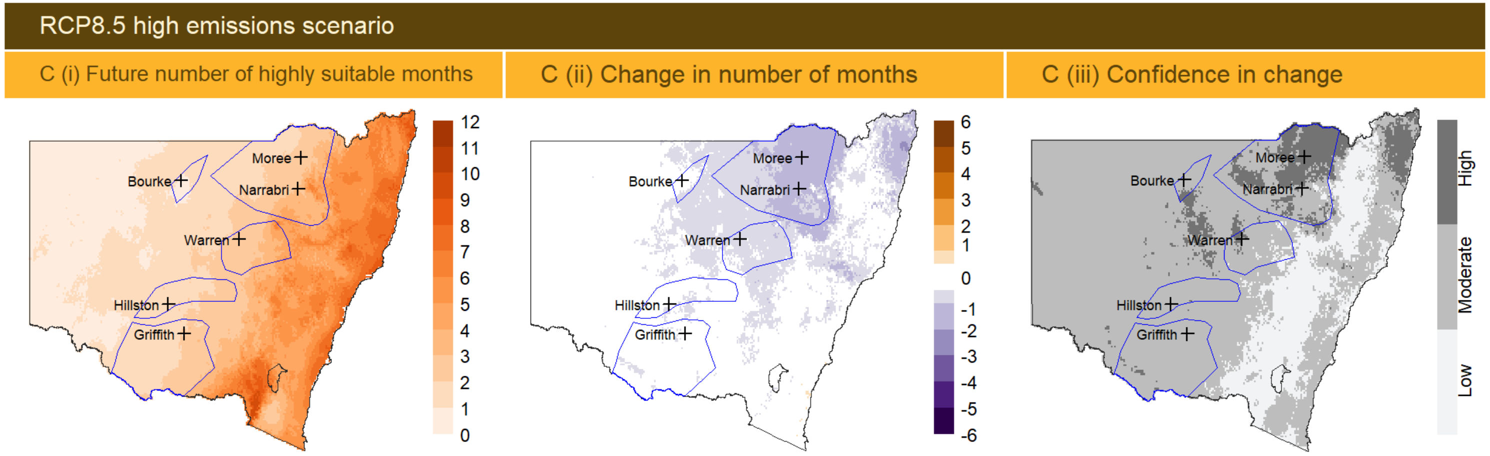
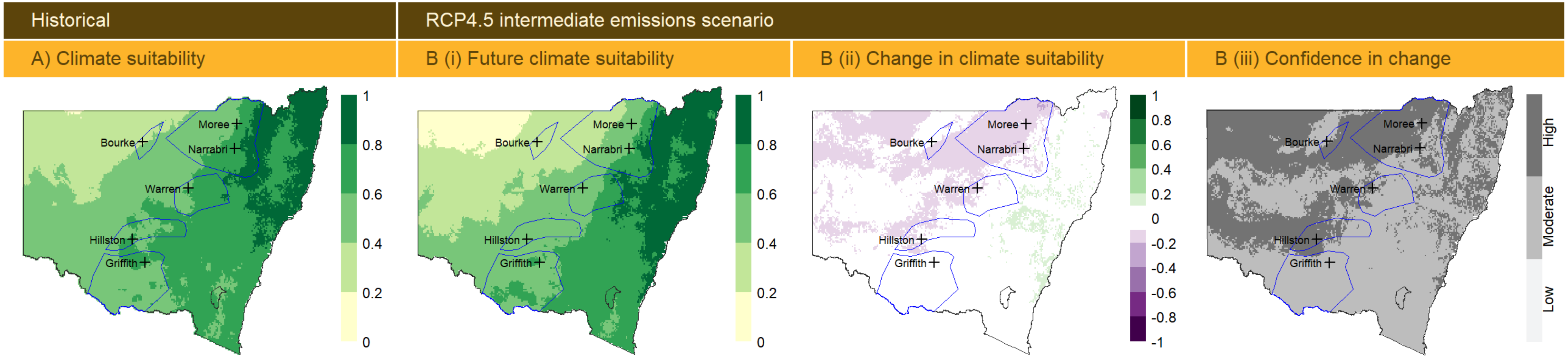


Figure 12: The number of highly suitable months measures the months in which climate suitability is greater than or equal to 0.6. The panel is comprised of 7 maps: A) shows the historic number of highly suitable months; B) and C) show the future number of highly suitable months for the intermediate and 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). Sites of importance where Verticillium wilt is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

Non-defoliating pathotype climate suitability for December



Findings: Climate suitability is expected to decrease minimally to moderately across most cotton areas outlined in blue on the maps under both emission scenarios. The decrease is more pronounced under the high emissions scenario near the sites of Moree, Narrabri, Warren and Bourke. Changes in temperature and rainfall lead to this decrease, and these changes in December are likely to lead to the defoliating pathotype dominating in these areas.

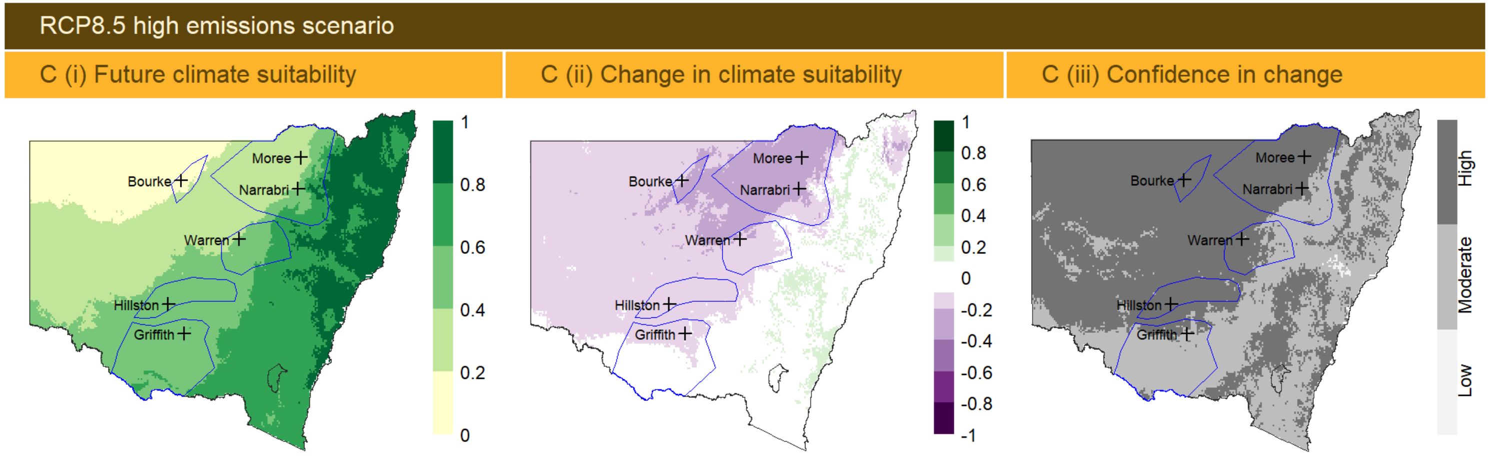


Figure 13: Climate suitability for the non-defoliating pathotype for December in NSW. The panel is comprised of 7 maps: A) shows the historic climate suitability; B) and C) show future climate suitability for the intermediate and high emissions scenarios, respectively; (i) shows future climate suitability, (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). Sites of importance in Verticillium wilt monitoring are marked by black crosses, and the blue polygons show the cotton valleys .

Non-defoliating pathotype climate suitability calendar

Figure 14: climate suitability calendar for non-defoliating pathotype. The calendar displays the historical and future climate suitability, change in suitability and confidence in change for each site of interest. It shows two emissions scenarios, the intermediate emissions scenario, RCP4.5, on the left and the high emissions scenario, RCP8.5, on the right. The climate suitability categories represent median values within a 10km radius of each location.

Findings: Climate suitability is expected to decrease minimally to moderately from November to March at Moree, Bourke, and Narrabri. At Warren and Hillston, climate suitability sees a minimal decrease during the summer months, particularly under a high emissions scenario. At Griffith, a minimal decrease is likely only in December under the high emissions scenario. These changes are more pronounced under a high emissions scenario. Declines in climate suitability are due to changes in temperatures and rainfall. These changes could see a redistribution of pathotypes, with the defoliating pathotype dominating the warmer northern regions. All sites are expected to maintain historical levels of low to moderate climate suitability from April through October, with some months of high suitability during the same period at Narrabri. These months in the future will probably experience a similar impact from non-defoliating pathotypes as observed in the past.

Changes in climate suitability for defoliating pathotype

Annual climate suitability trends across NSW

The number of months each year in which the climate suitability is classified as 'highly suitable' ('high' or 'very high') is used as a measure of climate suitability for the defoliating pathotype. This varies between different regions of the state, as shown in Figure 15**.**

For the defoliating pathotype, by 2050, the number of highly suitable months in the northern cotton valleys (West Namoi, Gwydir/Namoi and Macquarie) of the state are likely to increase by 1 to 2 months per year under both emissions scenarios (*moderate to high confidence*). This trend is expected to spread to the southern cotton regions (Lachlan and Murrumbidgee) under the high emissions scenario (*moderate to high confidence*). Most of the rest of the state is likely to experience negligible change in the number of highly suitable months under both emissions scenarios (*moderate to high confidence*).

Spatial trends: defoliating pathotype distribution

The trends in climate suitability across the year have been analysed, however, in this section, the spatial distribution of the defoliating pathotype is examined for key months of the year. Potential changes for the defoliating pathotype in the cotton valleys include:

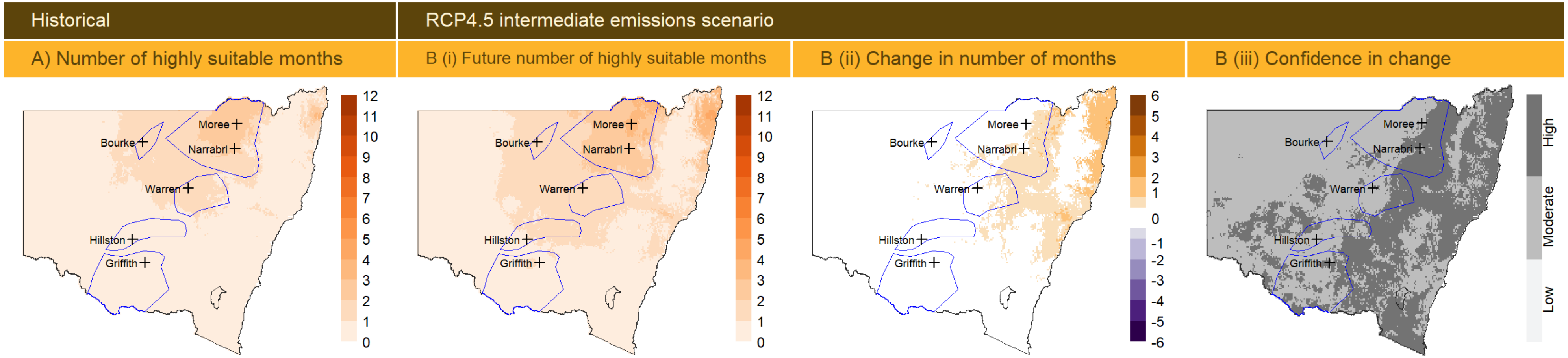
- **October to April**: there are likely to be minimal to moderate increases in climate suitability in most cotton valleys. The increases are likely to be greatest under the high emissions scenario (*moderate to high confidence*) (Figure 16 and Appendix Figure A23. November climate suitability for *Verticillium* defoliating pathotype A24 and A13 to A16)
- **May to September**: Climate suitability in all cotton valleys is expected to remain similar to what has been historically experienced under both emissions scenarios (*moderate to high confidence*) (Appendix Figure A17 to A21).

Monthly trends in climate suitability in NSW cotton valleys

The defoliating pathotype climate suitability calendar (Figure 17) shows the expected temporal change in monthly climate suitability throughout the year around sites of importance for the defoliating pathotype. An analysis of future climate suitability around these sites provides insights into potential future monthly trends by 2050.

- **Increased climate suitability is expected** at Narrabri and Warren in October, December, March, and April under the high emission scenarios (*high confidence*). A similar trend is observed at Moree, with changes expected in all these months except March. At Bourke, increases are only expected in October (*high confidence*). At Griffith and Hillston, increases are likely in November, December, and March (*moderate to high confidence*). Similar changes may be observed under intermediate emission scenarios, but they are expected to occur in fewer months.
- **Maintained historical climate suitability** for all regions is expected from May to September.

Defoliating pathotype: number of highly suitable months



Findings: In cotton-growing regions, particularly under high-emission scenarios, the number of highly suitable months for defoliating pathotype is expected to increase minimally to moderately. This increase in climate suitability is widespread in the northern regions of West Namoi, Gwydir/Namoi, and Macquarie, while changes in the southern regions, like Lachlan and Murrumbidgee, are more localised. The increase in suitable months for the defoliating pathotype are likely to lead to the defoliating pathotype dominating in these areas.

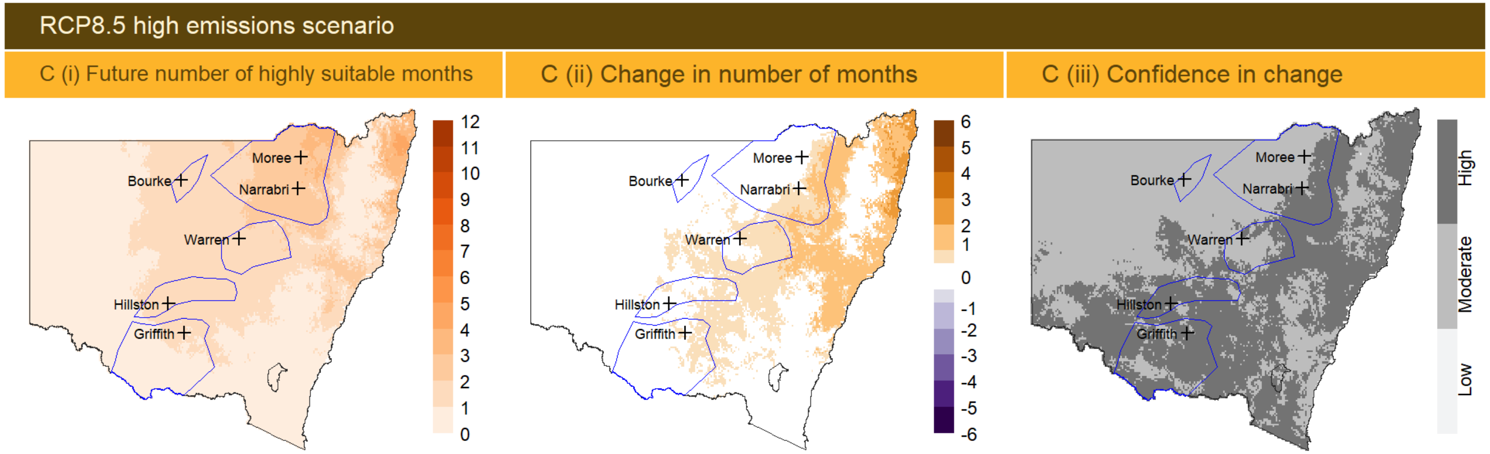
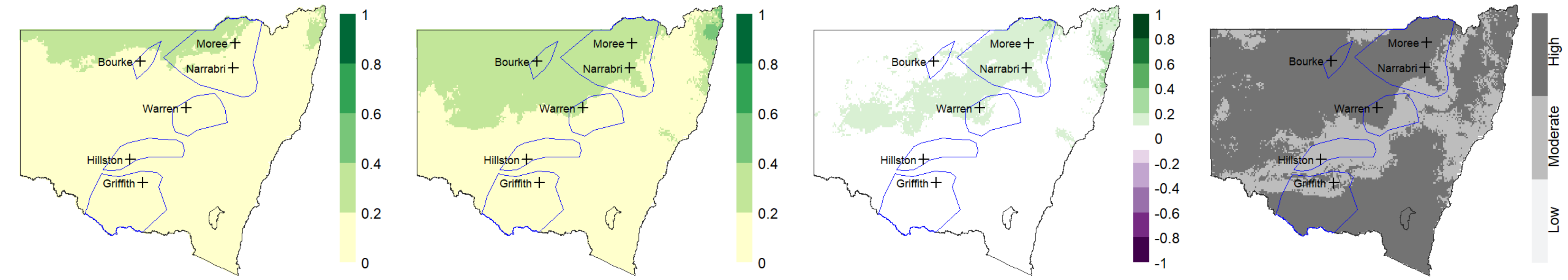


Figure 15: The number of highly suitable months measures the months in which climate suitability is greater than or equal to 0.6. The panel is comprised of 7 maps: A) shows the historic number of highly suitable months; B) and C) show the future number of highly suitable months for the intermediate and 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). Sites of importance where Verticillium wilt is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

Defoliating pathotype climate suitability for October

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: Climate suitability is expected to increase minimally to moderately across most cotton areas outlined in blue on the maps under both emission scenarios. The increase is more pronounced under the high emissions scenario near Moree, Narrabri, Bourke, Warren and Hillston sites. Changes in temperature and rainfall lead to this decrease. These changes in October could negatively impact cotton by increasing the risk of early infection following planting by the defoliating pathotype.

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

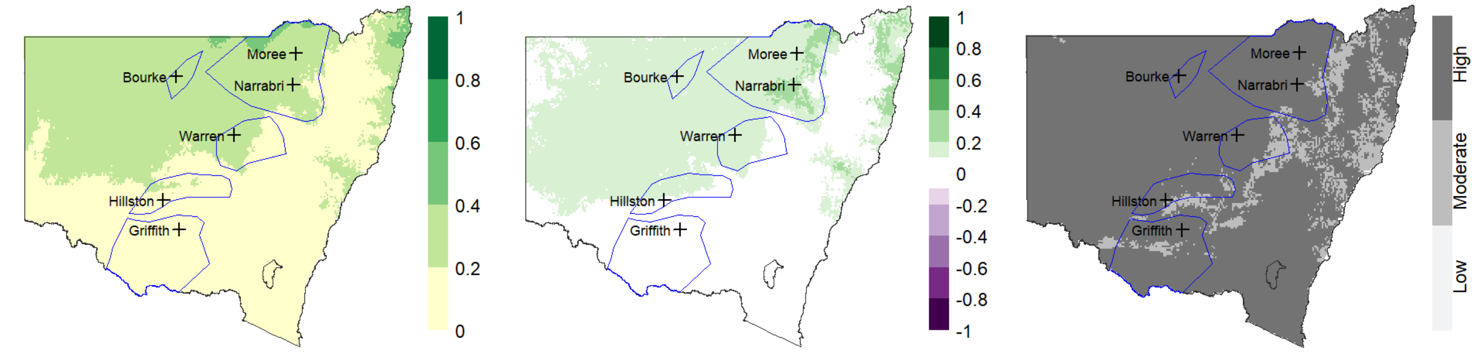


Figure 16: Climate suitability for defoliating pathotype in October in NSW. The panel is comprised of 7 maps: A) shows the historic climate suitability; B) and C) show future climate suitability for the intermediate and high emissions scenarios, respectively; (i) shows future climate suitability, (ii) 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). Sites of importance in Verticillium wilt monitoring are marked by black crosses, and the blue polygons show the cotton valleys.

Defoliating pathotype climate suitability calendar

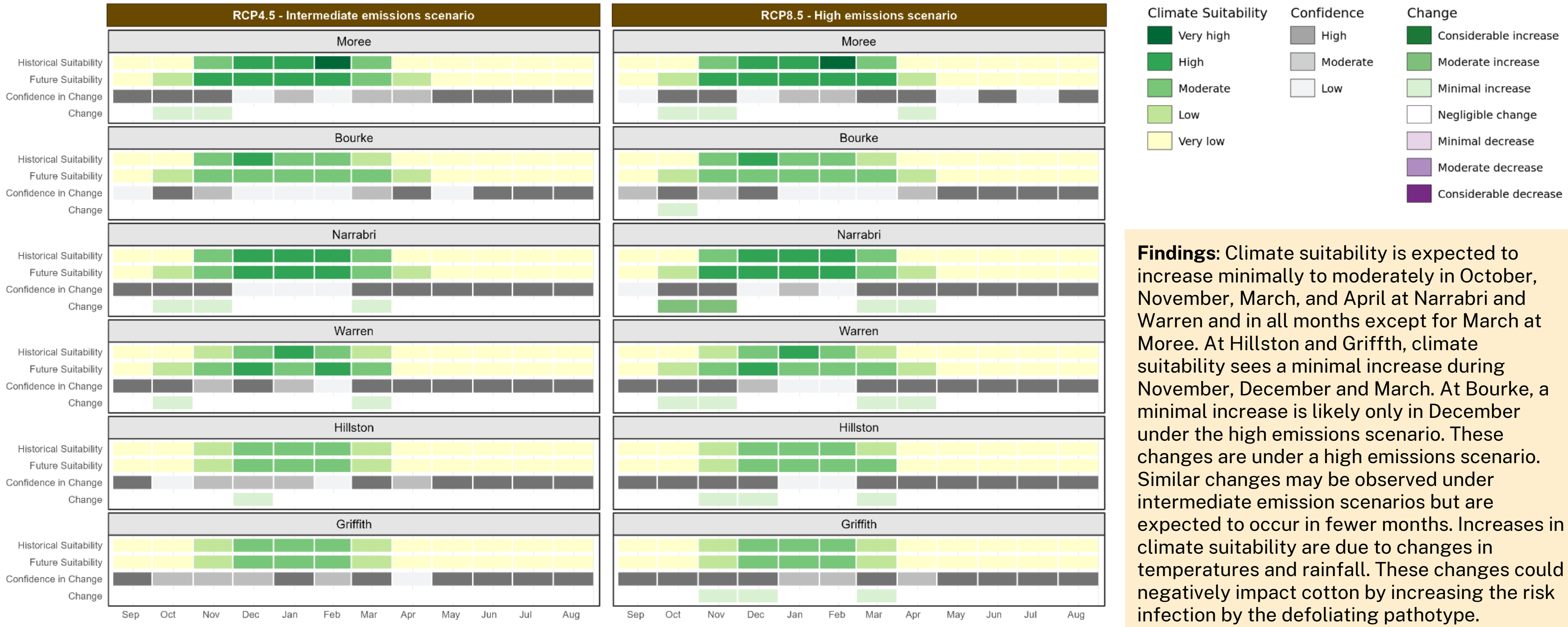


Figure 17: climate suitability calendar for the defoliating pathotype. The calendar displays the historical and future climate suitability, change in suitability and confidence in change for each site of interest. It shows two emissions scenarios, the intermediate emissions scenario, RCP4.5, on the left and the high emissions scenario, RCP8.5, on the right. The climate suitability categories represent median values within a 10km radius of each location.

Findings: Climate suitability is expected to increase minimally to moderately in October, November, March, and April at Narrabri and Warren and in all months except for March at Moree. At Hillston and Griffth, climate suitability sees a minimal increase during November, December and March. At Bourke, a minimal increase is likely only in December under the high emissions scenario. These changes are under a high emissions scenario. Similar changes may be observed under intermediate emission scenarios but are expected to occur in fewer months. Increases in climate suitability are due to changes in temperatures and rainfall. These changes could negatively impact cotton by increasing the risk infection by the defoliating pathotype.
All sites are expected to maintain historical levels of very low to low climate suitability from April through October. These months in the future will probably experience a similar impact from defoliating pathotypes as observed in the past.

Changes in climate suitability for the dormant stage

Annual climate suitability trends: impacts on different regions in NSW

The number of months each year in which the climate suitability is classified as ‘highly suitable’ (‘high’ or ‘very high’) is used as a measure of climate suitability for the dormant stage. This varies between different regions of the state, as shown in Figure 18.

For the dormant stage, by 2050, the number of highly suitable months in the southern cotton valleys and eastern edge of the Moree growing region are likely to increase by 1 to 2 months per year under both emissions scenarios (*moderate to high confidence*). Under the high emissions scenario the Bourke growing region and he western part of the Moree growing region are likely to decrease by 1 to 2 months per year under both emissions scenarios (*moderate to high confidence).*

Spatial trends: how climate change will alter the dormant stage distribution across NSW

The trends in climate suitability across the year have been analysed, however, in this section, the spatial distribution of the dormant stage is examined for key months of the year. Potential changes in the dormant stage in the cotton valleys include:

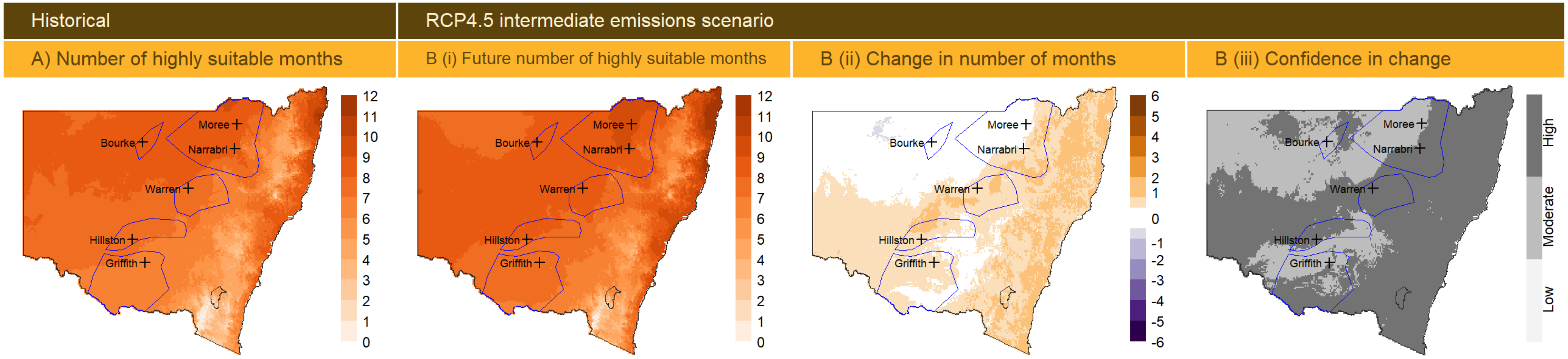
- **May, June, August and September***:* there are likely to be minimal to moderate increases in the northern cotton valleys, with changes extending to southern regions in May and September. The increases are likely to be greatest under the high emissions scenario (*moderate to high confidence*) (Figure 19 and Appendix Figure A30, A32 and A33).
- **November to March***:* there is likely to be a minimal to moderate decrease in most cotton valleys throughout these months under the high emissions scenario (*moderate to high confidence*) and, to a lesser extent, under the intermediate emission scenario (*low to high confidence*) (Appendix Figures A25 to A27, A35 and A36).
- **April, June and October***:* Climate suitability in all cotton valleys is expected to remain similar to what has been historically experienced under both emissions scenarios (*moderate to high confidence*) (Appendix Figure A28, A30 and A34).

Monthly trends in cotton valleys: how climate change will alter climate suitability throughout the year

The dormant life stage climate suitability calendar (Figure 20) shows the expected temporal change in monthly climate suitability throughout the year around sites of importance for *Verticillium*. An analysis of future climate suitability around these sites provides insights into potential future monthly trends by 2050.

- **Increased climate suitability is expected** at Moree, Bourke and Narrabri in August, May and June sites under the high emission scenarios. At Warren, Griffith and Hillston, increases are likely in May and September (*moderate to high confidence*). Similar changes may be observed under the intermediate emission scenarios.
- **Decreased climate suitability is expected** at Moree, Bourke and Narrabri between November and March under the high emission scenarios (*moderate to high confidence*). At Warren, Griffith and Hillston, decreases are likely across the summer months (*moderate to high confidence*). Similar changes may be observed under the intermediate emission scenarios.
- **Maintained historical climate suitability** is likely in Moree, Bourke, Narrabri, Warren, Griffith and Hillston across several months during autumn, winter and spring under high the emission scenarios (*moderate to high confidence*).

Dormant life stage: number of highly suitable months



Findings: In cotton-growing regions, particularly under high-emission scenarios, the number of highly suitable months for the dormant stage is expected to increase slightly in all areas except for West Namoi. West Namoi and parts of Gwydir/Namoi are likely to decrease the number of highly suitable months under high-emission scenarios. These changes potentially pose challenges to the cotton industry, particularly in selecting alternate non-host crops and controlling weed hosts.

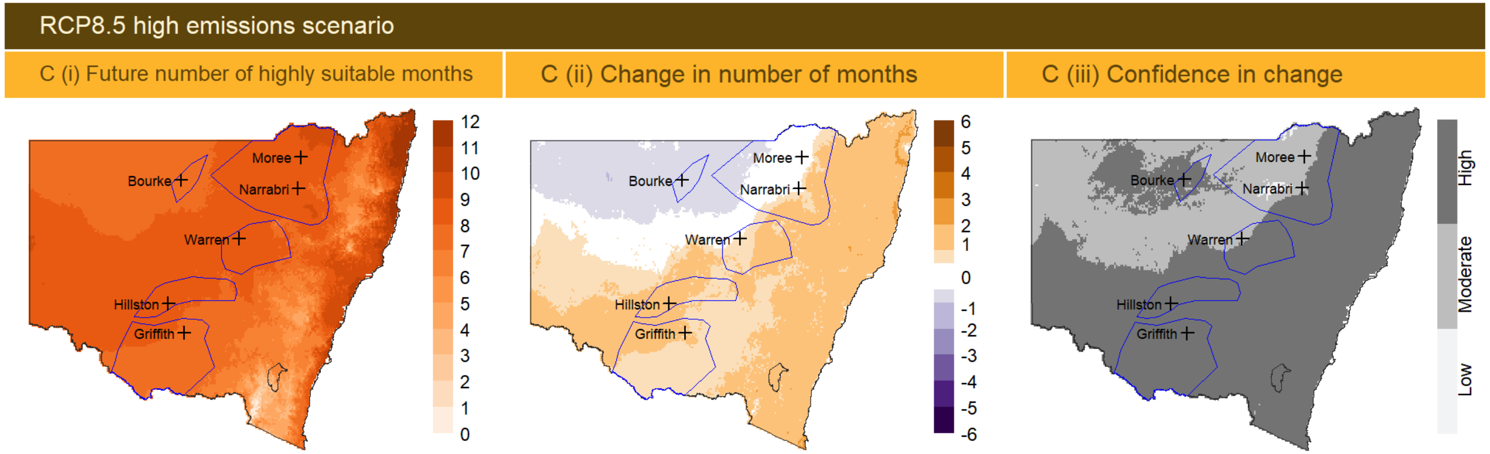
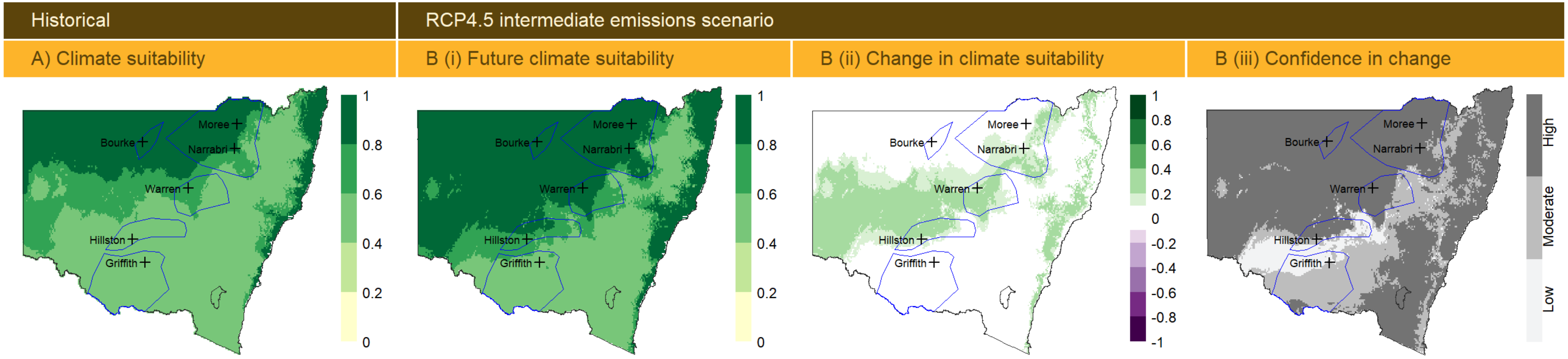


Figure 18: The number of highly suitable months measures the months in which climate suitability is greater than or equal to 0.6. The panel is comprised of 7 maps: A) shows the historic number of highly suitable months; B) and C) show the future number of highly suitable months for the intermediate and 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). Sites of importance where Verticillium wilt is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

Dormant life stage climate suitability for May



Findings: Climate suitability is expected to increase minimally to moderately across most cotton areas outlined in blue on the maps under both emission scenarios. The increase is more pronounced under the high emissions scenario near the sites of Narrabri, Warren, Hillston and Bourke. These changes in May are likely to lead to the increased need to incorporate crop stubble soon after harvest to reduce the amount of *Verticillium* overwintering.

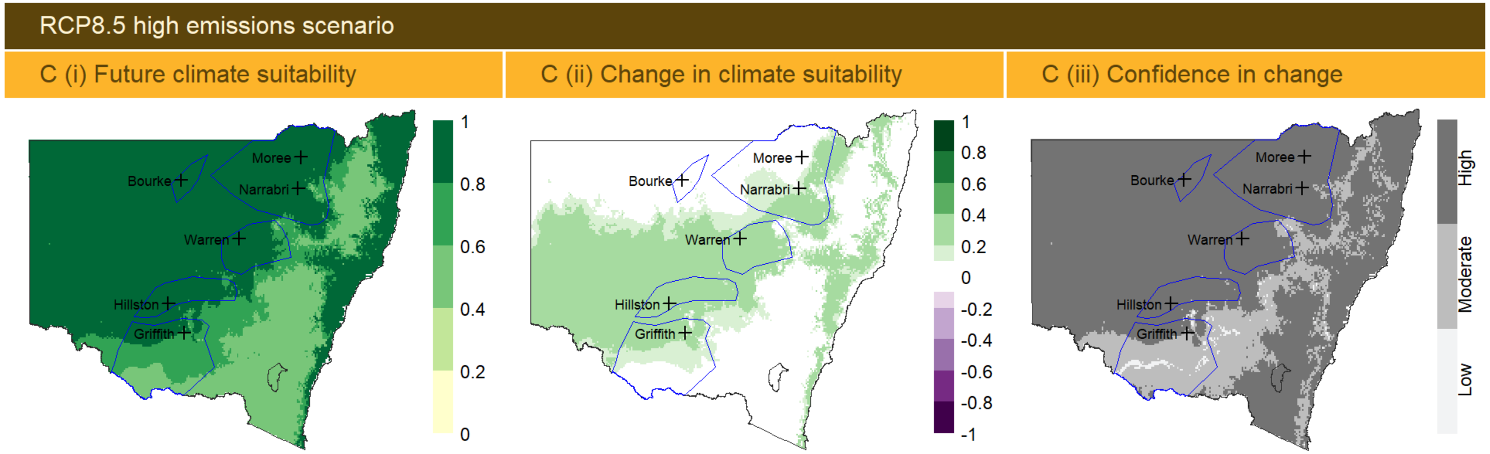


Figure 19: Climate suitability for dormant life stage in NSW for May. The panel is comprised of 7 maps: A) shows the historic climate suitability; B) and C) show future climate suitability for the intermediate and high emissions scenarios, respectively; (i) shows future climate suitability, (ii) shows 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). Sites of importance in Verticillium wilt monitoring are marked by black crosses, and the blue polygons show the cotton valleys.

Dormant life stage climate suitability calendar

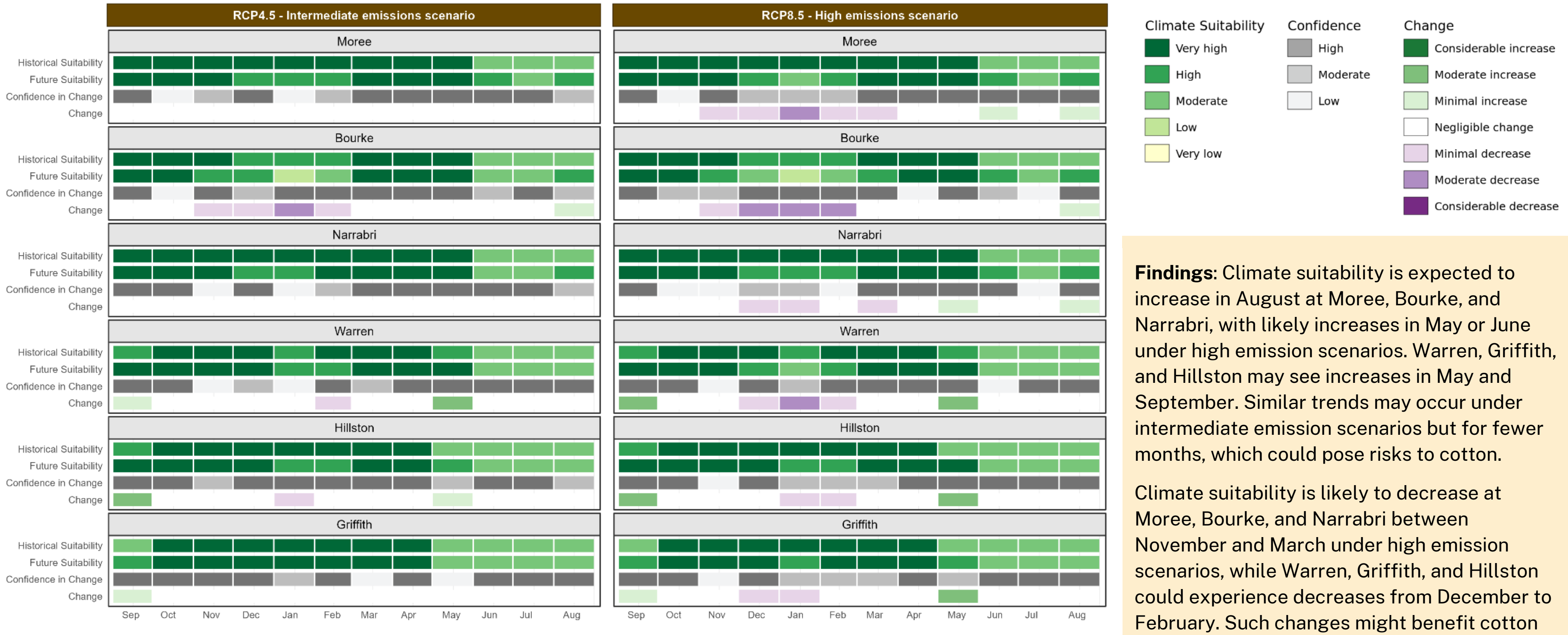


Figure 20: climate suitability calendar for the dormant life stage. The calendar displays the historical and future climate suitability, change in suitability and confidence in change for each site of interest. It shows two emissions scenarios, the intermediate emissions scenario, RCP4.5, on the left and the high emissions scenario, RCP8.5, on the right. The climate suitability categories represent median values within a 10km radius of each location.

Findings: Climate suitability is expected to increase in August at Moree, Bourke, and Narrabri, with likely increases in May or June under high emission scenarios. Warren, Griffith, and Hillston may see increases in May and September. Similar trends may occur under intermediate emission scenarios but for fewer months, which could pose risks to cotton.

Climate suitability is likely to decrease at Moree, Bourke, and Narrabri between November and March under high emission scenarios, while Warren, Griffith, and Hillston could experience decreases from December to February. Such changes might benefit cotton by reducing the surviving inoculum that remains dormant in the soil.

Overall, historical climate suitability is expected to be maintained at all sites during some or all months in winter, spring, and autumn, suggesting that impacts will remain similar to those observed in the past.

Key findings and insights from a changing climate

The results of this study provide insights into the historical and potential future climate suitability for *Verticillium*, and for individual pathogen life stages, in cotton-producing valleys in NSW.

Key insights for the northern cotton valleys

The northern cotton valleys of West Namoi, Gwydir/Namoi, and Macquarie are expected to experience changes in climate by 2050. These changes are likely to alter which pathotypes are dominant in these regions.

Historically, Verticillium wilt has had a higher incidence in the cooler regions of Gwydir/Namoi and Macquarie. By 2050, the number of suitable months for the non-defoliating pathotype in these areas is expected to decrease by 1 to 2 months per year under both emissions scenarios. However, in the same areas, the number of suitable months for the defoliating pathotype, more common in the warmer regions, is projected to increase by 1 to 2 suitable months per year, under both emissions scenarios.

These changes indicate a shift in the pathotype distribution and dominance in the West Namoi, Gwydir/Namoi, and Macquarie regions. It suggests that the defoliating pathotype is likely to become more prevalent than the non-defoliating pathotype, due to warmer conditions in the future. This shift could present challenges for the cotton industry in these valleys, as the defoliating pathotype can lead to significant decreases in yield associated with leaf loss and boll loss. Current strategies in place for managing Verticillium wilt, which are the same for both pathotypes, will need to continue to be applied, and cotton producers should consider the following:

- Submit plant samples of suspected infected plants for accurate diagnostic and identification of pathotype.
- Select varieties with the highest tolerance.
- Plant early to avoid the crop finishing in cooler weather.
- Manage nutrients and water requirements accordingly.
- Apply labelled product to reduce the development of microsclerotia in season.
- Control weeds and alternate hosts.
- Incorporate stubble as soon after harvest as possible.
- Manage irrigation timing to avoid cooling the soil profile (which favours the non-defoliating pathotype).

Key insights for the southern cotton valleys

The southern cotton valleys of Lachlan and Murrumbidgee are also expected to experience changes in climate by 2050. These changes are likely to alter which pathotypes dominate in these regions.

Historically, the non-defoliating pathotype was reported in the cooler regions of Lachlan and Murrumbidgee. By 2050, the number of suitable months for this pathotype in these areas is expected to remain similar to historical levels under both emissions scenarios. Additionally, the defoliating pathotype, has also been reported in these regions, albeit less commonly. By 2050, the number of suitable months for the defoliating pathotype in these cooler regions is projected to increase by 1 to 2 suitable months per year in the same areas by 2050 under both emissions scenarios.

These changes indicate a shift in the pathotypes in the Lachlan and Murrumbidgee regions, suggesting that the prevalence of the defoliating pathotype may increase in those valleys, due to warmer conditions in the future. This shift could present challenges for the cotton industry in these valleys, as the defoliating pathotype can lead to significant decreases in yield associated with leaf loss and boll loss. Current strategies in place for managing Verticillium wilt, which are the same for both pathotypes, will need to continue to be applied, and cotton producers in those regions should consider the following:

- Submit plant samples of suspected infected plants for accurate diagnostic and identification of pathotype.
- Select varieties with the highest tolerance.
- Plant early to avoid the crop finishing in cooler weather.
- Manage nutrients and water requirements accordingly.
- Apply labelled product to reduce the in-season development of the pathogen.
- Control weeds and alternate hosts.
- Incorporate stubble as soon after harvest as possible.

Key insights for the dormant life stage for all cotton valleys

The *Verticillium* pathogen can survive dormant for more than 10 years in the soil, from whence it can germinate and infect host plants via the roots and cause wilting, dieback, leaf loss and even plant death.

By 2050, there are likely to be minimal to moderate increases in climate suitability for dormant *Verticillium* in May, June, August and September in northern NSW cotton valleys. In the southern cotton-growing regions this increase is expected to occur in May and September. The increases are likely to be greatest under the high emissions scenario.

The increase in climate suitability for the dormant life stage poses challenges for the cotton industry, as it is likely to impact management strategies for dealing with that life stage. These strategies rely on planting a non-host crop during the cooler months, to reduce pathogens in the soil, and regular control of weeds known to be hosts, which can be a reservoir ('green bridge') for the fungal pathogen. A longer dormant phase with more suitable climate conditions may necessitate changes to these approaches in the future. As a result, the following strategies may need to be considered in these regions:

- Avoid back-to-back planting of cotton.
- Introduce longer fallow periods between cotton crops.
- Apply fungicides throughout the growing season to reduce the development of the pathogen in the soil.
- Greater control of weeds and alternate hosts, possibly using spot spraying technology.
- Harrowing during the off-season to encourage natural breakdown of stubble and reduce survival of dormant microsclerotia
- Irrigation of fallow fields to enable wetting and drying of soil, promoting natural decline of dormant *Verticillium*.

What is a green bridge?

A 'green bridge' refers to weeds and other plants that provide a habitat for disease and insect pests to survive on from one cropping season to the next. This vegetation can grow in the paddock, alongside fence lines and on headlands, roadsides and non-crop land. Green bridges can be germinated seed from the previous crop, local weeds germinating from summer rainfall, germinating weeds blown in from or susceptible native vegetation.

Expected challenges for primary industries

The effects of Verticillium wilt on the cotton industry in NSW will depend on

- the future distribution of cotton-growing in NSW,
- changes in production timings, and
- the overlap between susceptible life stages of cotton and the lifecycle of *Verticillium*.

Climate change is likely to alter the number of months in which the climate is suitable for *Verticillium,* potentially shifting the distribution of the pathogen across NSW.

Changing climate suitability for *Verticillium* under a warmer climate in 2050 may affect Verticillium wilt prevalence in cotton grown across NSW. Cotton in the north of the state may be particularly affected, due to the increased climate suitability for the defoliating pathotype, potentially leading to increased economic losses due to the disease.

Reduced climate suitability for the non-defoliating pathotype may provide some opportunity for growers in the north of NSW, although this may be counteracted by increases in climate suitability for the defoliating strain.

The occurrence of more suitable climatic conditions during the dormant life stage is expected to increase, bringing with it the risk of the pathogen remaining viable in the soil (potentially for more than 10 years).

A minimal to moderate increase in climate suitability may occur across inland NSW in spring, which moves southward towards summer by 2050. This change may pose increased risks for cotton production, as the increase in climate suitability matches planting dates for the southern growing region.

Infection of vulnerable early-season cotton plants can cause significant yield loss. Management practices that can help to reduce losses from the disease include planting resistant varieties, managing crop residues after harvest, rotating non-susceptible crops and controlling weeds to prevent the green bridge.

Verticillium: where to from here?

Future priorities

We have assessed the future climate suitability for *Verticillium* as a prerequisite for effective planning decisions and for developing management strategies to address future climate change impacts.

The results presented in this report have identified changes in climate suitability for *Verticillium* that are likely to have a moderate impact on the cotton industry in NSW. More research is needed to best advise impacted industries on adaptations and management techniques for Verticillium wilt, looking forward to 2050.

Effective management approaches must be carefully planned, evaluated and deployed to minimise disruptions and unnecessary costs. The cotton industry may need to consider starting surveillance earlier in spring and implementing broad-reaching Verticillium wilt education programs. These programs would raise awareness of the increased risk and provide management strategies for regions not previously affected. There is also an increased need for cotton cultivars to have resistance/tolerance to both pathotypes, given changes in their distributions which are expected to occur.

Finally, additional work is needed to understand the financial and market access impacts of increased pressure from Verticillium wilt for the cotton industry.

Addressing the gaps, barriers and challenges

The information generated by this project has helped to identify future climate vulnerabilities of *Verticillium*. However, knowledge gaps were identified during the development of the MCA model.

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

- Breeding cotton varieties with increased tolerance/resistance to both the non-defoliating and defoliating strains of *Verticillium*.
- Investigation into the different symptoms caused by Australian *Verticillium* pathotypes to those observed overseas.

This report aims to highlight these gaps to assist in directing future research and project development. It was not possible to cover all biosecurity risks that are important to NSW. Consideration should be given to modelling other significant biosecurity risks, like those listed in the national priority list of exotic environmental pests, weeds and diseases[10]. Expanding the range of the current modelling to be Australia-wide would provide valuable information for future industry planning and assist with inter-jurisdictional engagement if climate change is likely to shift biosecurity risks into new geographic regions.

[10] The National Priority List of Exotic Environmental Pests, Weeds and Diseases, https://www.agriculture.gov.au/biosecurity-trade/policy/environmental/priority-list

Conclusion

The Climate Vulnerability Assessment provides important baseline information to support state, regional and strategic industry-level planning for climate change, highlighting where management and investment should be prioritised to sustain and enhance cotton and limit the impacts of climate change on *Verticillium* pathotypes.

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

NSW DPIRD will use these findings to work 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 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.

Other Climate Vulnerability Assessments that may be of particular interest to *Verticillium* include:

- Irrigated Cotton
- Fusarium

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.

Contact us

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

Acknowledgements

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Thanks to all the NSW Department of Primary Industries staff who participated in the NSW DPI Biosecurity Team: Andrew Eliot, Andrew Sanger, Anil Raghavendra, Fiona Lidbetter, Jim Rothwell, Karen Kirkby, Kurt Lindbeck, Kurt Lindbeck, Polychronis Rempoulakis, Scott Charlton, Shannon Mulholland, Stephen Johnson and Will Cuddy.

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Appendix

Figure A1. January climate suitability for *Verticillium* non-defoliating pathotype

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

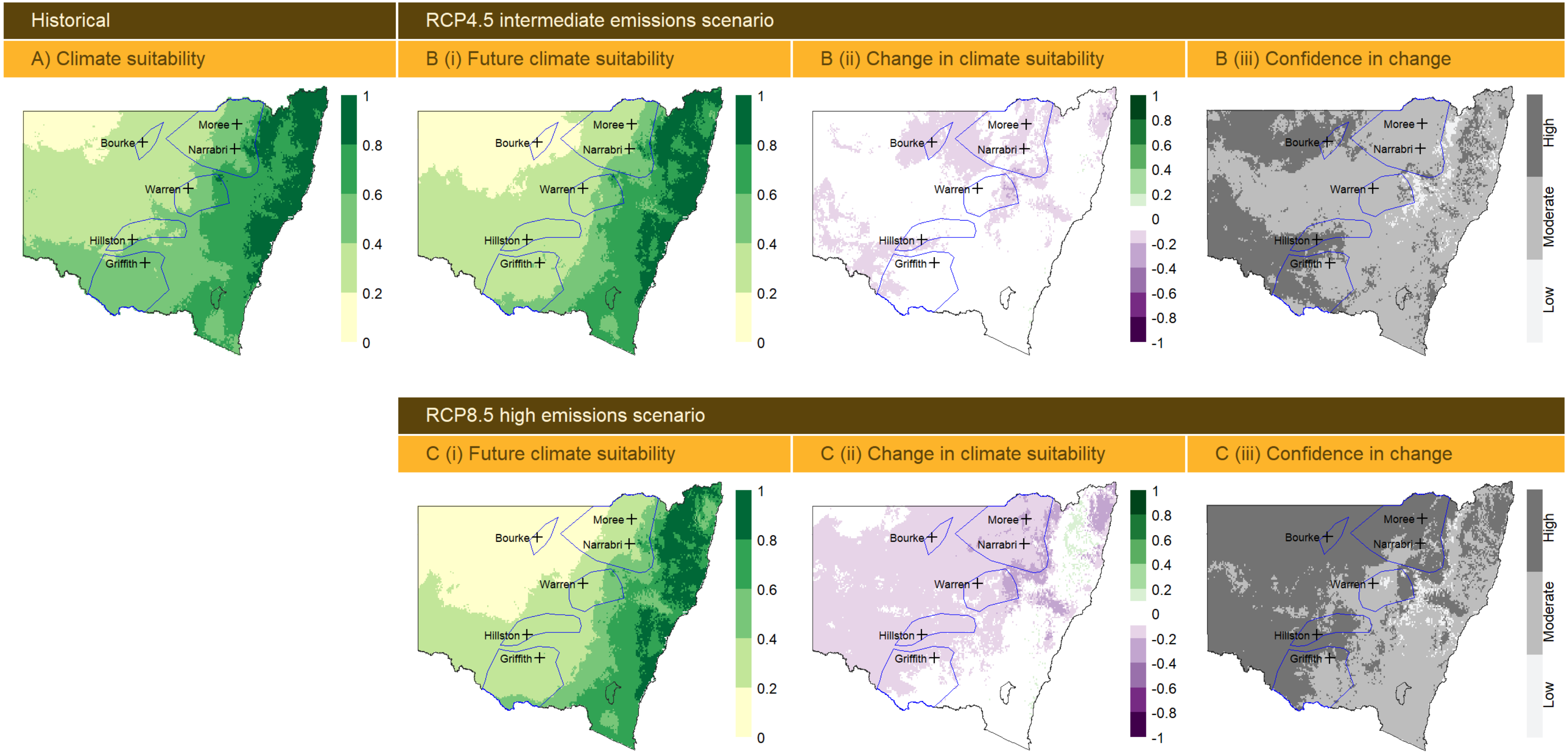


Figure A2. February climate suitability for *Verticillium* non-defoliating pathotype

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

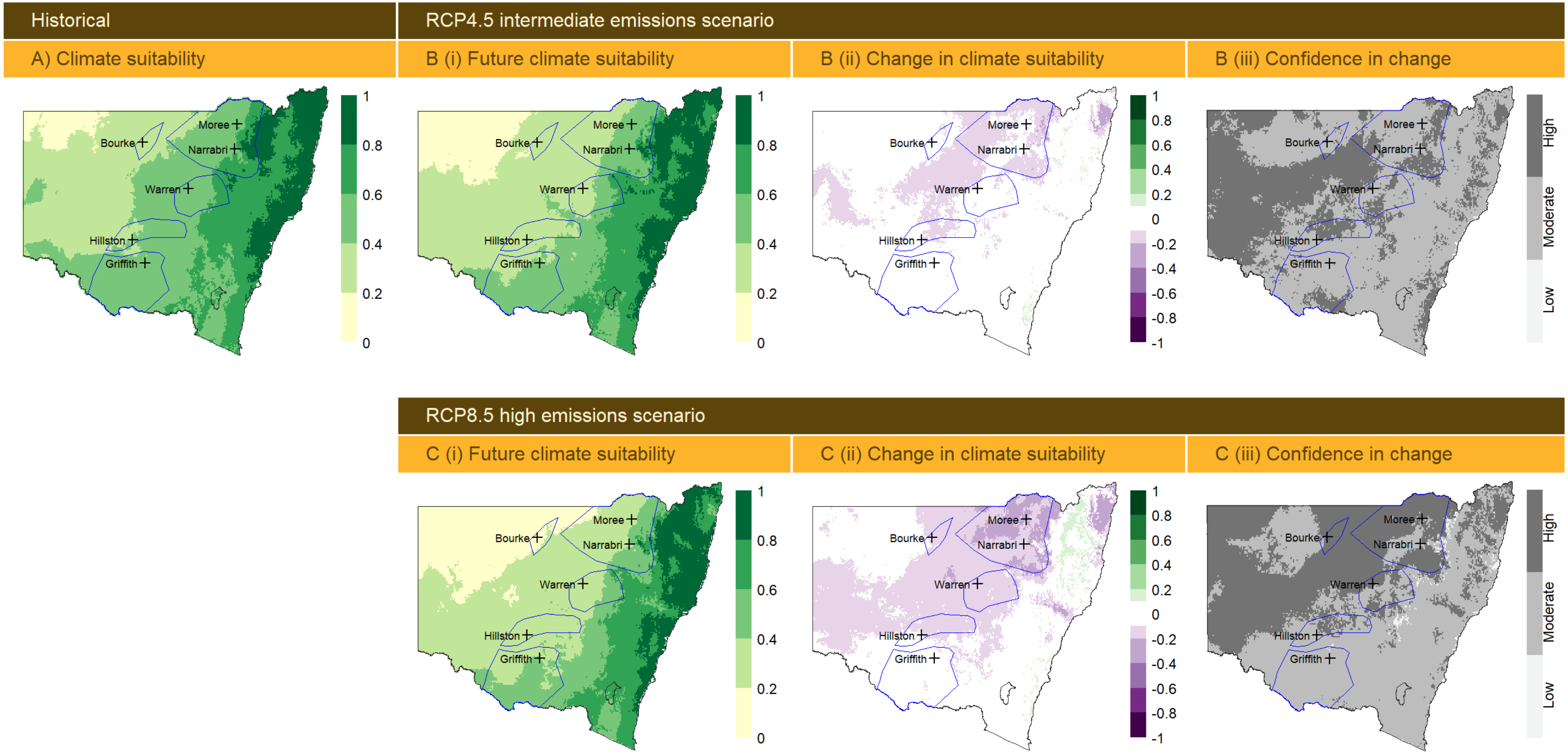


Figure A3. March climate suitability for *Verticillium* non-defoliating pathotype

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

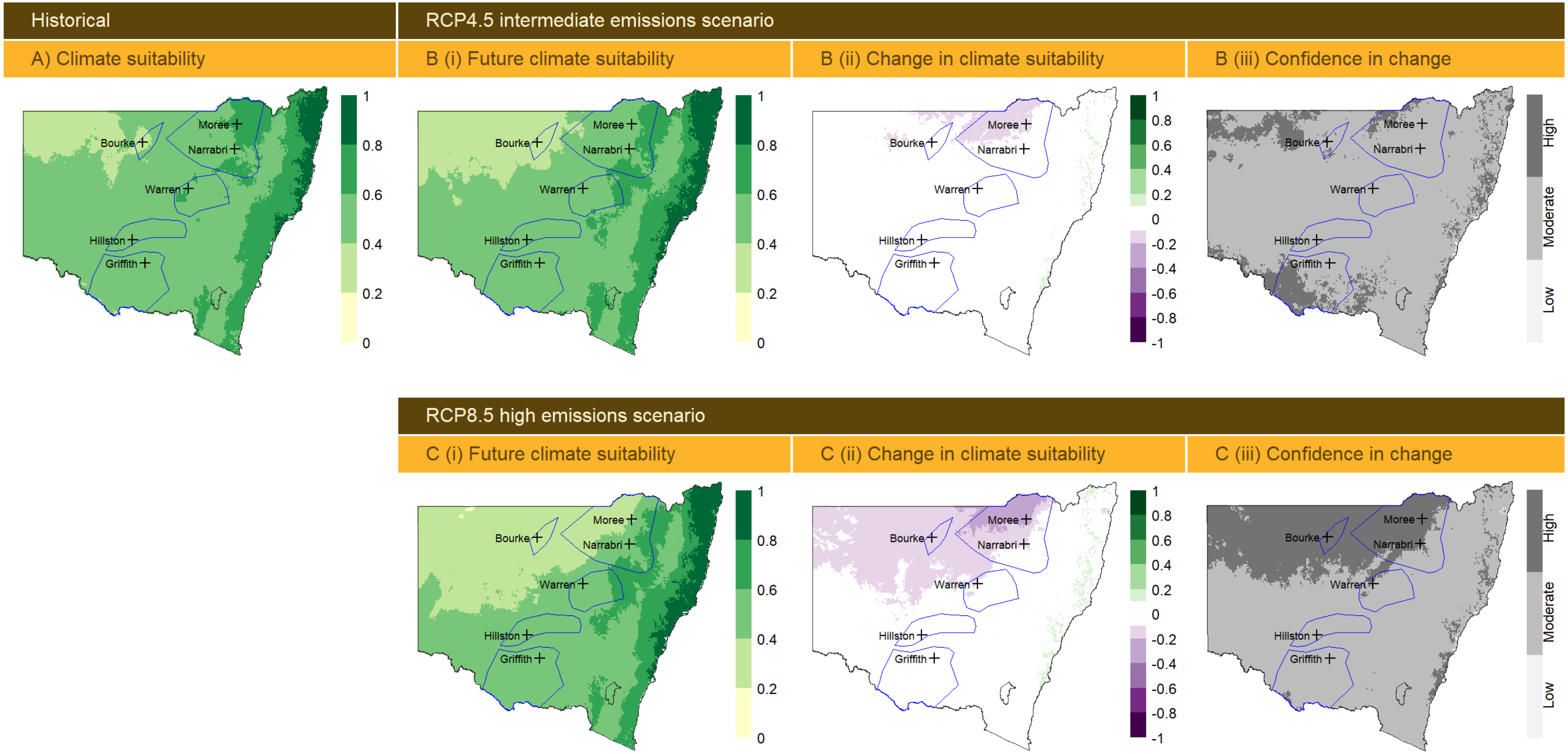


Figure A4. April climate suitability for *Verticillium* non-defoliating pathotype

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

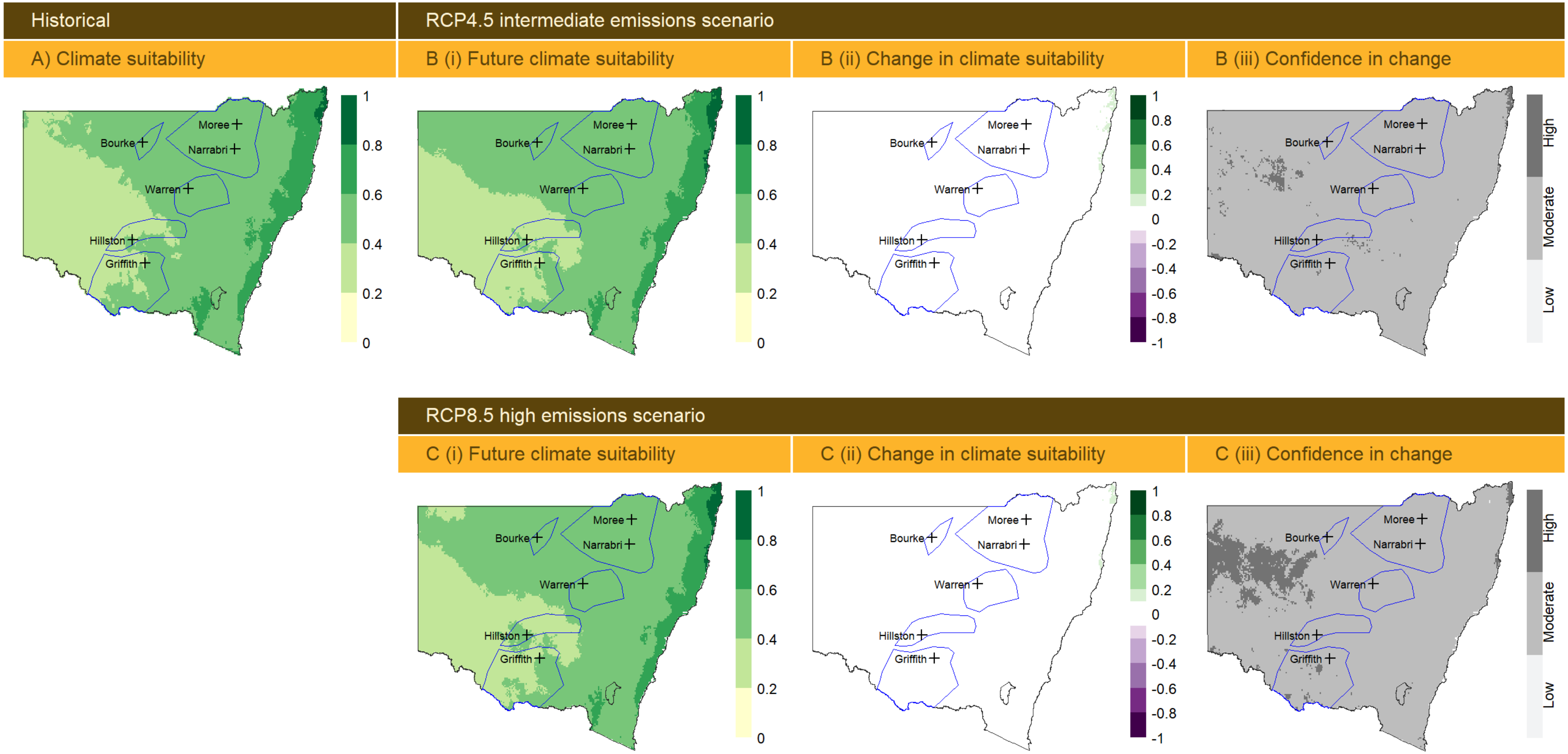


Figure A5. May climate suitability for *Verticillium* non-defoliating pathotype

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

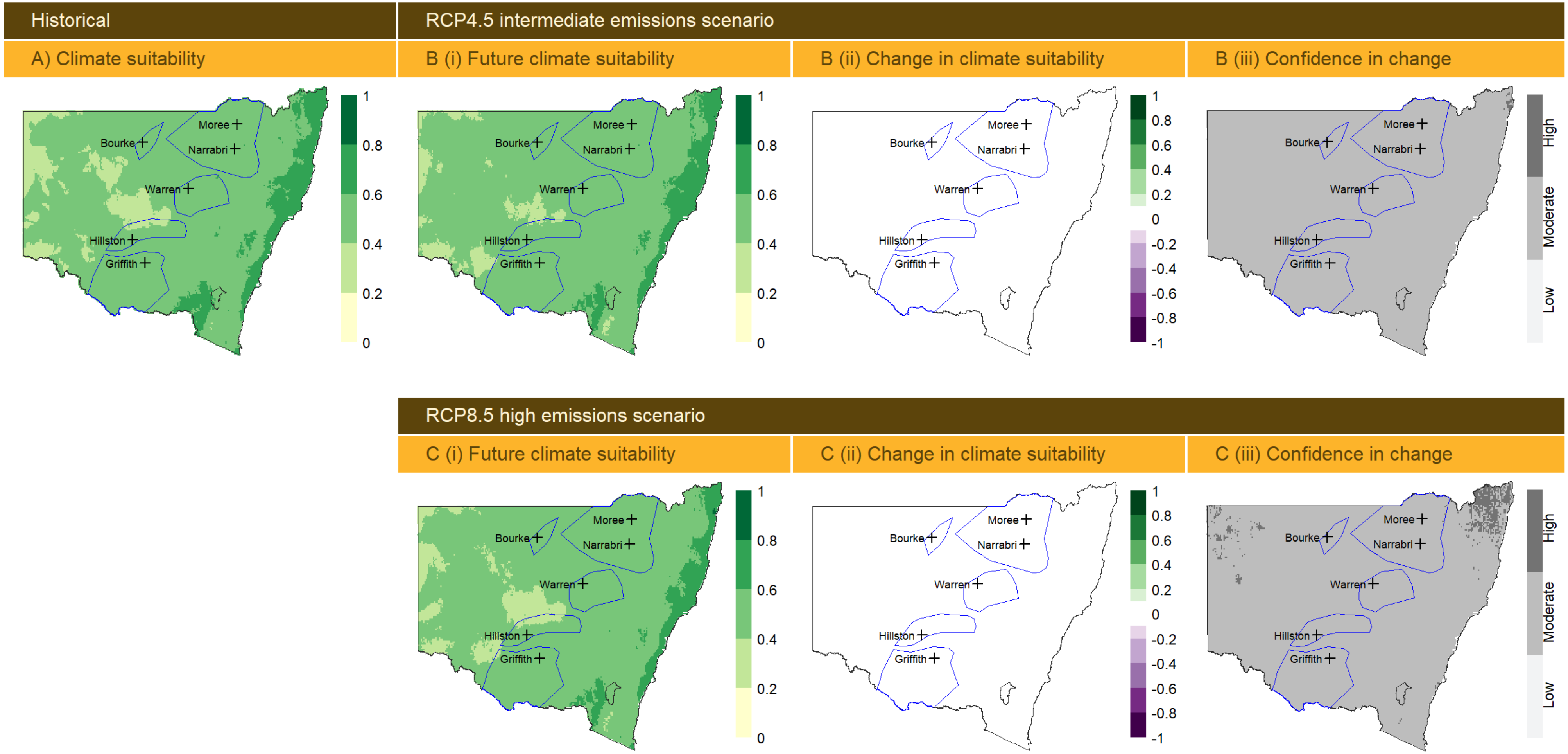


Figure A6. June climate suitability for *Verticillium* non-defoliating pathotype

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

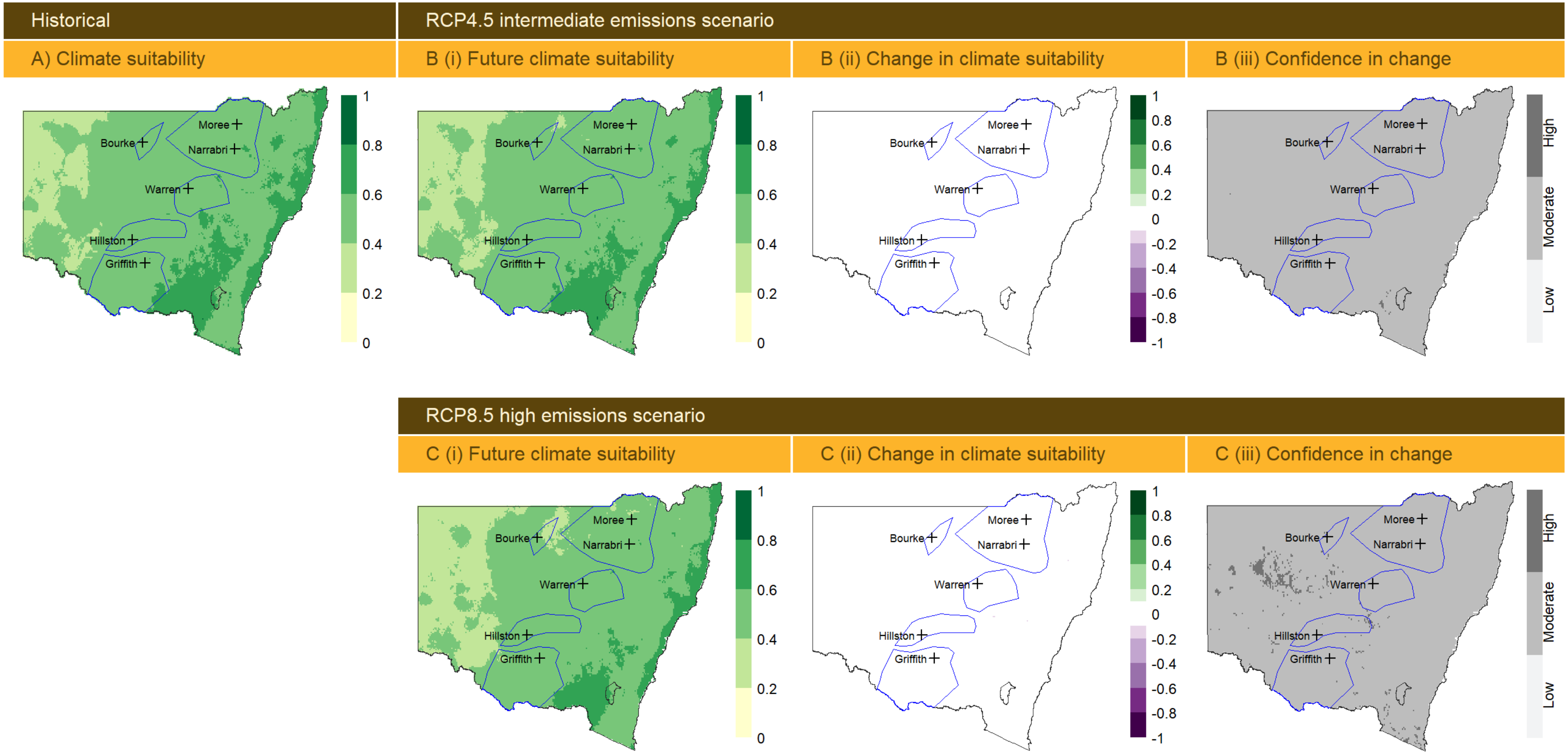


Figure A7. July climate suitability for *Verticillium* non-defoliating pathotype

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

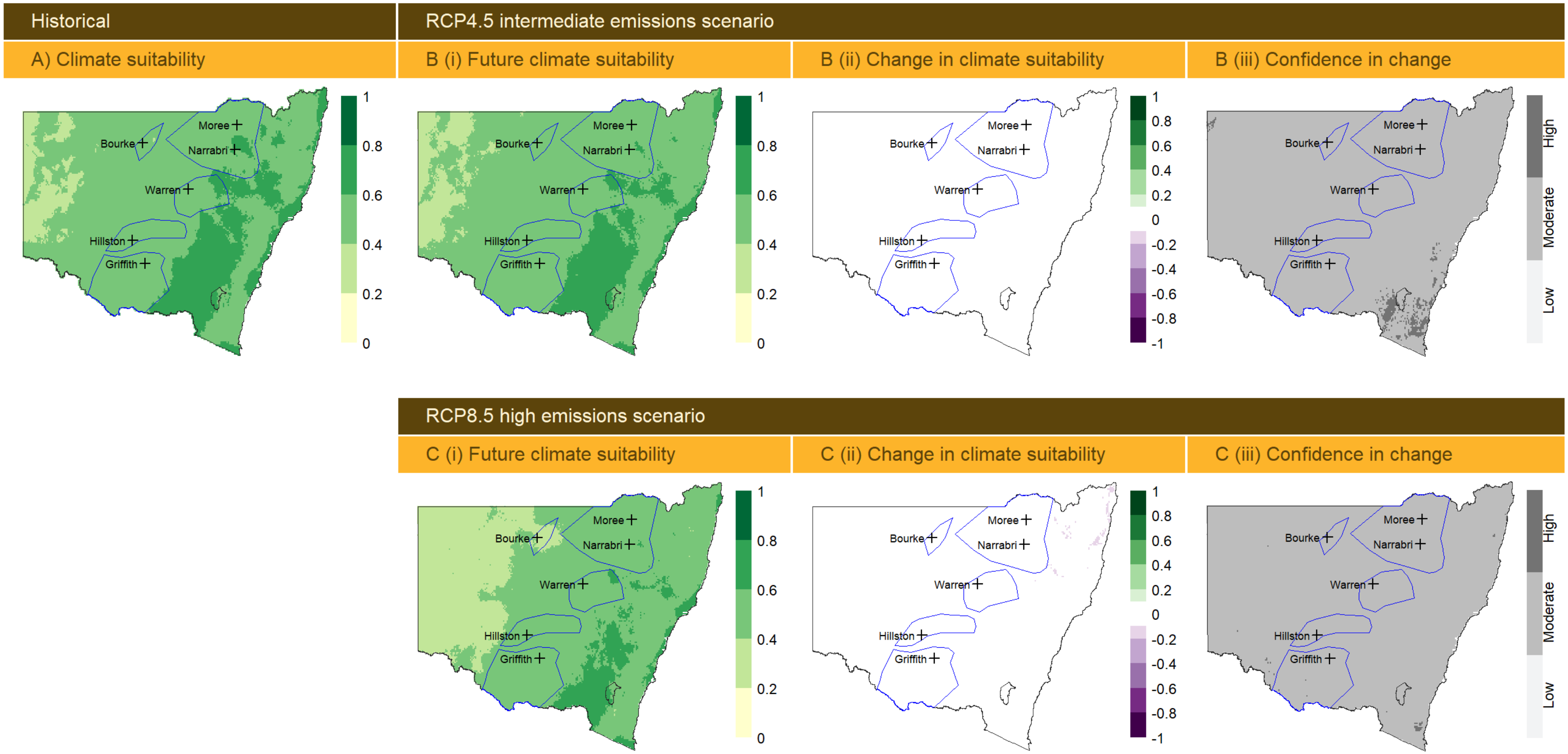


Figure A8. August climate suitability for *Verticillium* non-defoliating pathotype

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

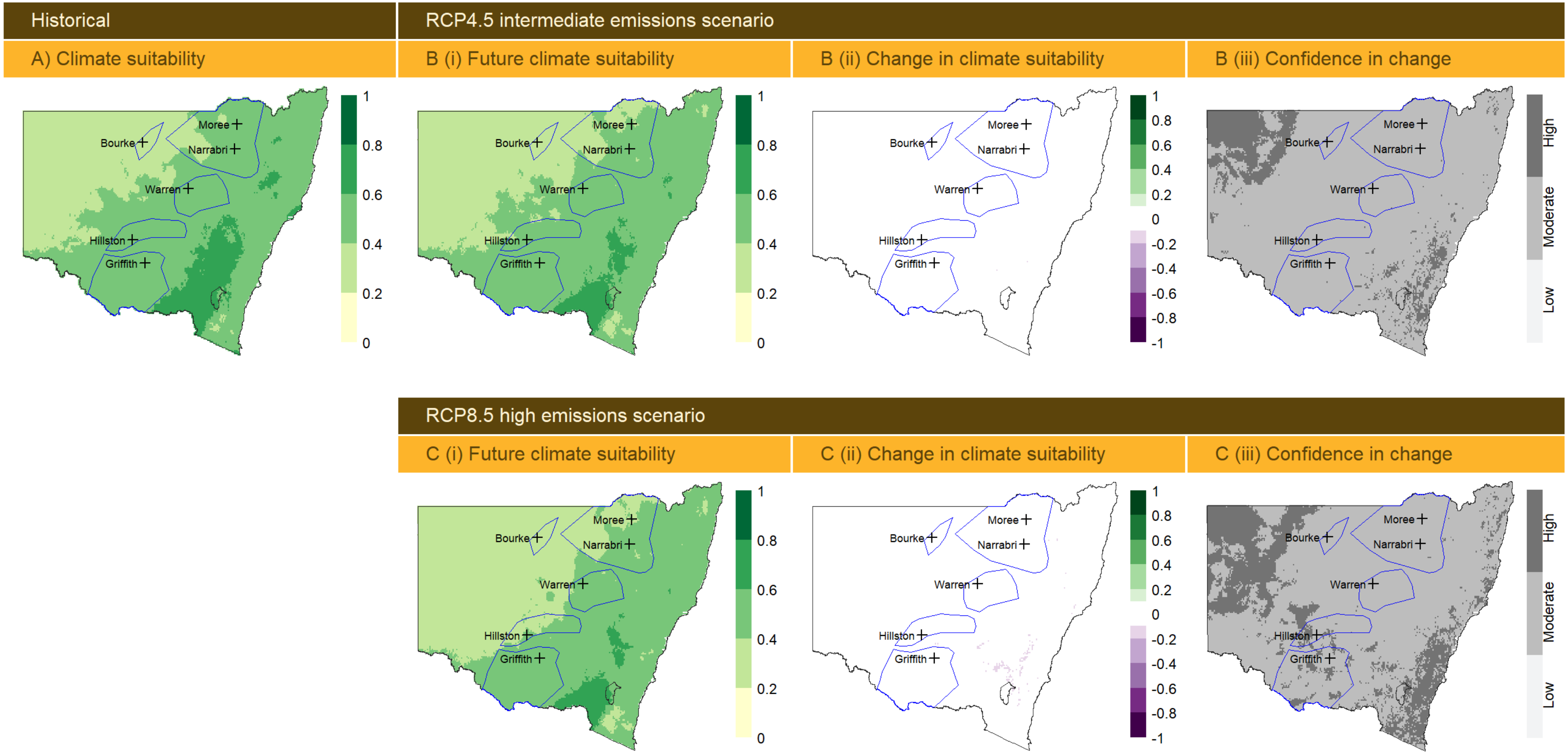


Figure A9. September climate suitability for *Verticillium* non-defoliating pathotype

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

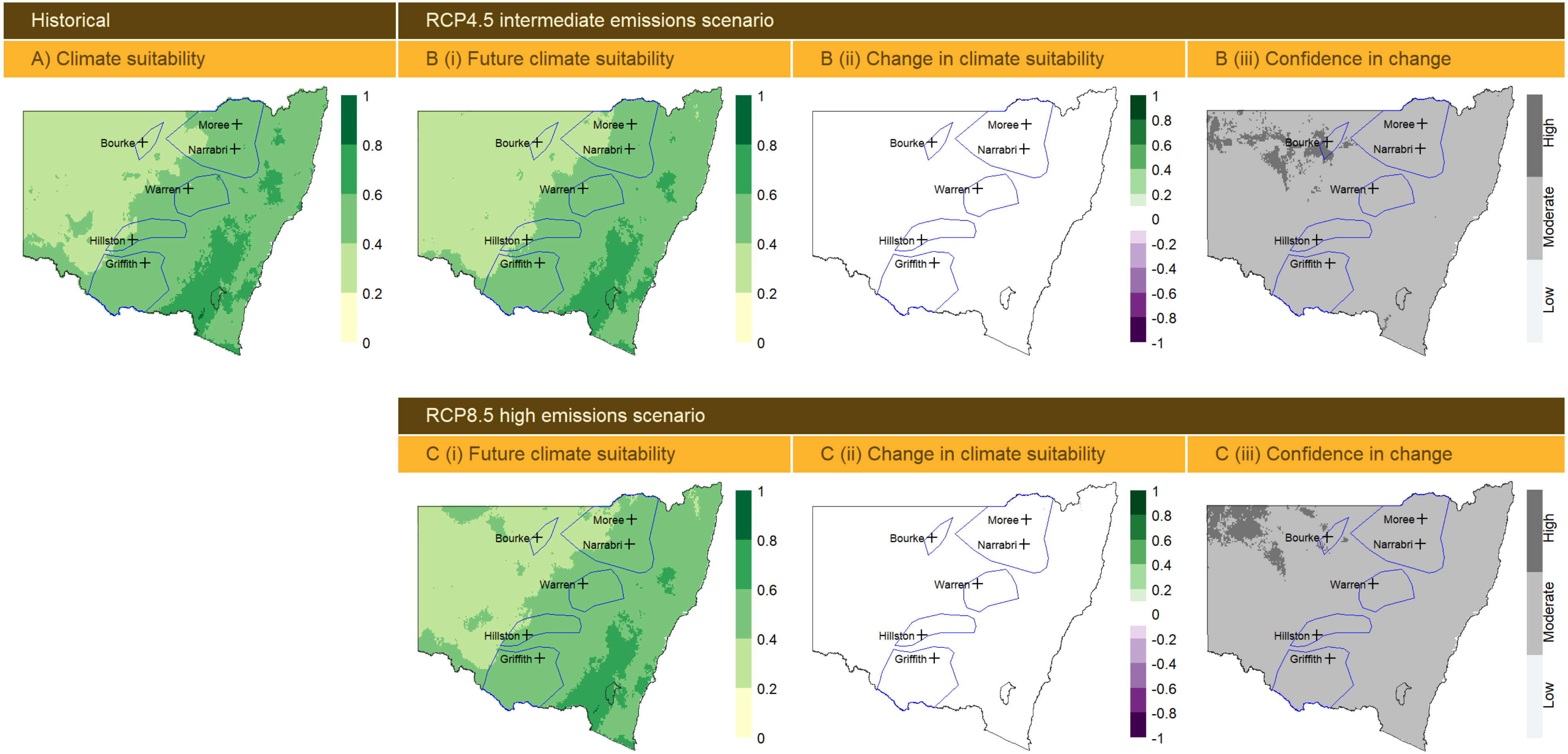


Figure A10. October climate suitability for *Verticillium* non-defoliating pathotype

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

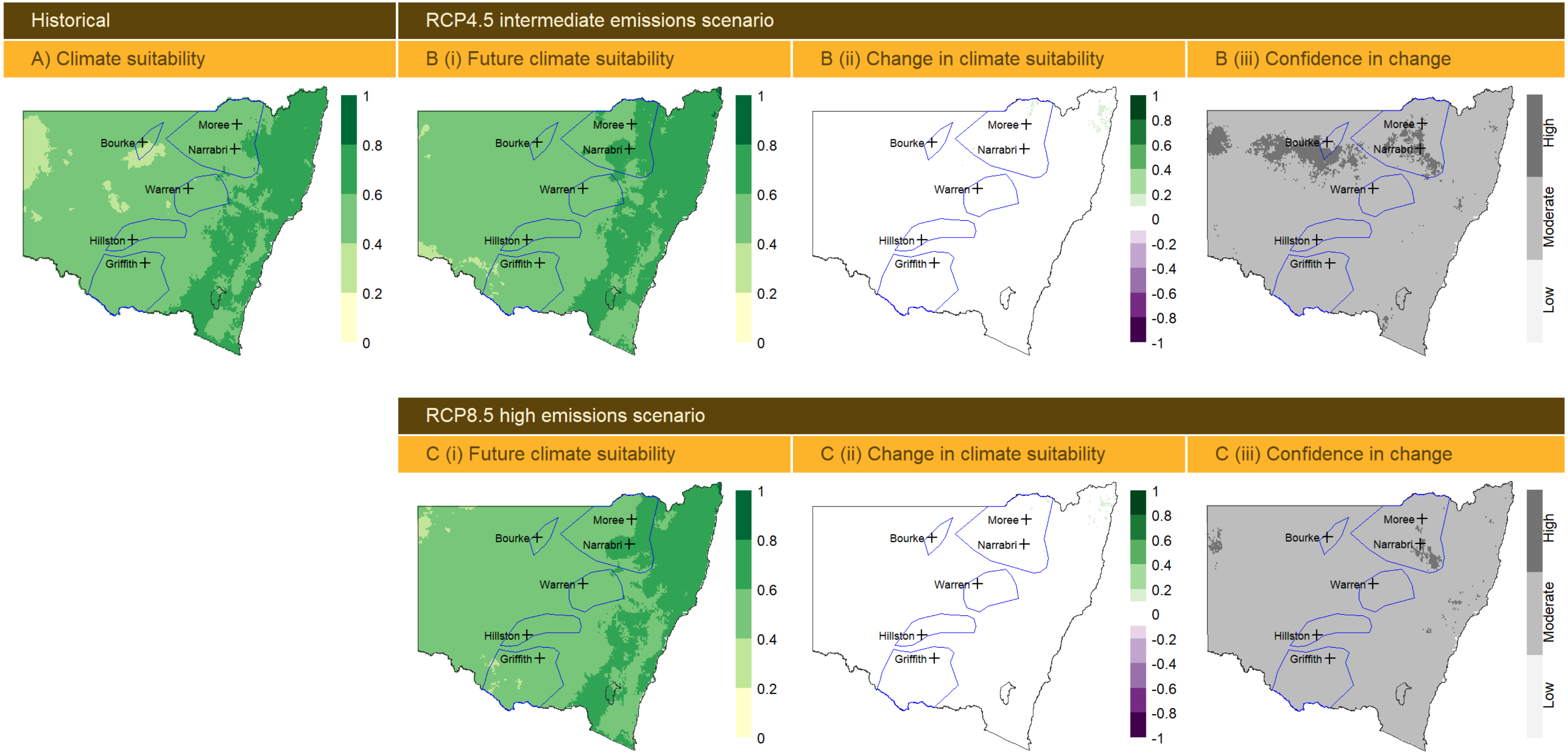


Figure A11. November climate suitability for *Verticillium* non-defoliating pathotype

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

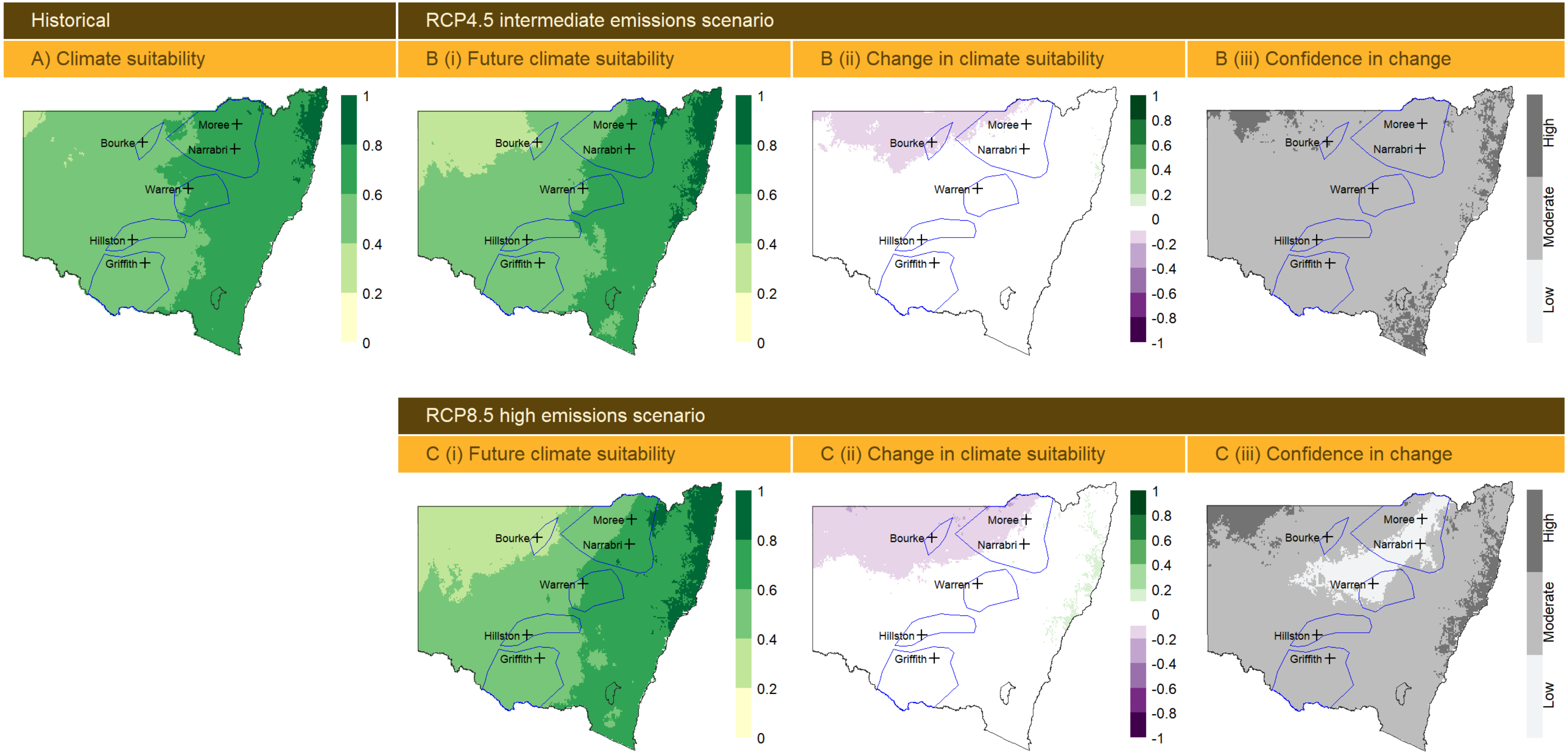


Figure A12. December climate suitability for *Verticillium* non-defoliating pathotype

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

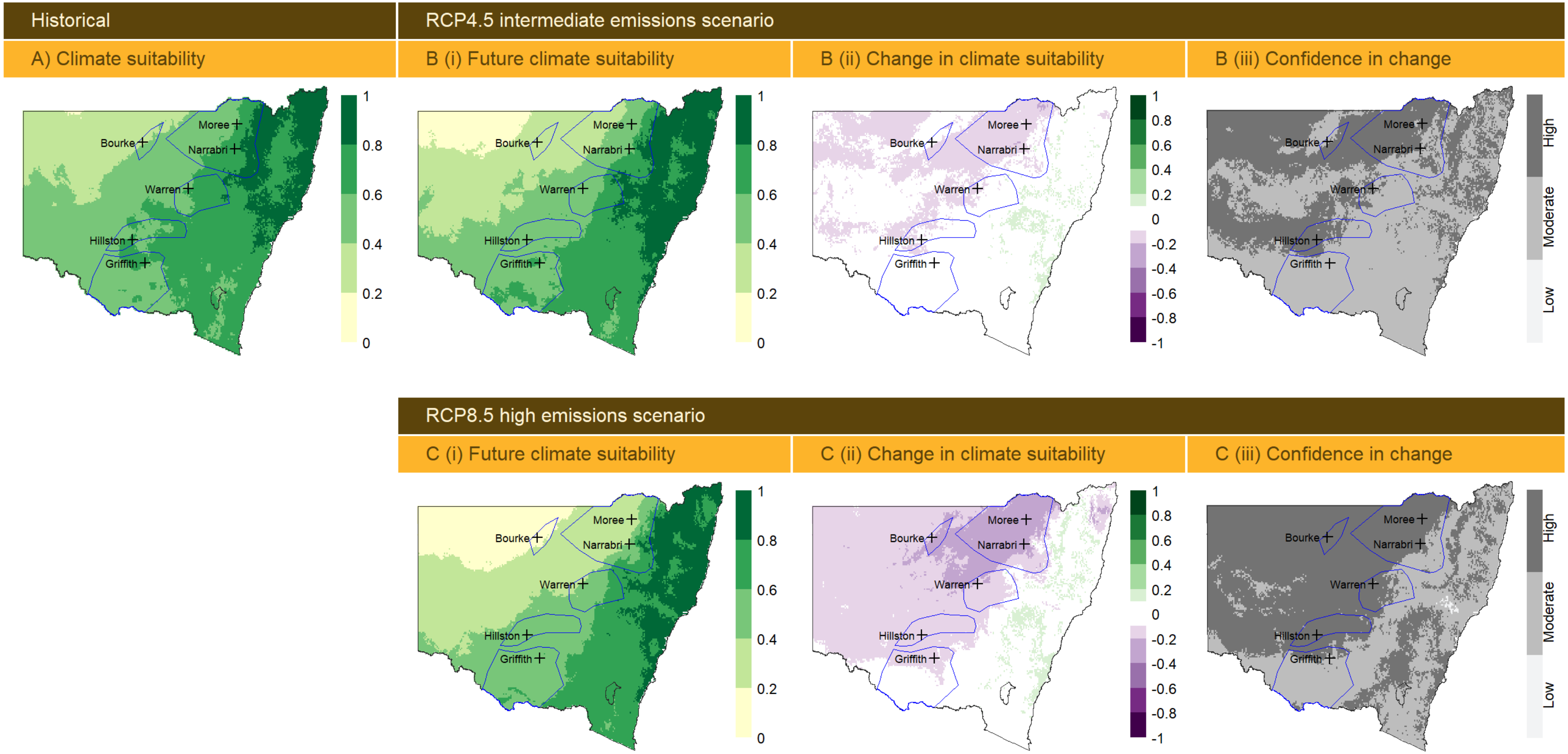


Figure A13. January climate suitability for *Verticillium* defoliating pathotype

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

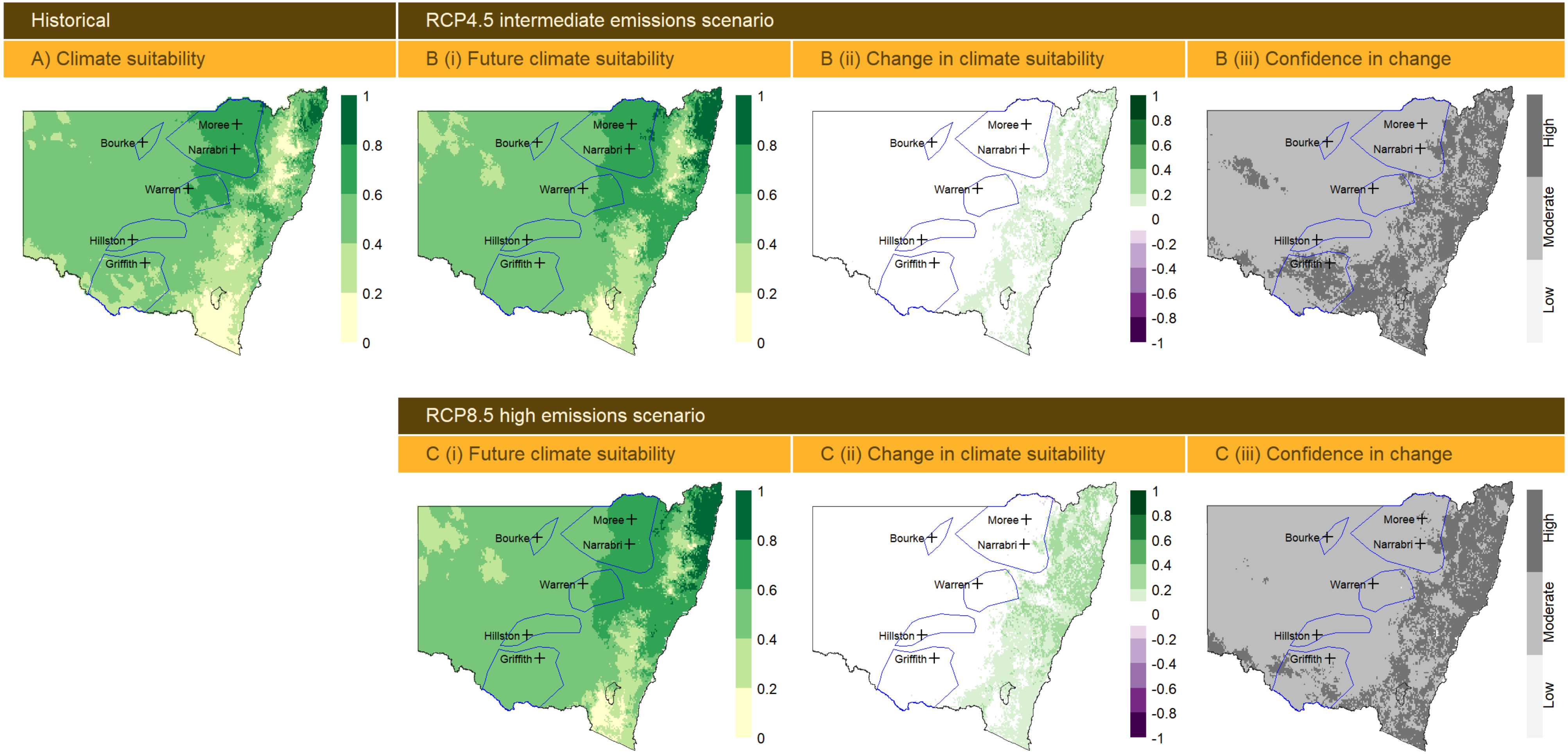


Figure A14. February climate suitability for *Verticillium* defoliating pathotype

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

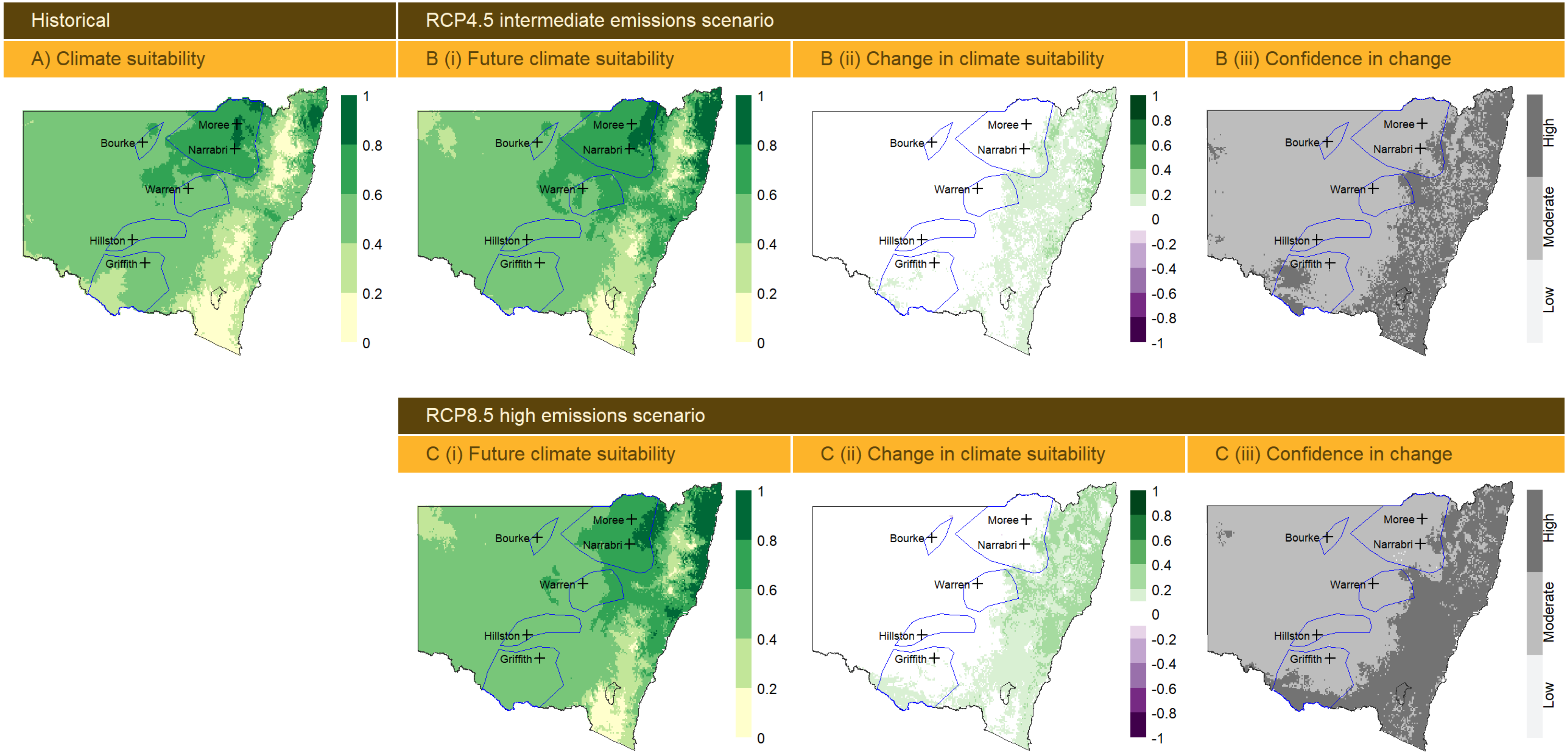


Figure A15. March climate suitability for *Verticillium* defoliating pathotype

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

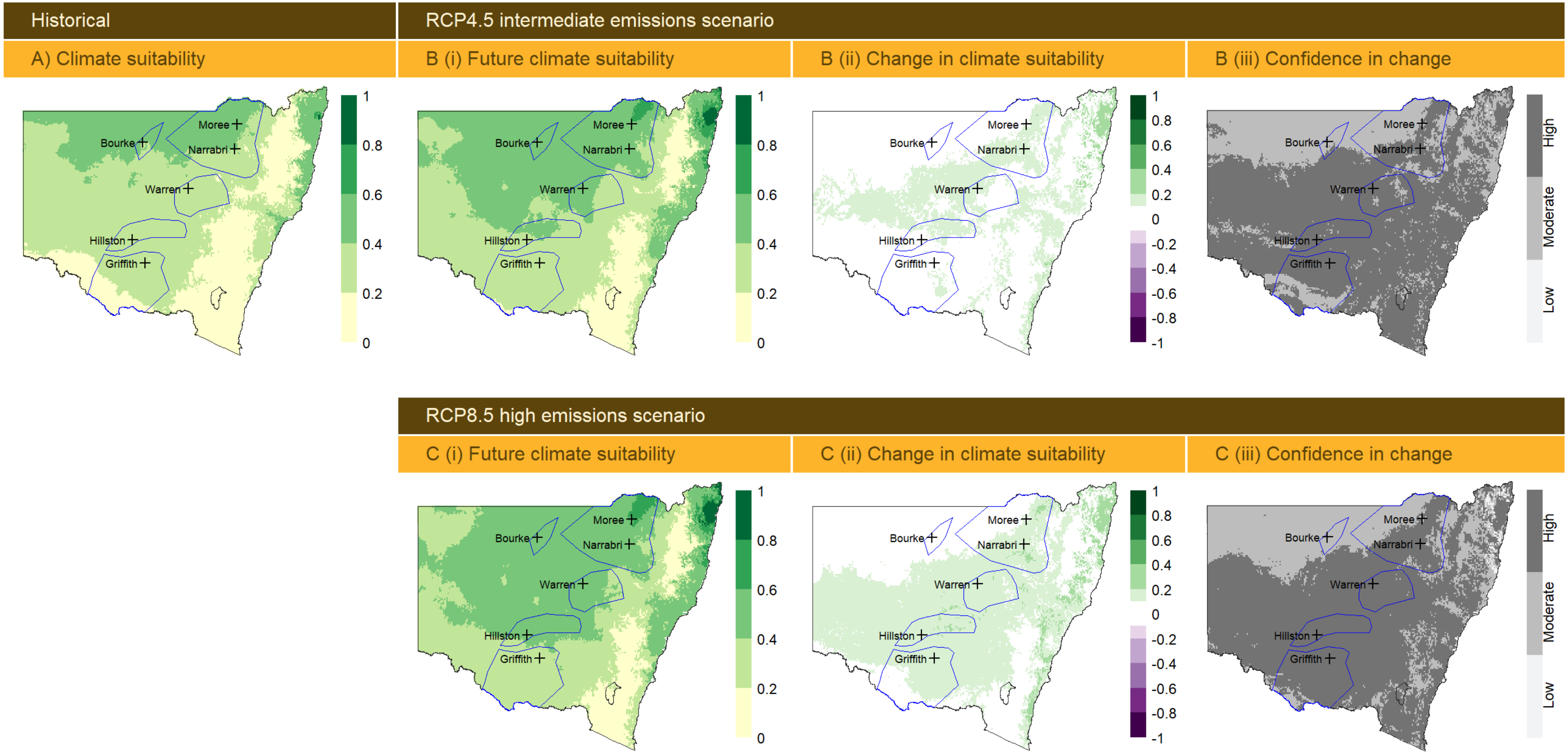


Figure A16. April climate suitability for *Verticillium* defoliating pathotype

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

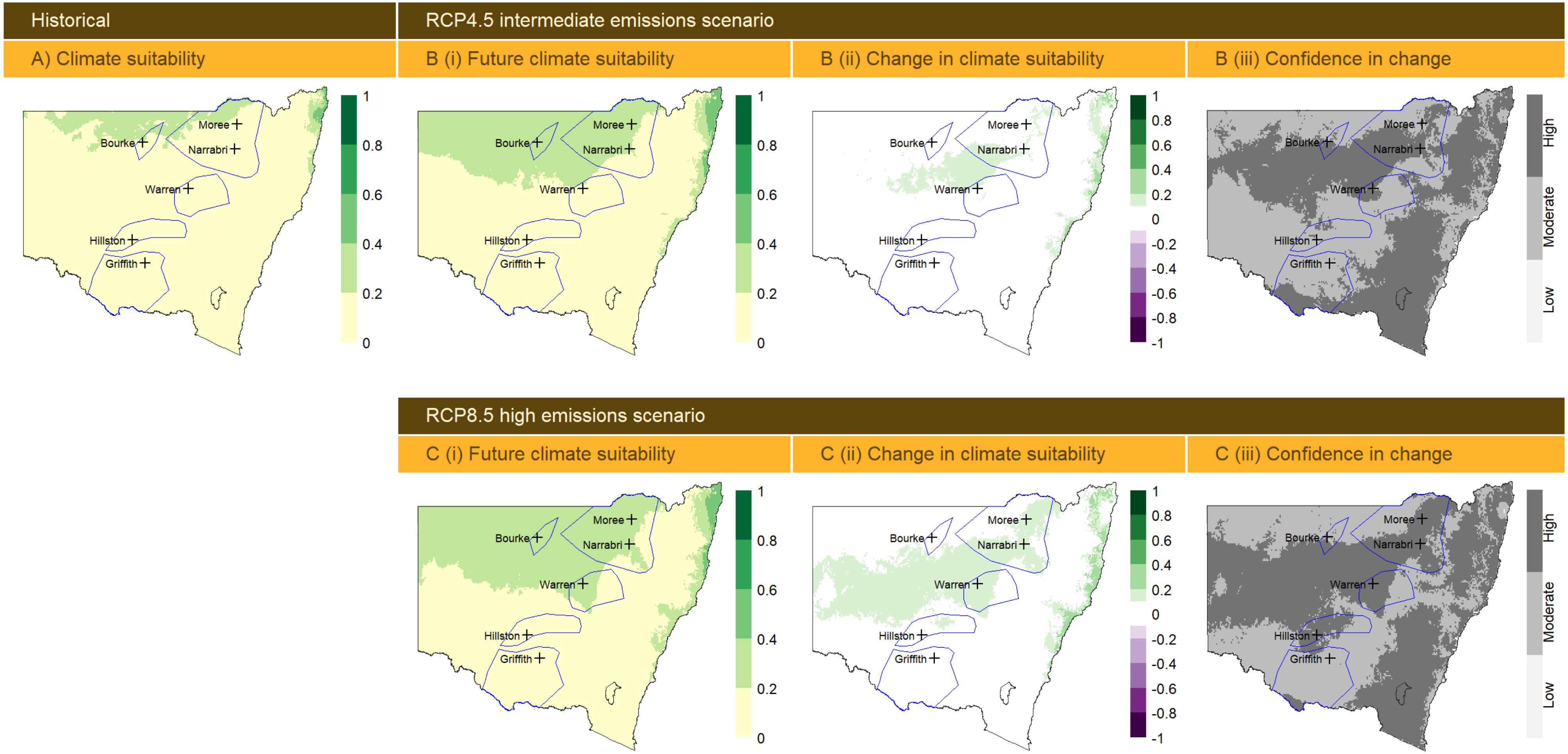


Figure A17. May climate suitability for *Verticillium* defoliating pathotype

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

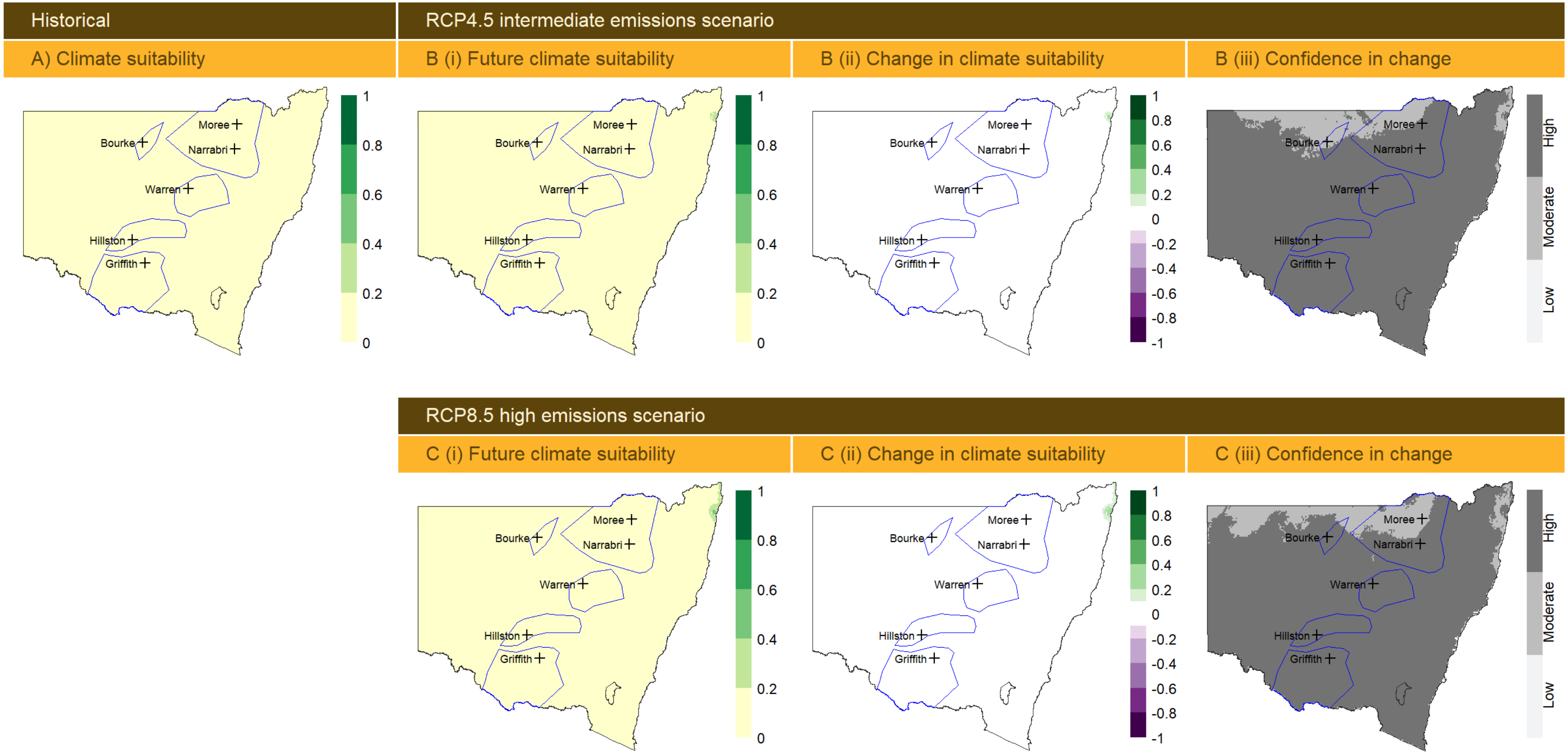


Figure A18. June climate suitability for *Verticillium* defoliating pathotype

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

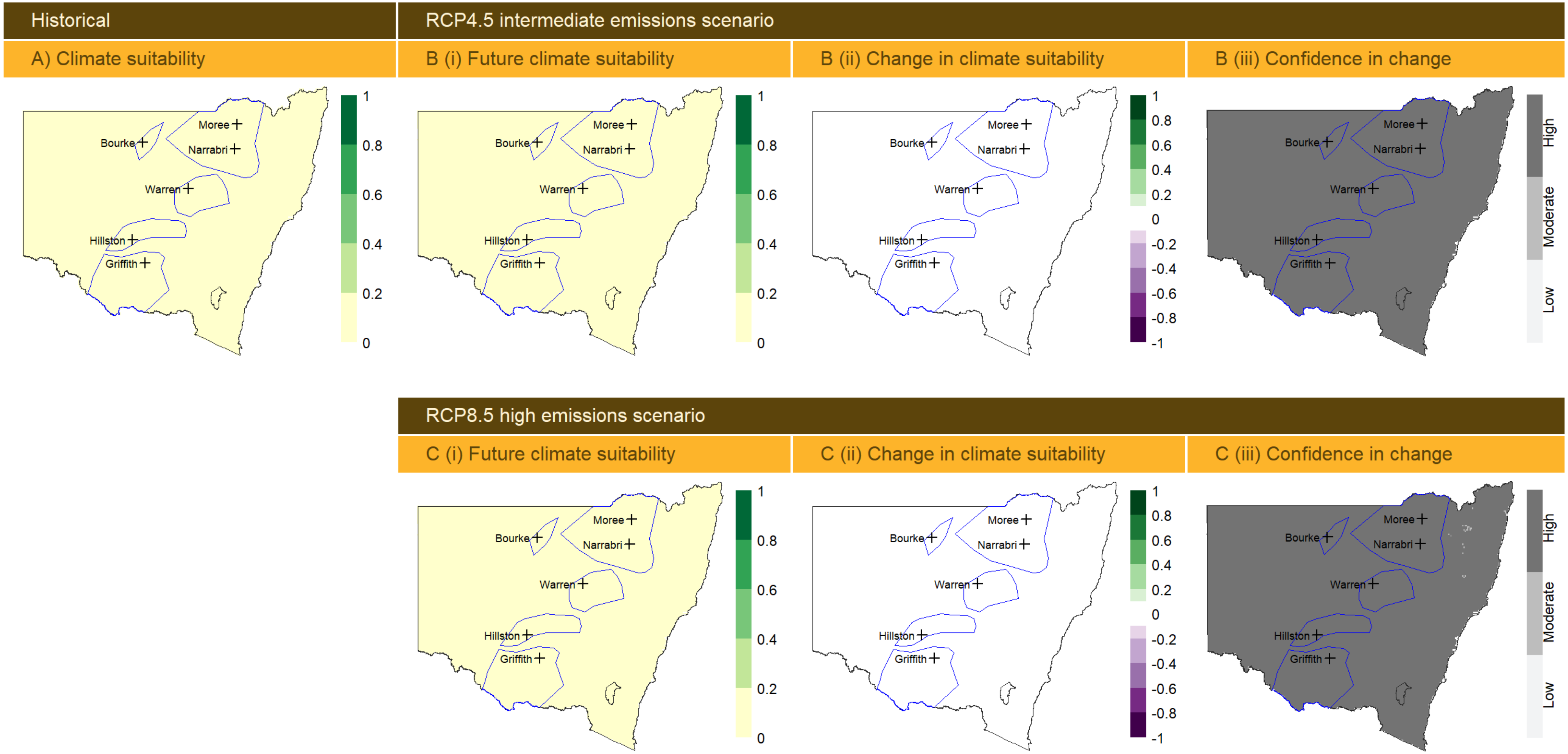


Figure A19. July climate suitability for *Verticillium* defoliating pathotype

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

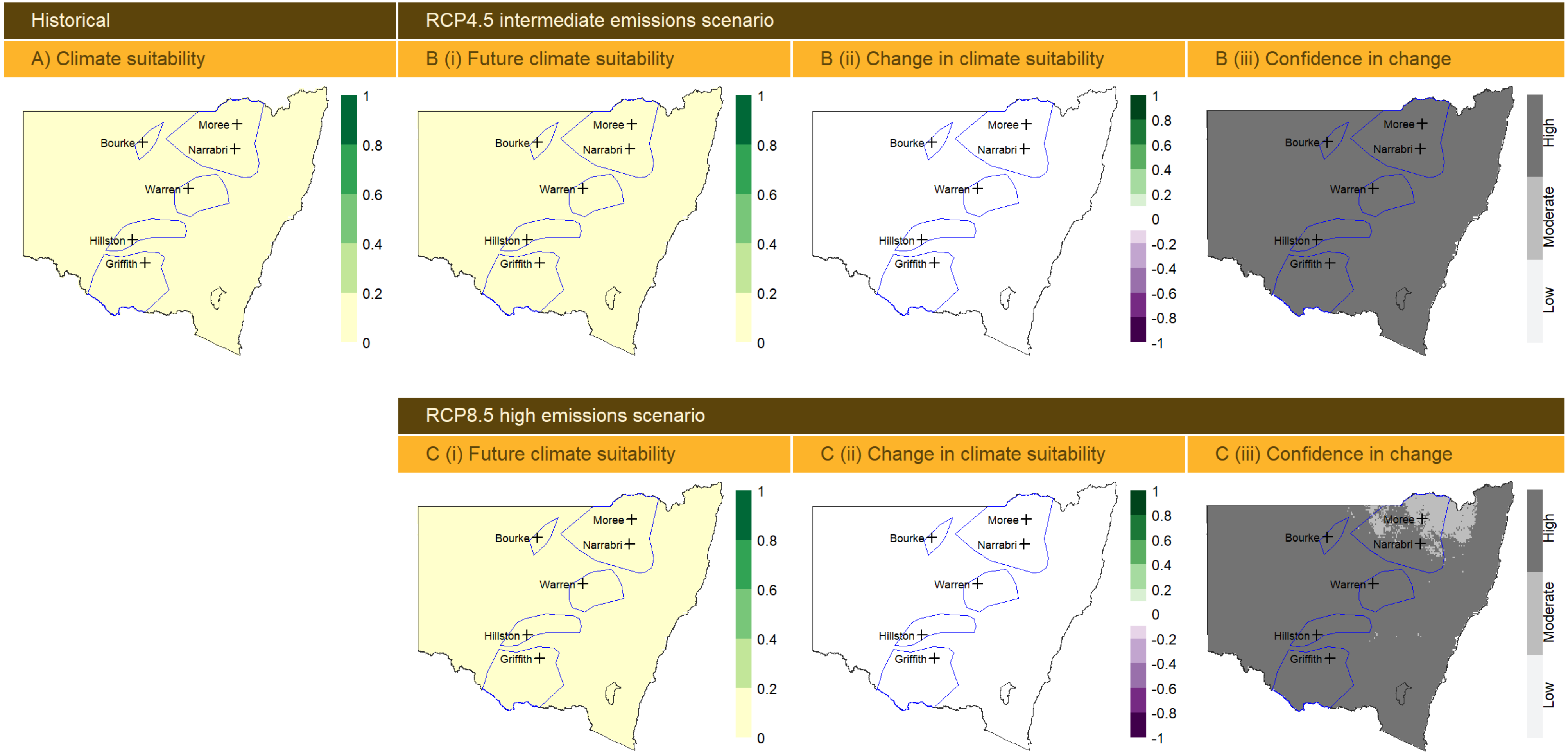


Figure A20. August climate suitability for *Verticillium* defoliating pathotype

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

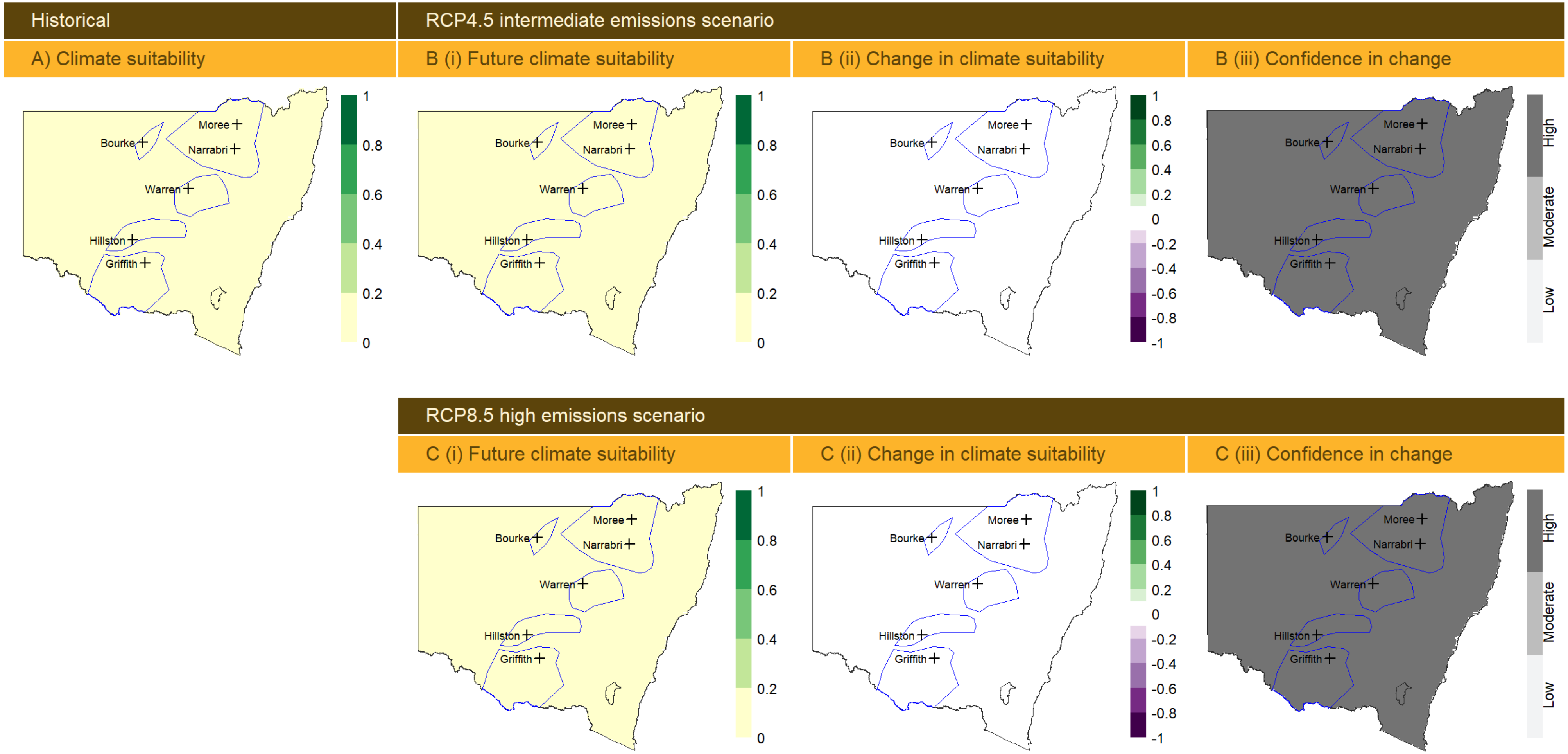


Figure A21. September climate suitability for *Verticillium* defoliating pathotype

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

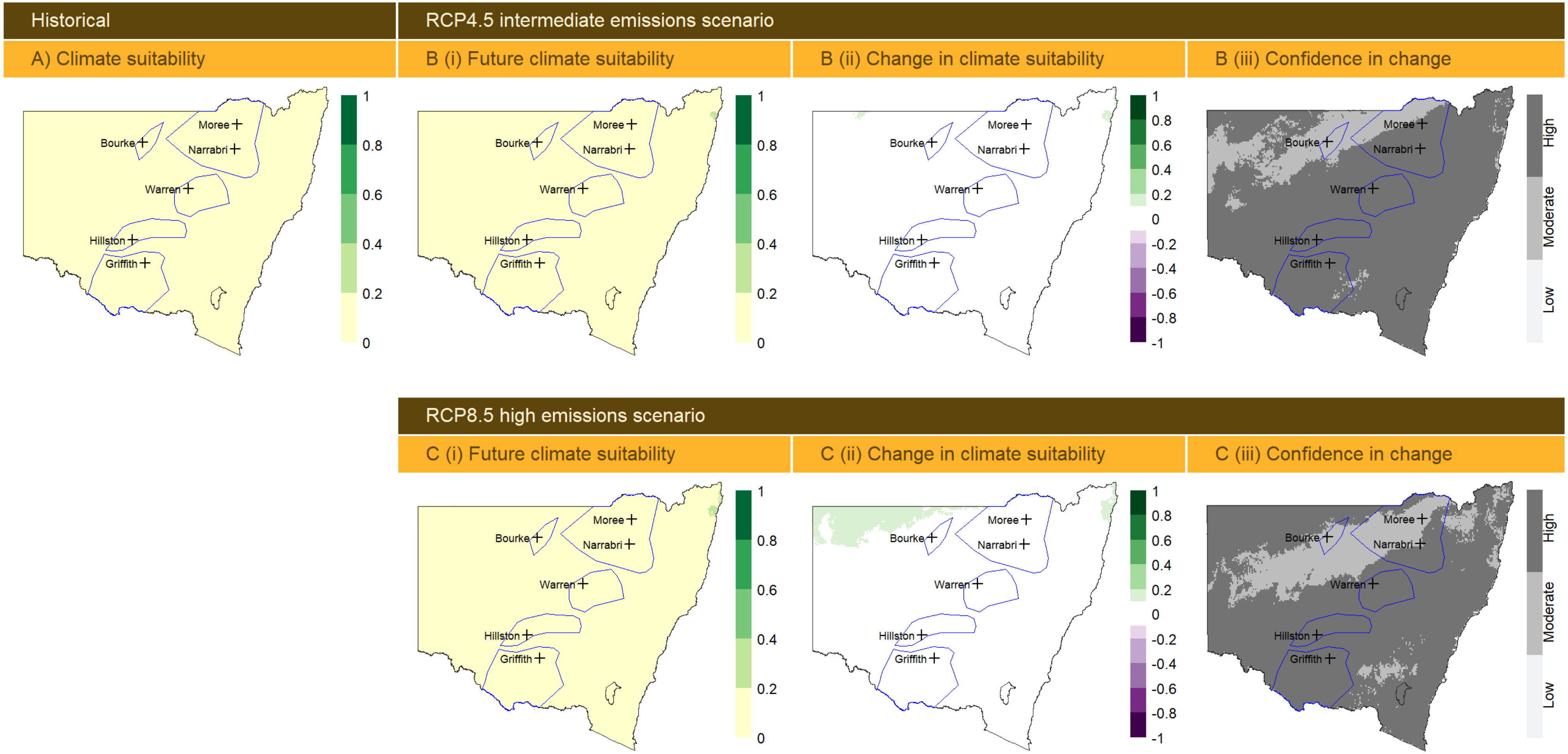


Figure A22. October climate suitability for *Verticillium* defoliating pathotype

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

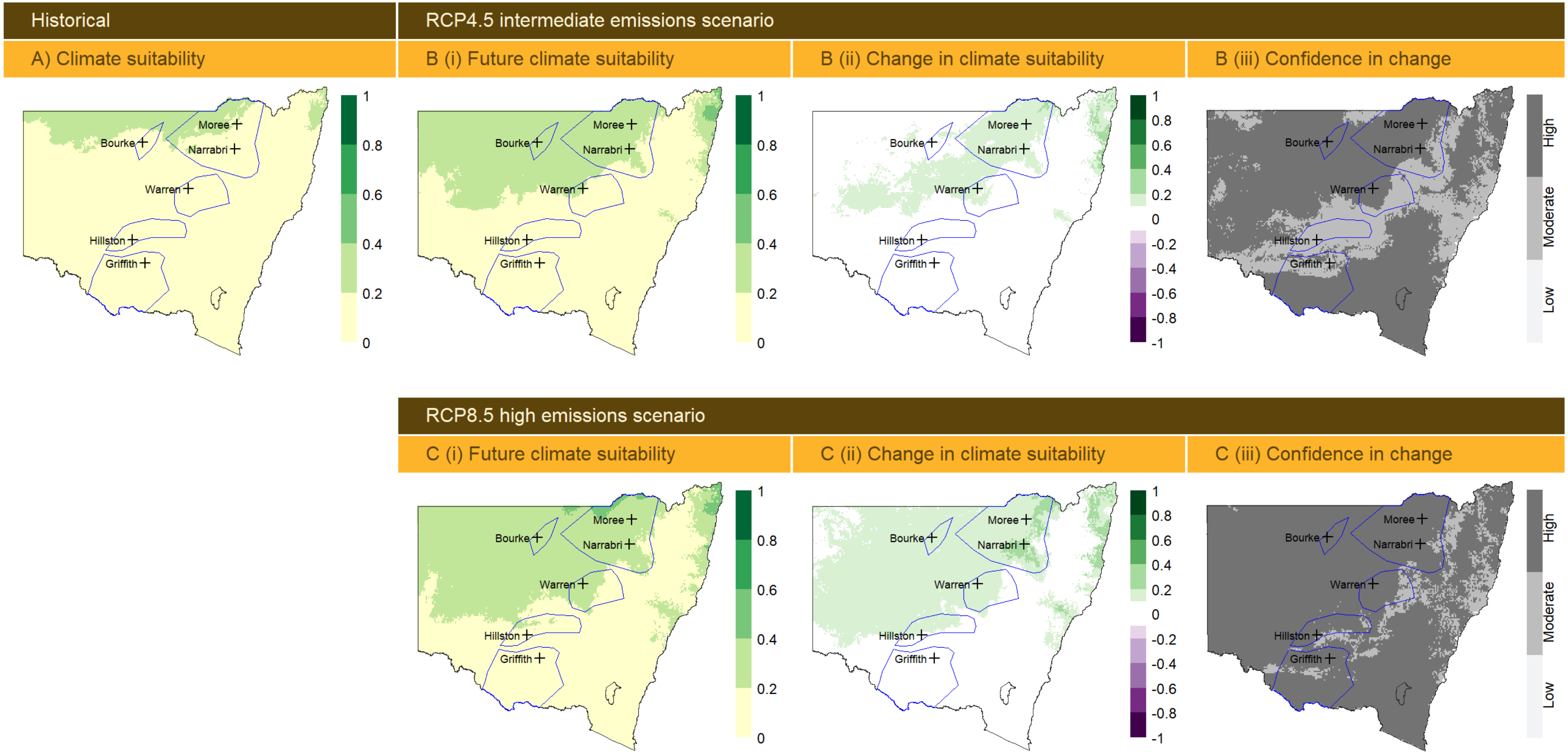


Figure A23. November climate suitability for *Verticillium* defoliating pathotype

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

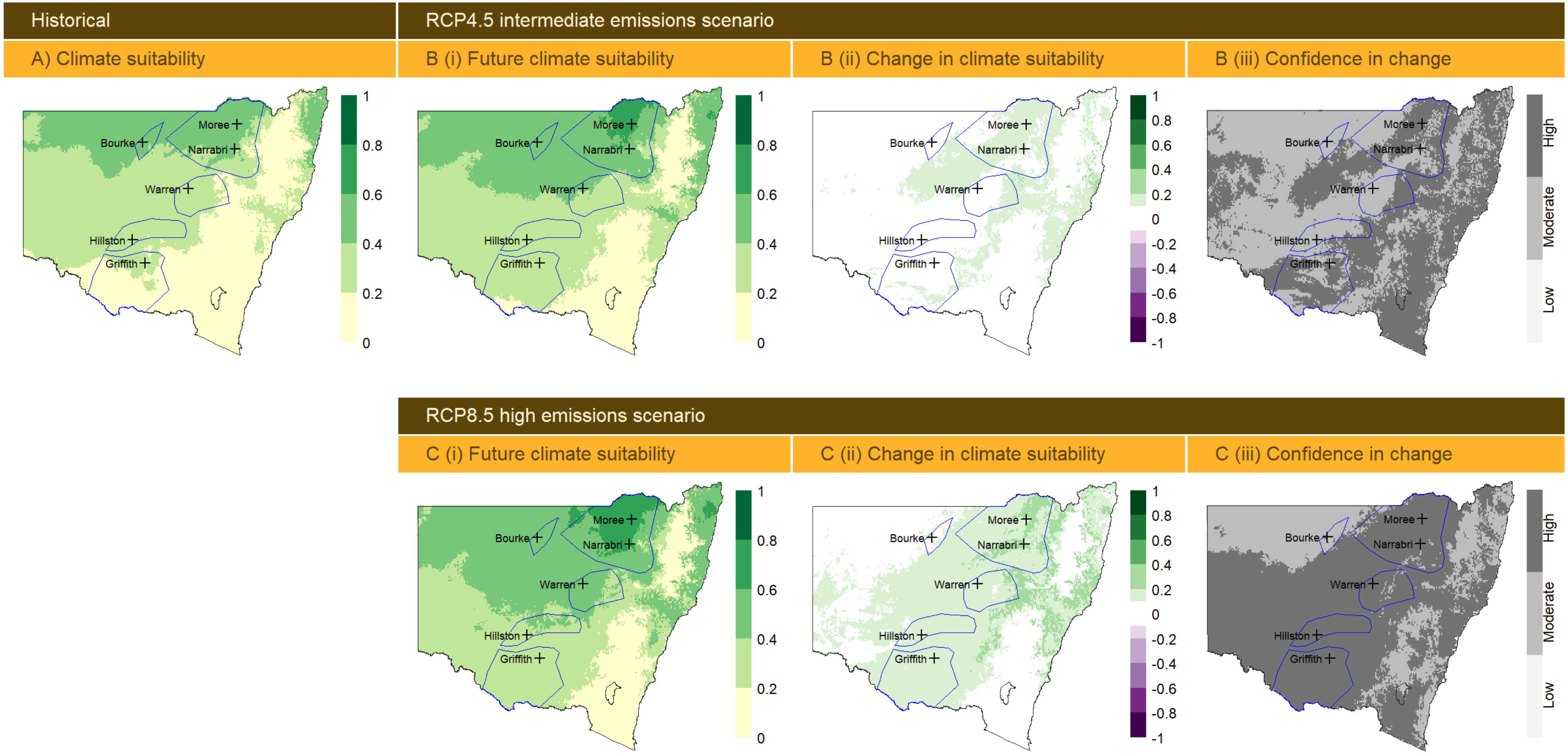


Figure A24. December climate suitability for *Verticillium* defoliating pathotype

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

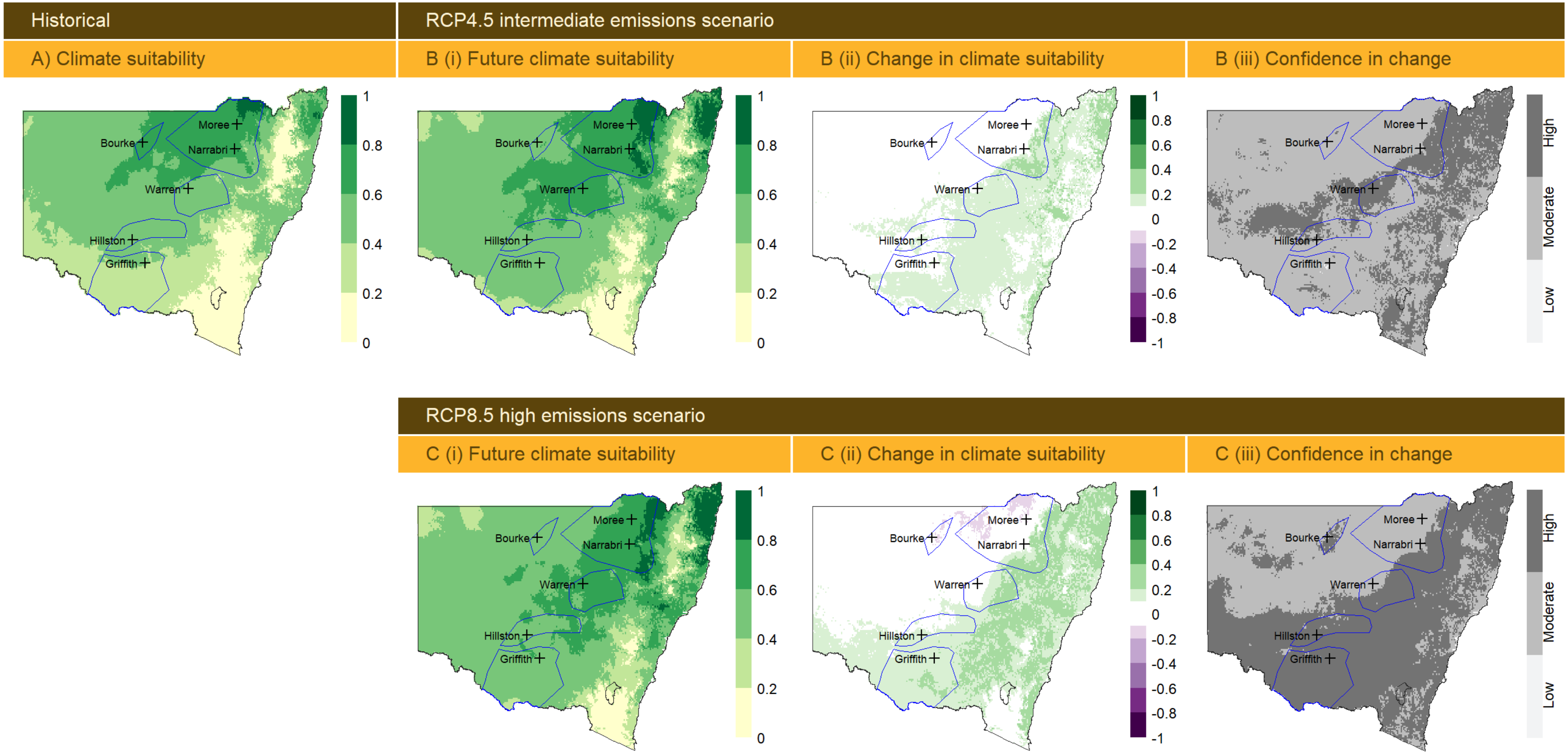


Figure A25. January climate suitability for *Verticillium* dormant phenophase

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

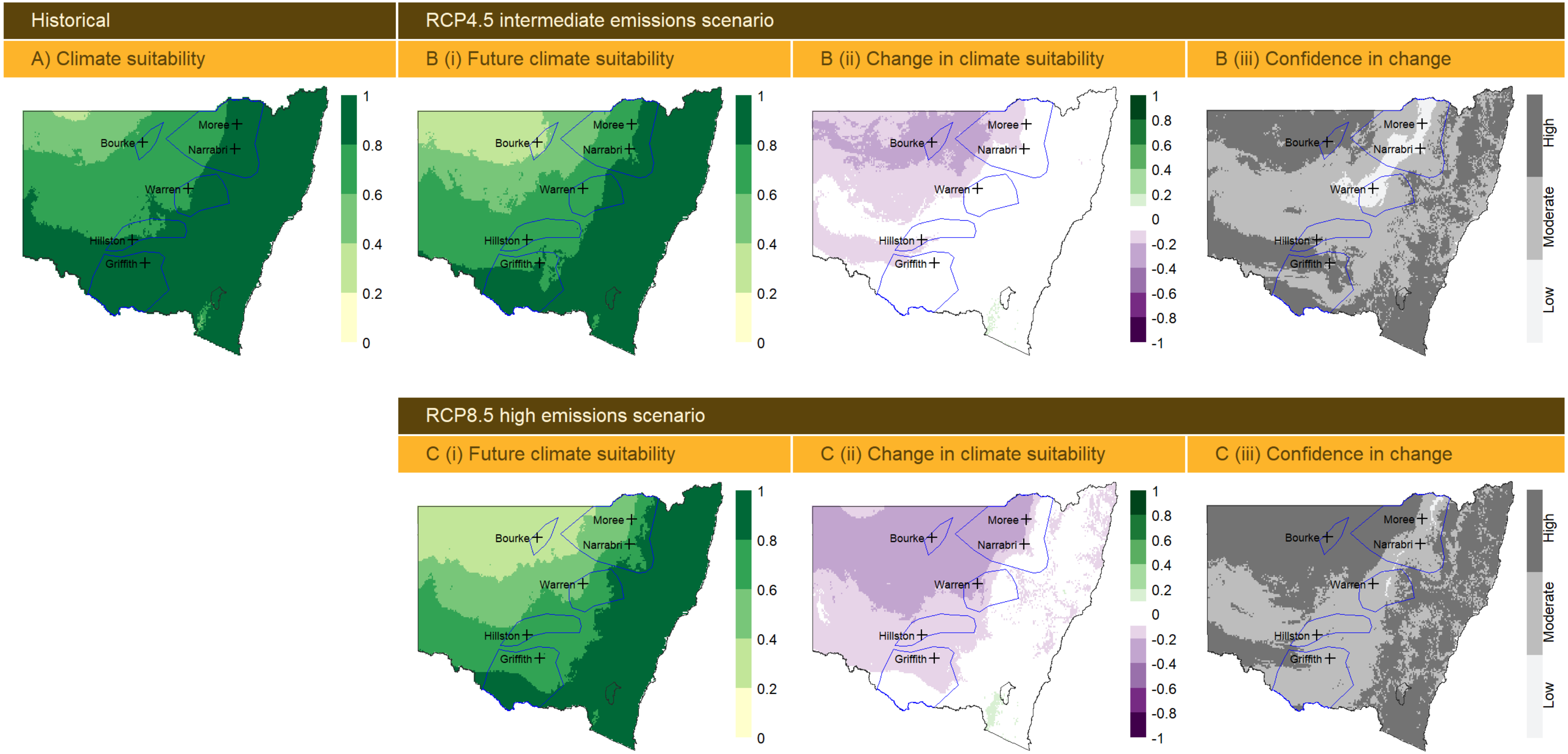


Figure A26. February climate suitability for *Verticillium* dormant phenophase

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

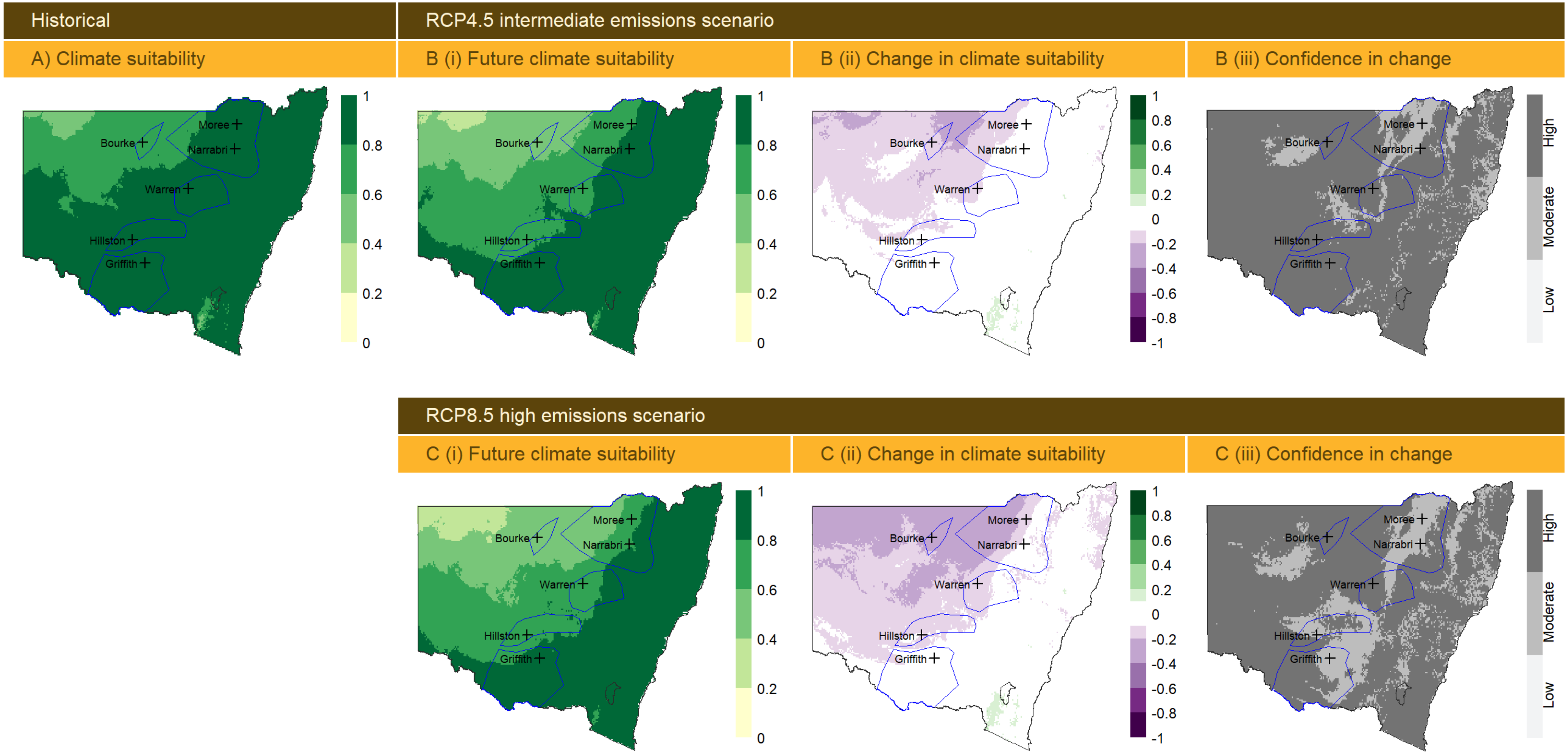


Figure A27. March climate suitability for *Verticillium* dormant phenophase

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

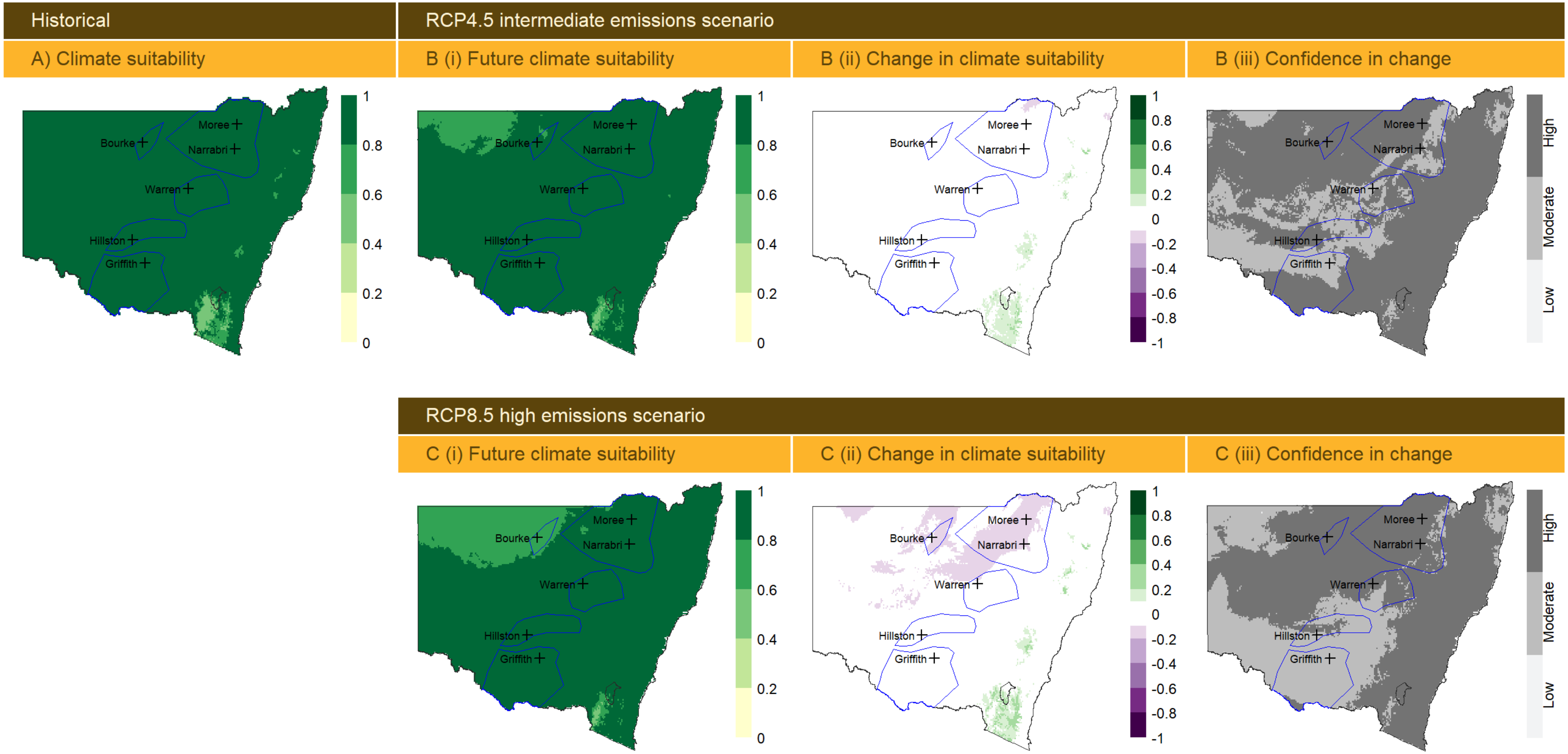


Figure A28. April climate suitability for *Verticillium* dormant phenophase

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

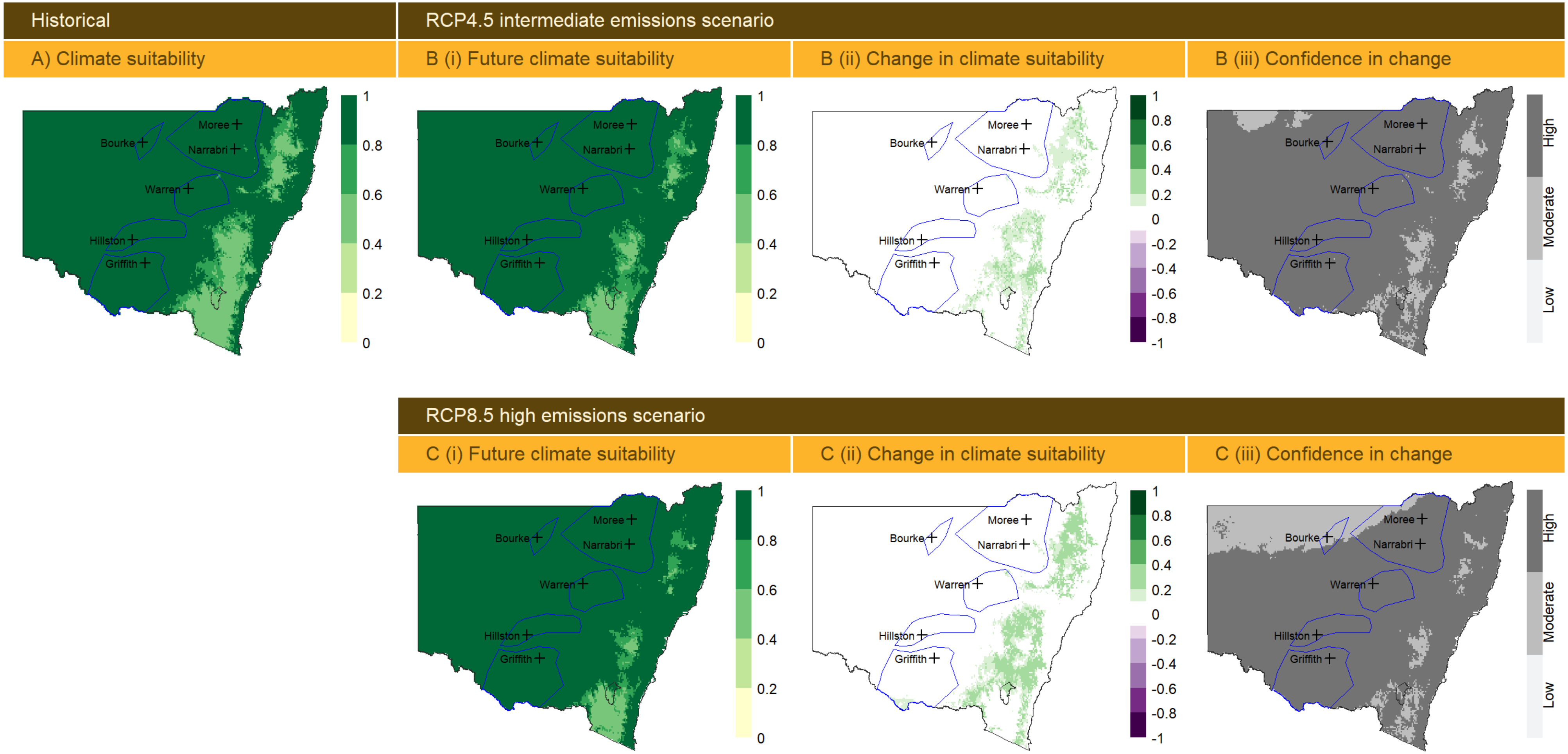


Figure A29. May climate suitability for *Verticillium* dormant phenophase

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

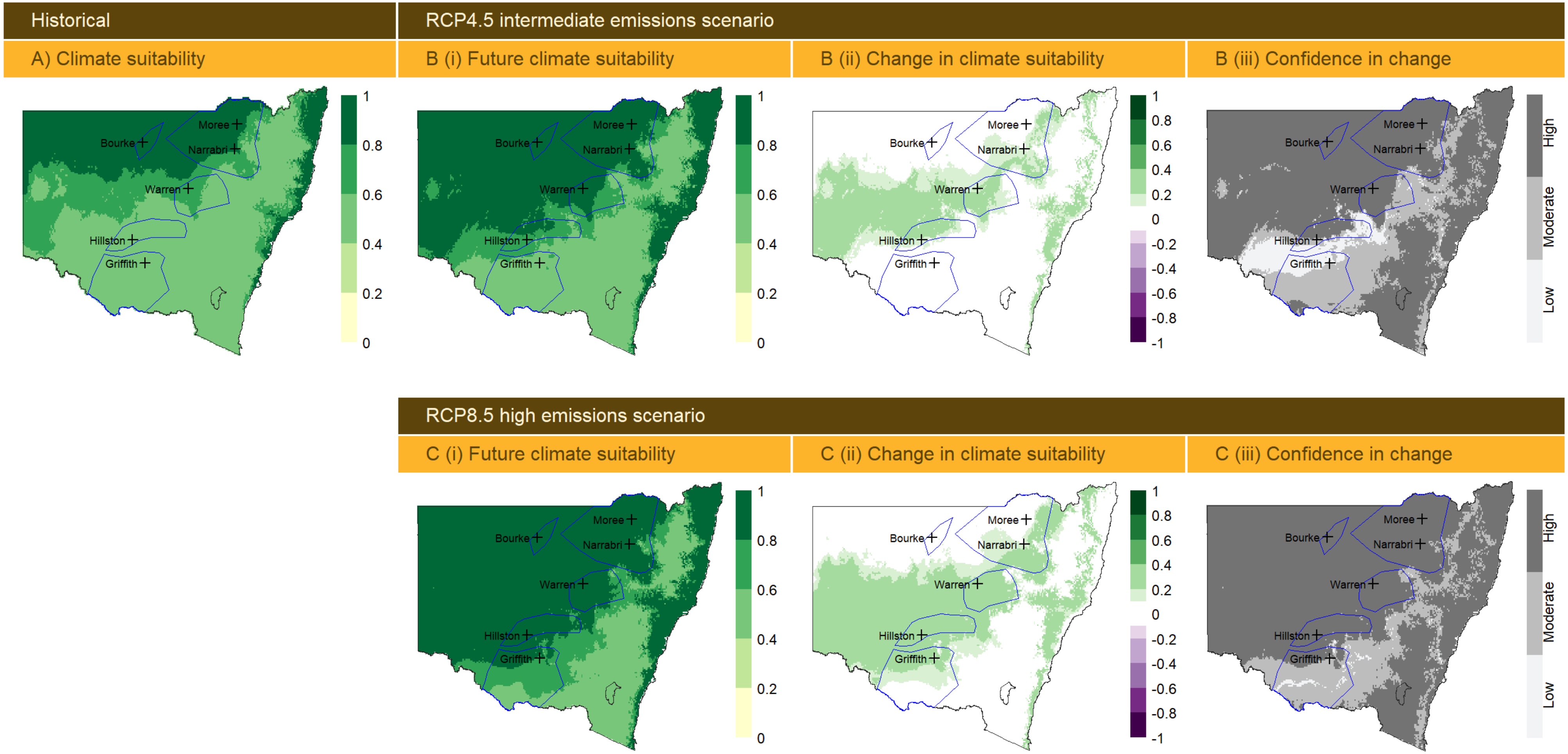


Figure A30. June climate suitability for *Verticillium* dormant phenophase

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

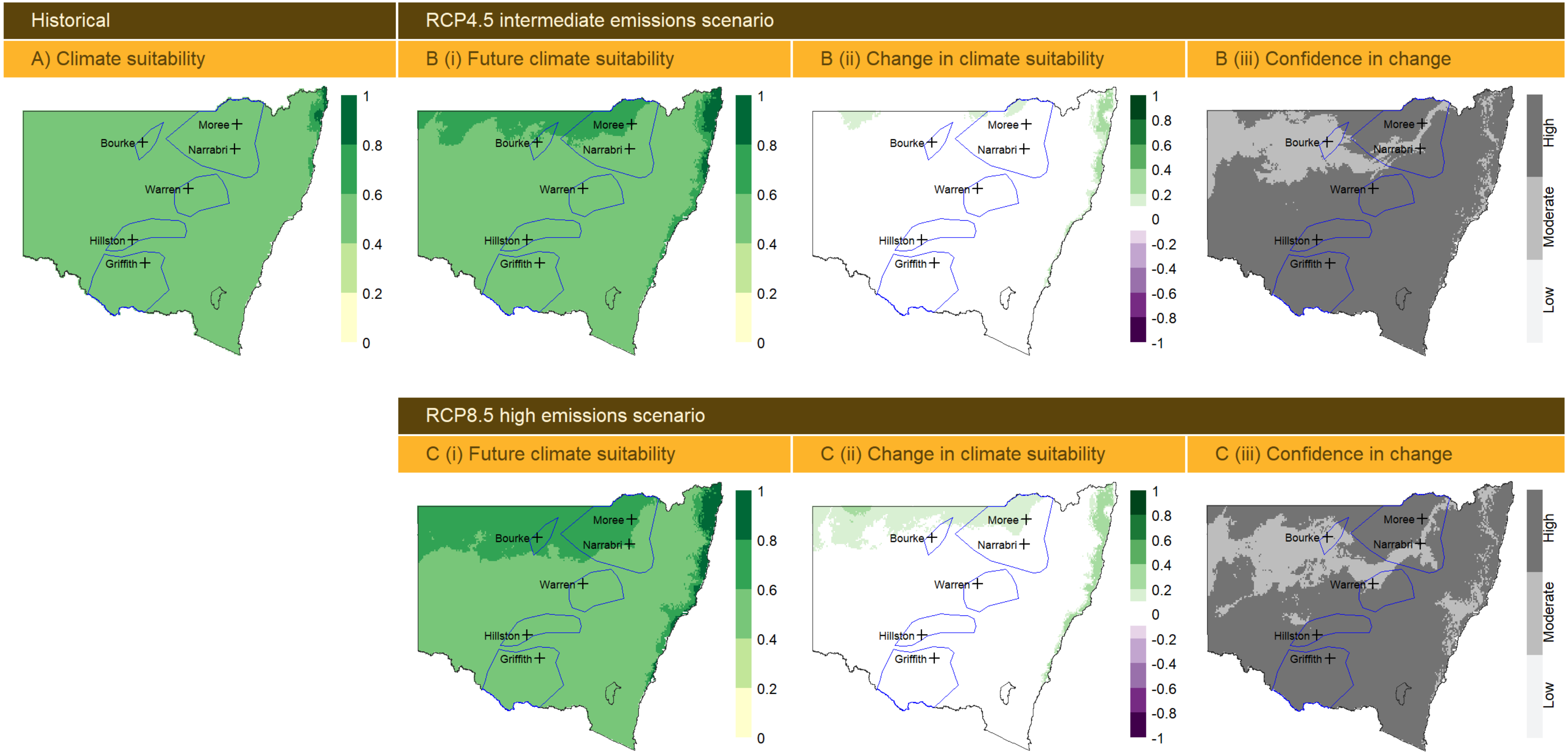


Figure A31. July climate suitability for *Verticillium* dormant phenophase

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

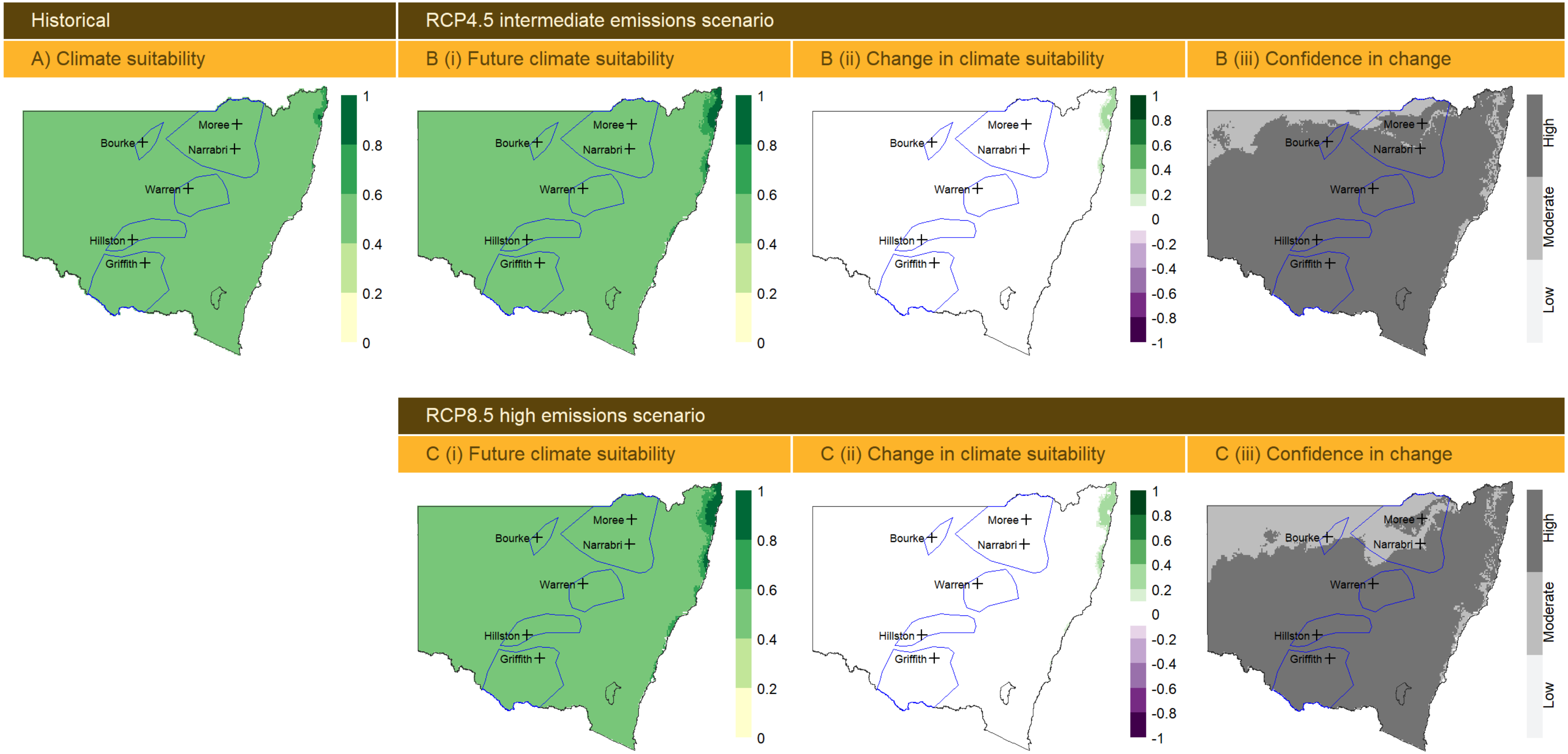


Figure A32. August climate suitability for *Verticillium* dormant phenophase

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

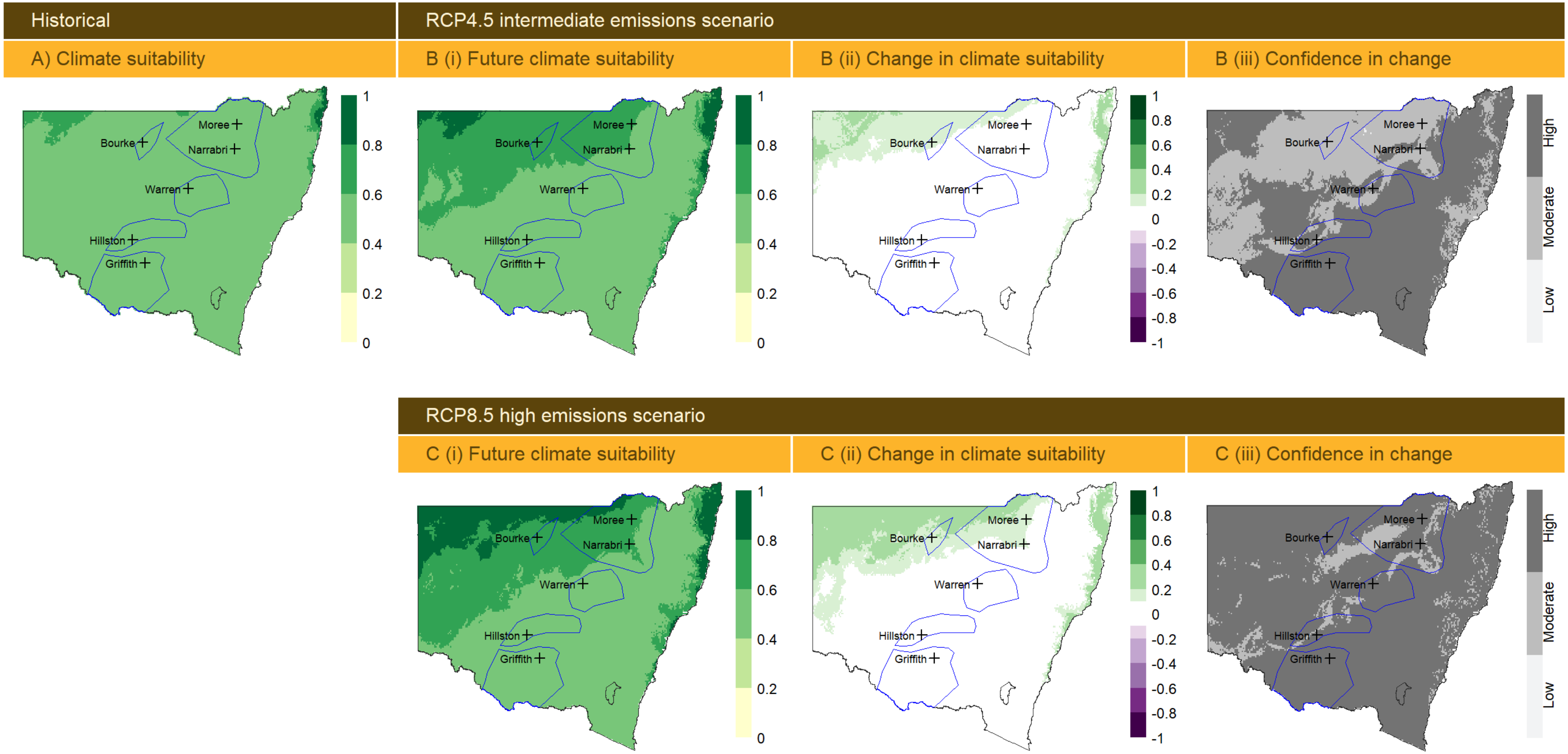


Figure A33. September climate suitability for *Verticillium* dormant phenophase

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

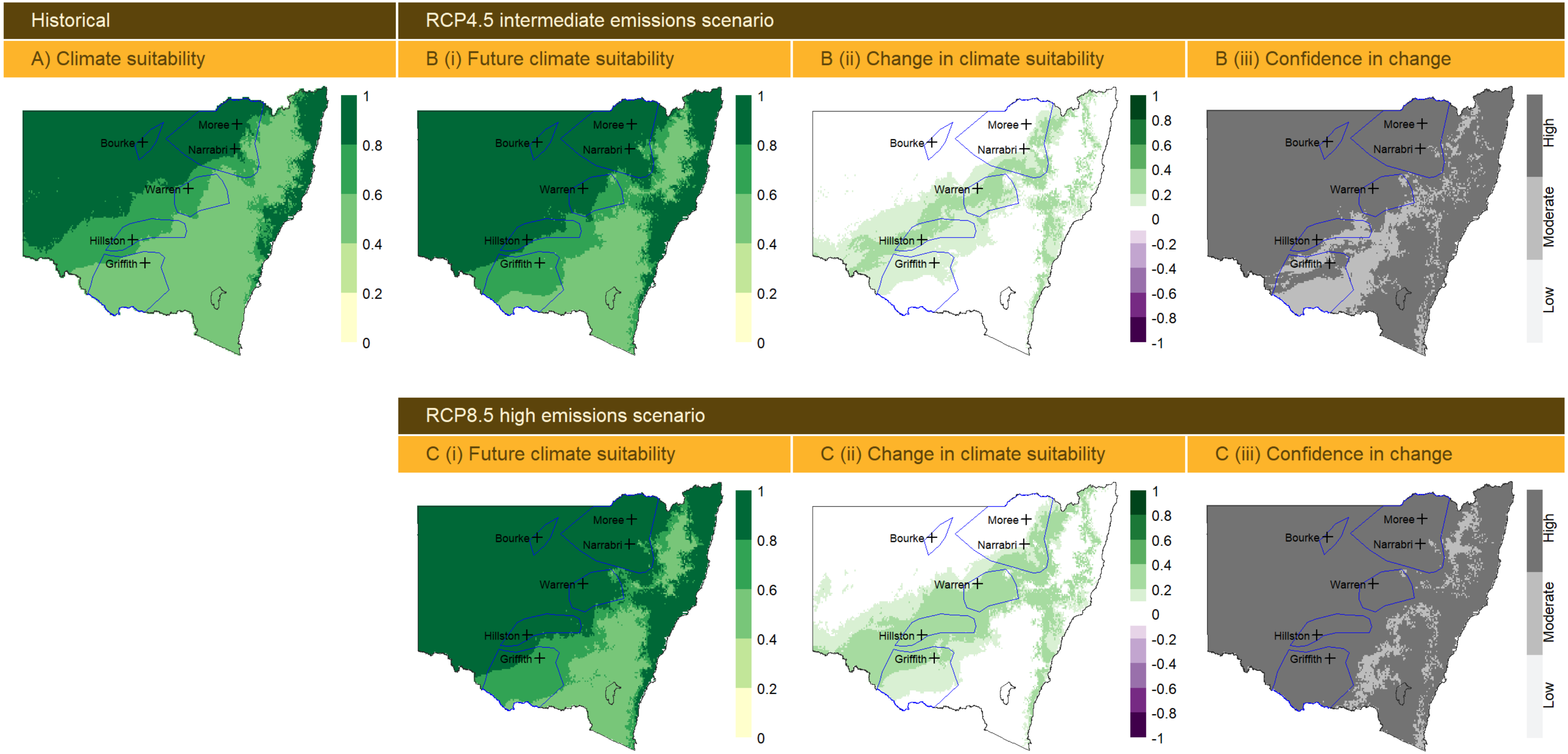


Figure A34. October climate suitability for *Verticillium* dormant phenophase

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

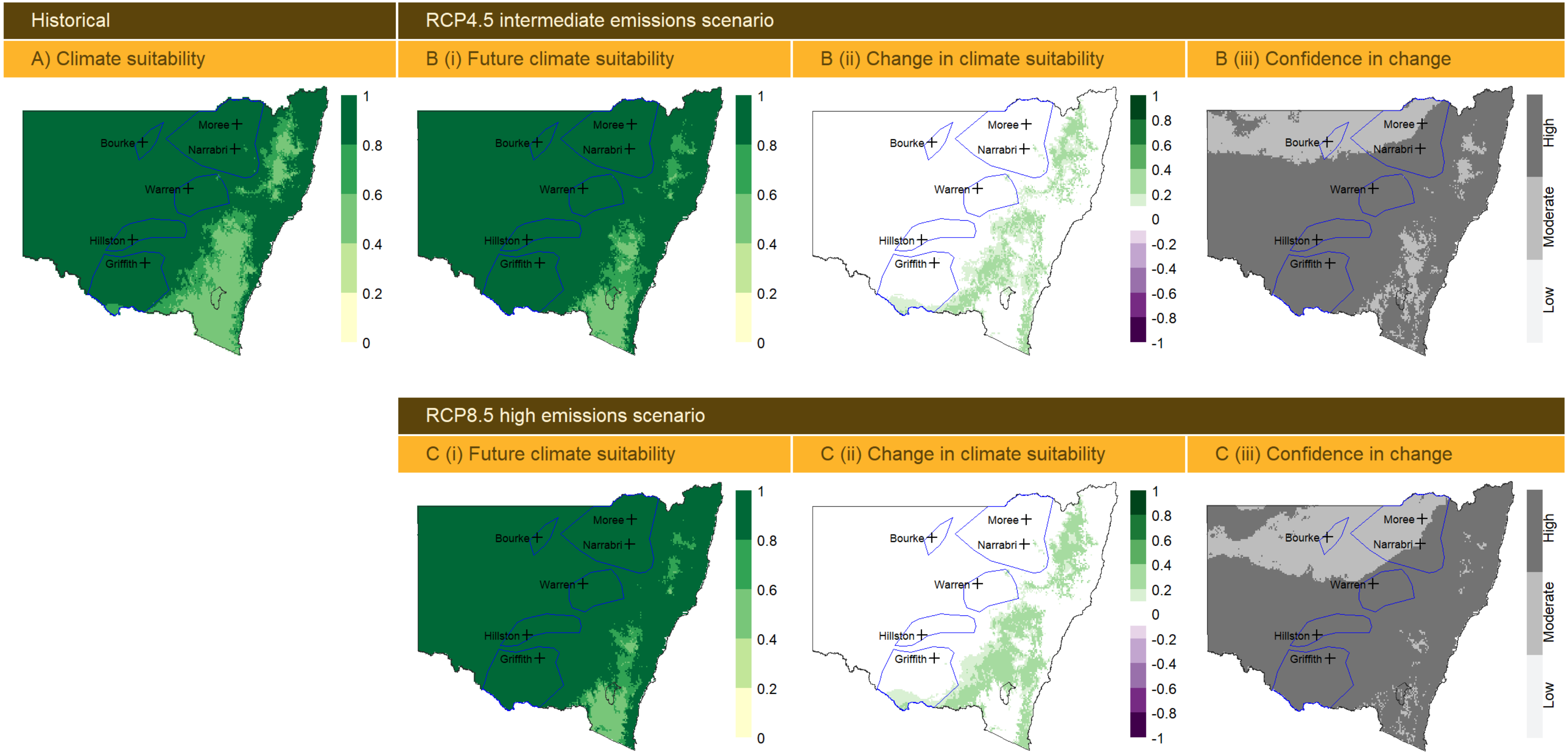


Figure A35. November climate suitability for *Verticillium* dormant phenophase

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.

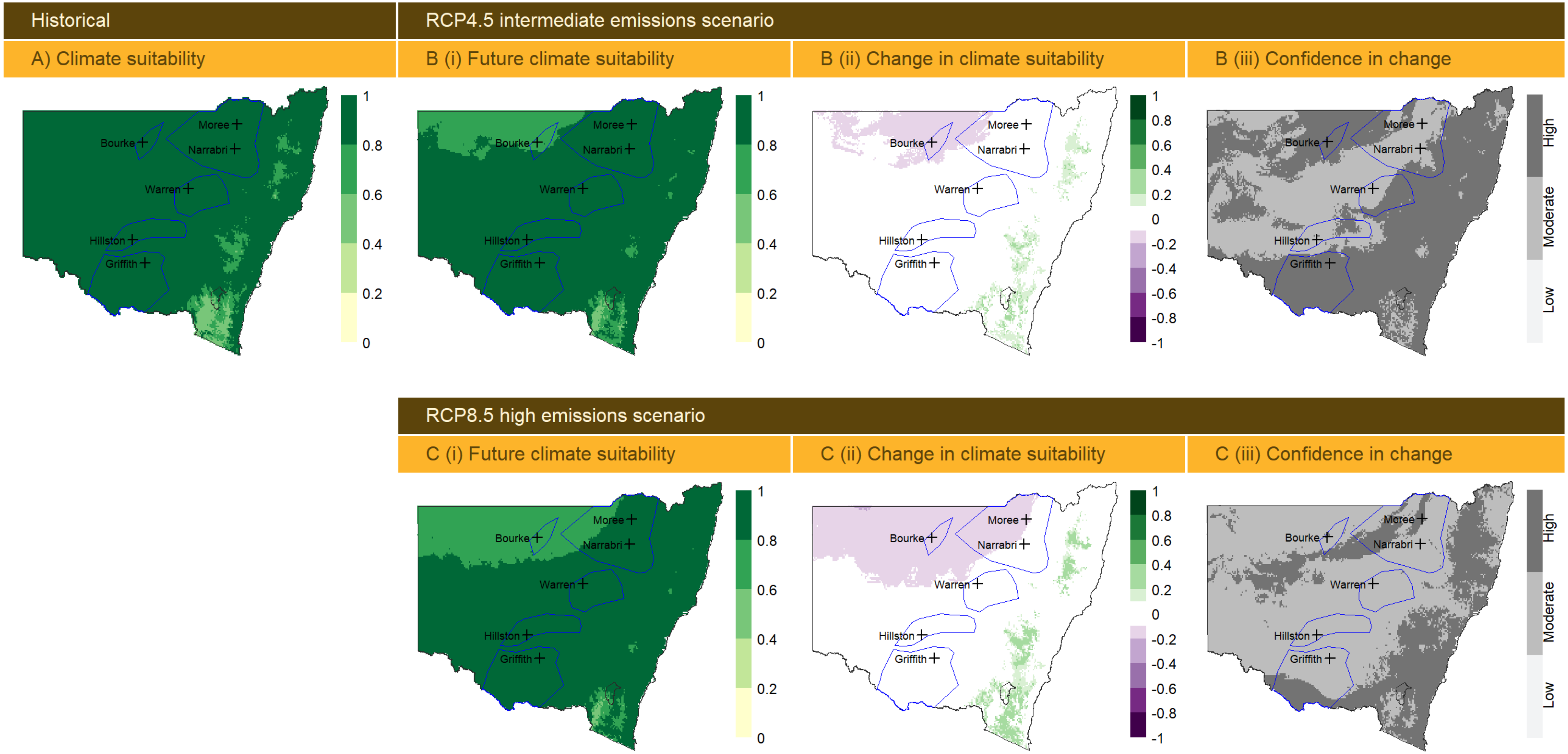
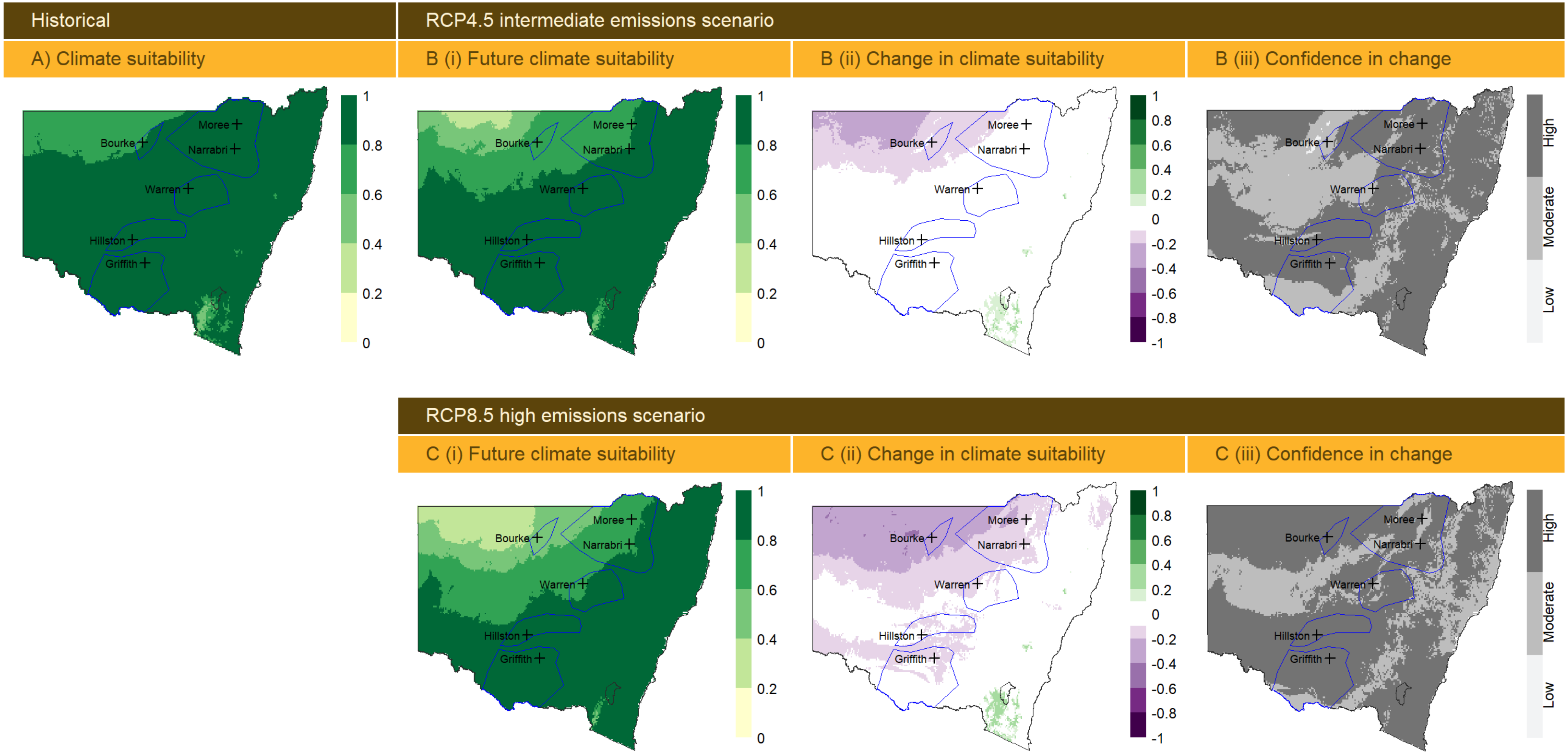


Figure A36. December climate suitability for *Verticillium* dormant phenophase

The panel is comprised of 7 maps: A) shows the historic 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). Sites of importance where *Verticillium* is currently found are marked by black crosses, and the blue polygons show the cotton valleys.



Primary Industries Climate Change Research Strategy

Climate Vulnerability Assessment

Verticillium Results Report

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