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Supplementary Material

Evaluation of management options for climate-change adaptation of threatened species: a case study of a restricted orchid

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Framework, adapted from Cross *et al.* (2012)

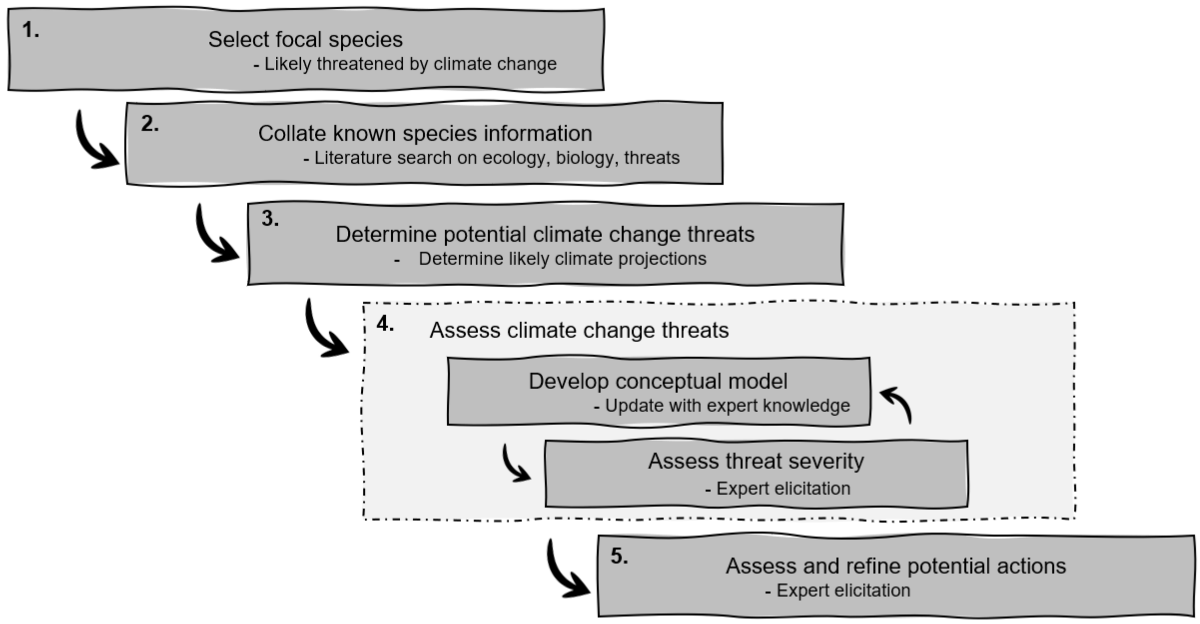


Fig. S1. Framework for incorporating climate change adaptation into species management, adapted from Cross *et al.* (2012) for rare or restricted species. Step 4 is an iterative process that can be updated to inform management actions (Step 5)

Photograph of *P. petilum* pollinator

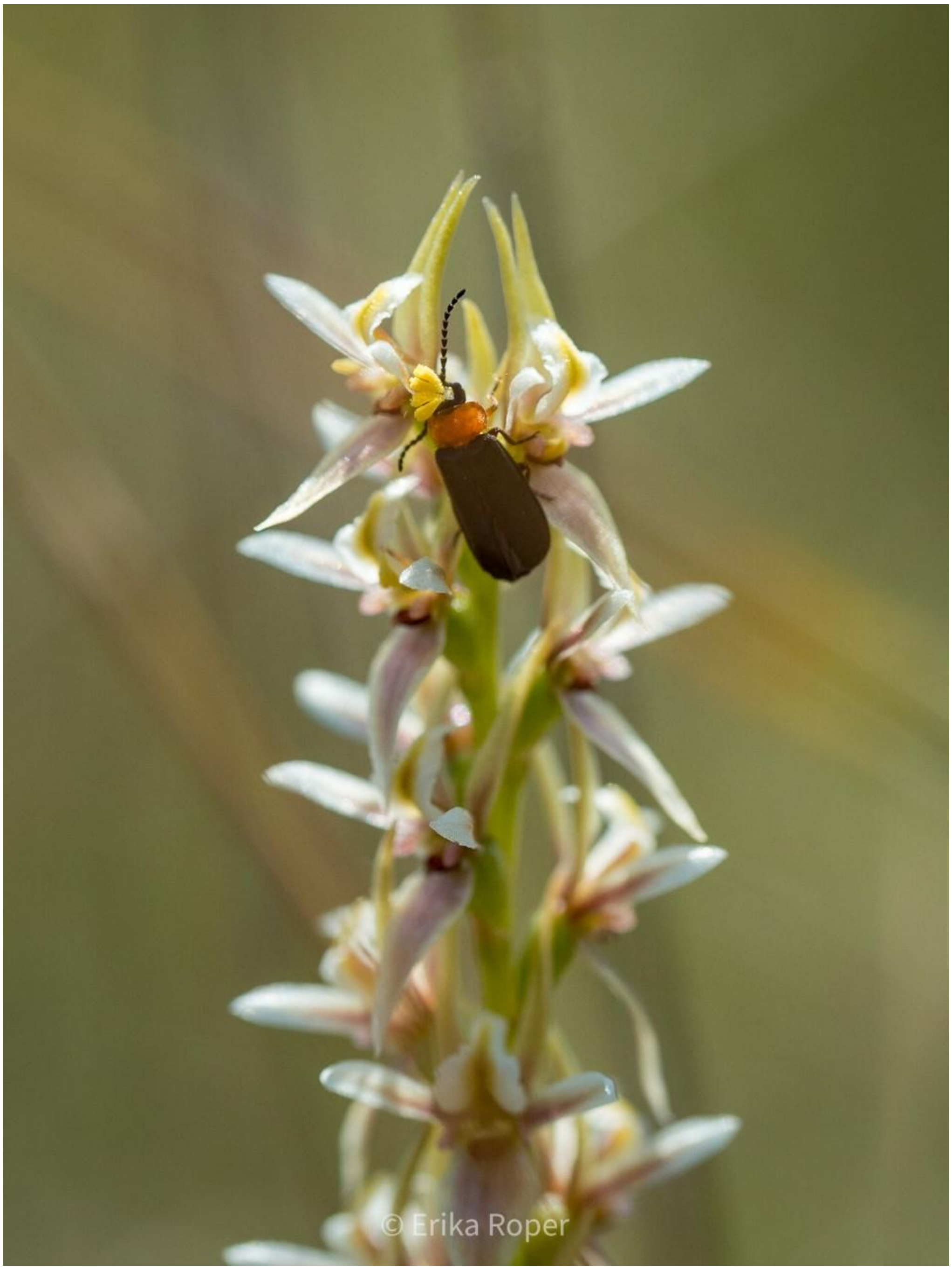


Fig. S2. Tricolor soldier beetle (*Chauliognathus tricolour*) was observed pollinating *P. petilum* (E. Roper, pers. comm., 2021).

Population information

Table S1. Population and habitat information for known *P. petilum* populations

Population name	Population size	Habitat	Notes
1. ACT			
Hall, ACT	Flowering individuals fluctuate yearly between 0 (1994) and 96 (1995). Median number of flowering individuals is 42	Yellow Box Blakely's Red Gum grassy woodland (*Eucalyptus melliodora* and *Eucalyptus blakelyi*). Native Kangaroo Grass (*Themeda triandra*), Wallaby grasses (*Rytidosperma spp.*) occur with patches of non-native grasses	Active burial site. Managed under Hall Cemetery Management Plan 2012. (Wilson et al. 2016; EPSD 2019)
2. South-eastern region			
Boorowa, NSW	2314 (2020 estimate).	Natural Temperate Grassland of the Southern Tablelands. Population occurs in open swards of tussock grass including *Bothriochloa macra*, *Pentapogon quadrifidus* and *Austrodanthonia* spp. Dense *Themeda triandra* swards occur	Actions proposed under Saving Our Species strategy (DECCW 2010; OEH 2021a)
Delegate, NSW	2101 (2020 estimate)	Natural Temperate Grassland of the Southern Tablelands with surrounding *Eucalyptus pauciflora*	Actions proposed under Saving Our Species Strategy (DECCW 2010; OEH 2021a)
3. Northern region			
Ilford, NSW	6 (2009 estimate)	Yellow Box Blakely's Red Gum grassy woodland. Dense cover of *Themeda triandra* and *Sorghum leiocladum*	Active but infrequent burials. Site occurs within conservation area (DECCW 2010)
Translocation (Hunter Valley) NSW	1824 individuals translocated between 2010-2015. Minimum of 4% and maximum of 63% detection of flowering individuals reported across years	Rehabilitated mixture of native and exotic grassland and woodland	Population translocated to rehabilitated mine site. (Bell 2020)
Muswellbrook (Hunter Valley), NSW	Unknown (small scattered populations)	Grasslands from former *Eucalyptus crebra*/*E. moluccana* woodlands.	Populations may be Prasophyllum sp. 'Wybong' (Bell 2020; OEH 2021a)

Climate change projections for south-eastern Australia

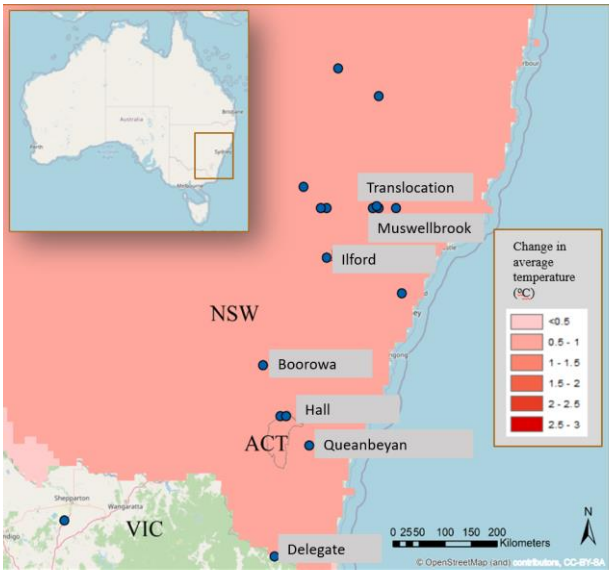
The following outlines a general summary of changes in climate in NSW and the ACT (OEH 2014a). Due to the annual life cycle of *P. petilum*, changes may affect populations during different seasons, hence why seasonal climate change is presented. NARCliM uses four global climate models (GCMs), downscaled by three regional climate models (RCMs) under the high emissions scenario (A2) from the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) to generate high resolution (10km) regional models for south-east Australia over three time periods (1990-2009 – baseline; 2020-2039 – near future; 2060-2079 – far future) (Evans et al., 2014).

Table S2. Climate changes for south-eastern Australia in each season for the near (2020-2039) and far (2060-2079) future (OEH 2014a)

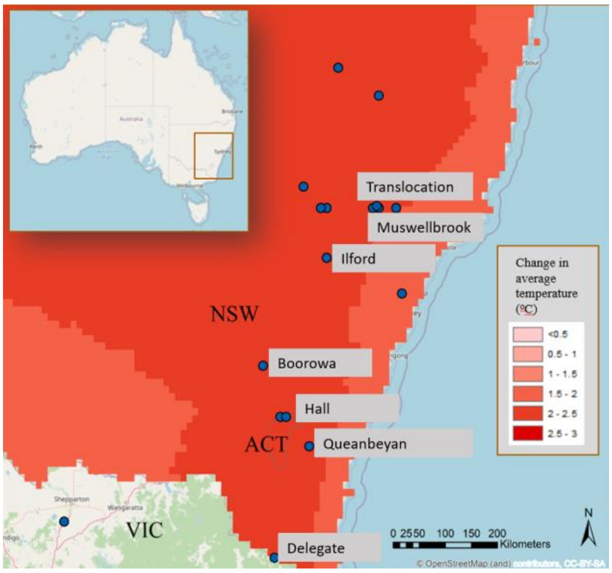
Summer	
Near Future	*Far Future*
Increased average (+0.6°C), maximum (+1°C) and minimum (+0.9°C) temperature[1]	Increased average (+2°C), maximum (+2.4°C) and minimum (+2.5°C) temperature
Increased number of hot days[2] (>35°C) (+5-10 days)	Increased number of hot days (>35°C) (+10-20 days)
Increased rainfall[3] (+0-5% in southern populations), decreased rainfall (-0-5% in Northern region)	Increased rainfall (+5-10% southern populations; +10-20% northern populations)
Increased fire weather (mean daily FFDI and severe FFDI days)	Increased fire weather (mean daily FFDI (+0.5-1) and severe FFDI days (+0-0.5 days)
Autumn	
Near Future	*Far Future*
Increased average (~+0.5°C), maximum (+0.5°C) and minimum (+0.6°C) temperature	Increased average (+2°C), maximum (+1.9°C) and minimum (+2.1°C) temperature
	Increased number of hot days (>35°C) (+0.5 days)
Increased rainfall (+5-10% southern populations, +10-20% northern populations)	Increased rainfall (+5-20%)
Winter	
Near Future	*Far Future*
Increased average (+0.4°C), maximum (+0.4°C) and minimum (+0.4°C) temperature	Increased average (+1.7°C), maximum (+1.6°C) and minimum (+1.6°C) temperature
Decreased rainfall (-0-5%), possible increase in Delegate population (+0-5%)	Decreased rainfall (-0-5% Hall; -10-20% Delegate), increased rainfall (+0-10% Boorowa, Ilford, Hunter Valley)
Increased fire weather (mean daily FFDI)	Increased fire weather (mean daily FFDI (+0-1))
Spring	
Near Future	*Far Future*
Increased average (+0.8°C), maximum (+o.8°C) and minimum (+0.7°C) temperature	Increased average (+2.3°C), maximum (+2.4°C) and minimum (+2.1°C) temperature
Increased number of hot days (>35°C) (+0-5 days)	Increased number of hot days (>35°C) (+5-10 days)
Decreased rainfall (-5-20% all populations)	Decreased rainfall (-5-20% all populations)
Increased fire weather (mean daily FFDI and severe FFDI days)	Increased fire weather (mean daily FFDI (+1-2) and severe FFDI days (0.5-1 day)

[1]approximate average change compared with baseline modelled climate (1990-2009)
[2]fewer hot days are projected in the south (Delegate), while more are projected in northern population locations
[3]average percentage rainfall increase compared with baseline

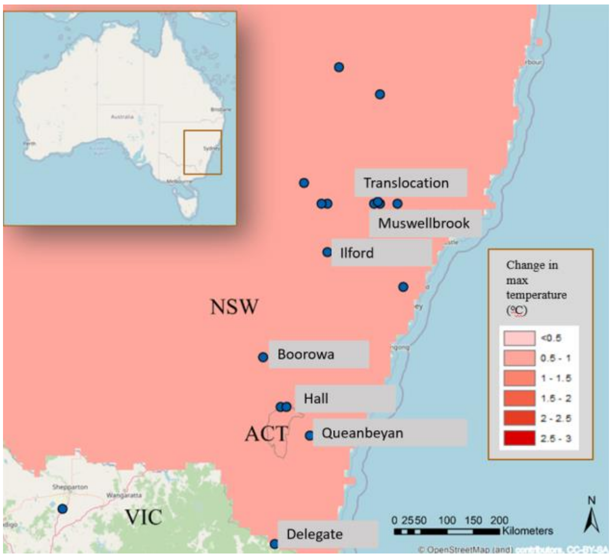
a) near future



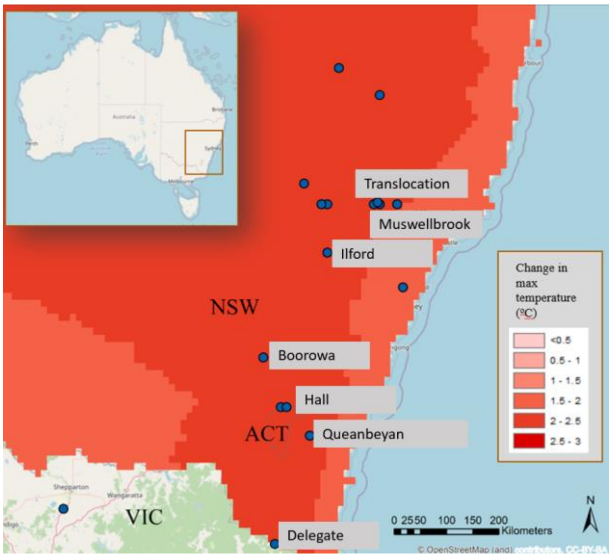
b) far future



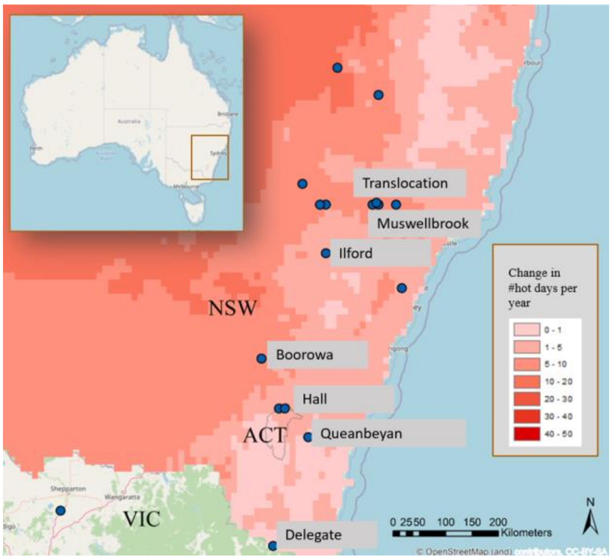
c) near future



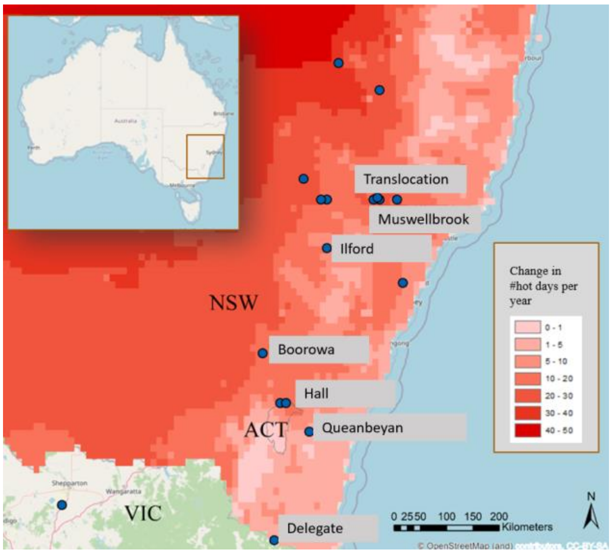
d) far future



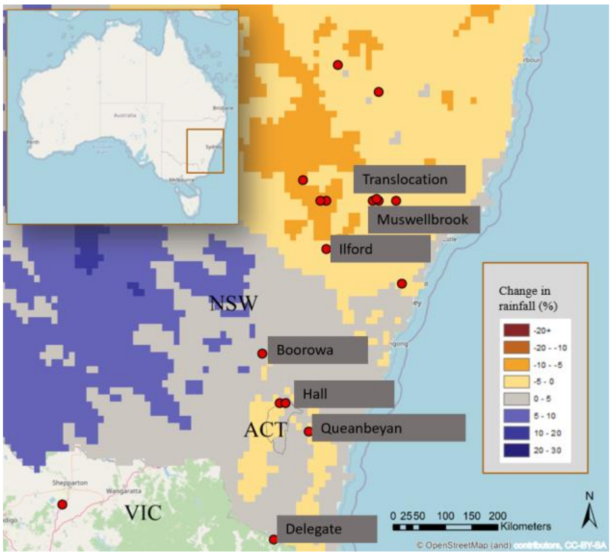
e) near future



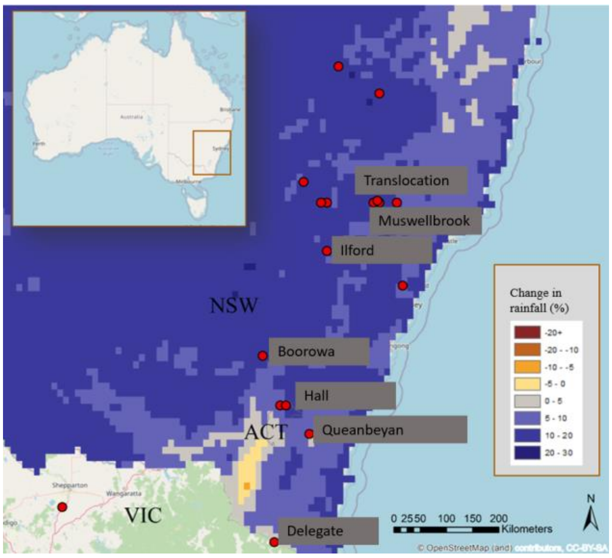
f) far future



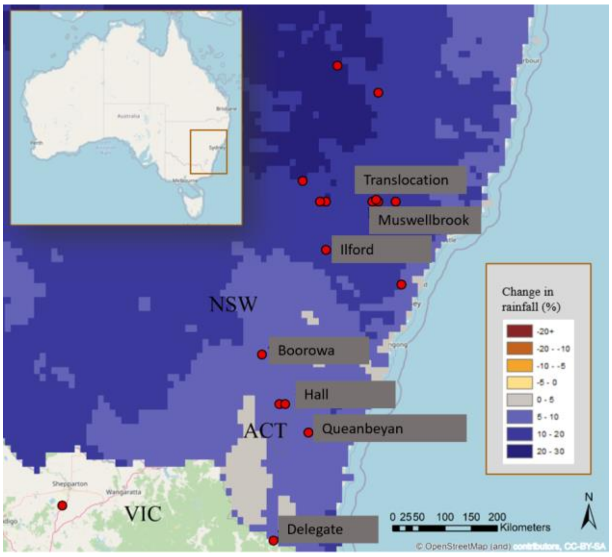
g) near future



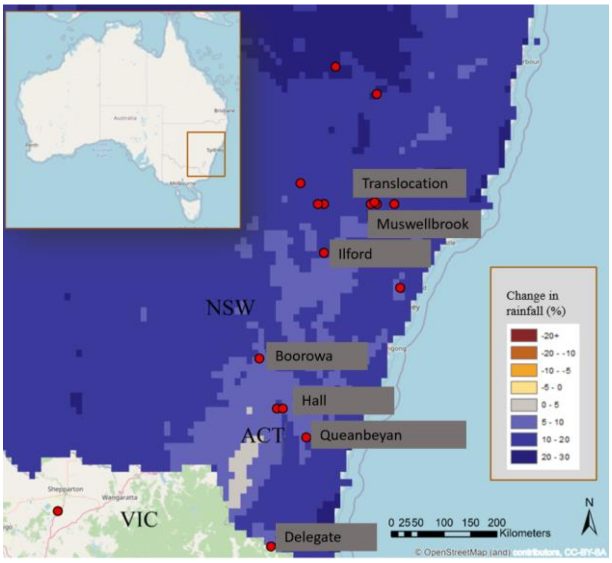
h) far future



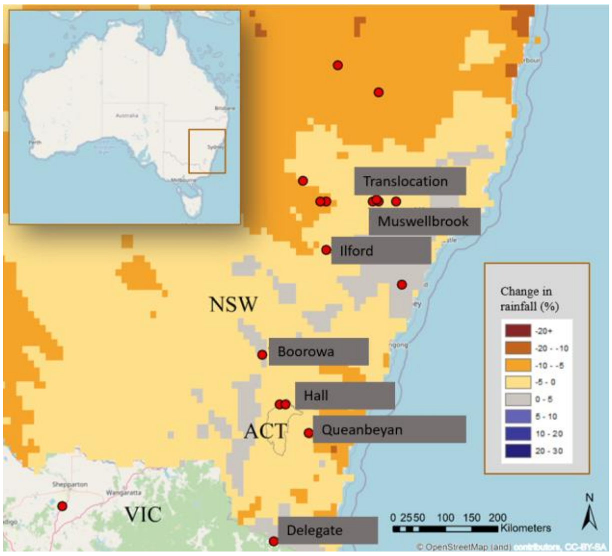
i) near future



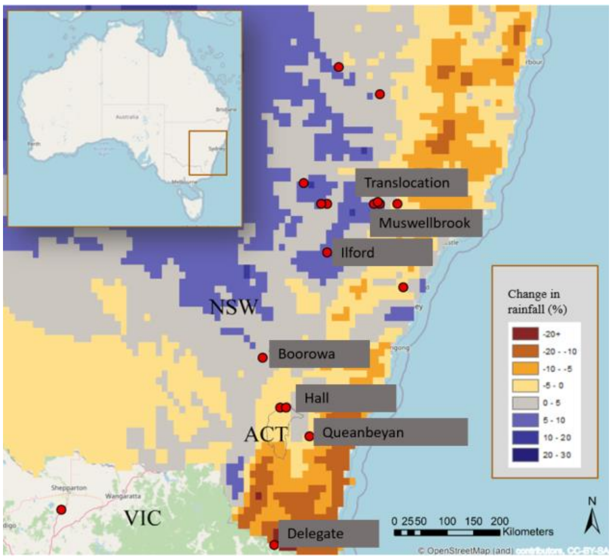
j) far future



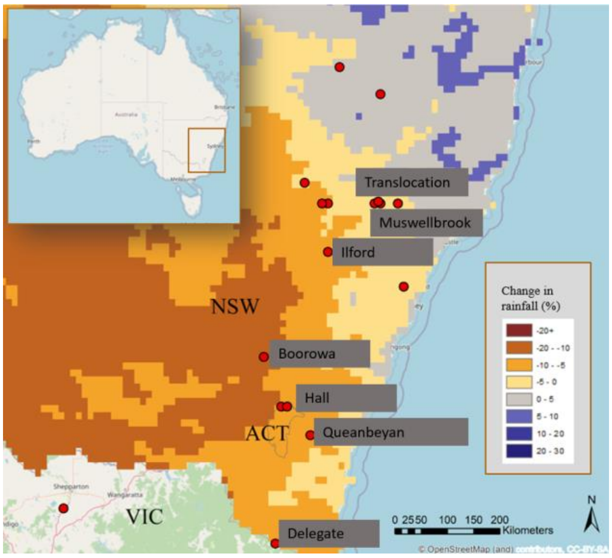
k) near future



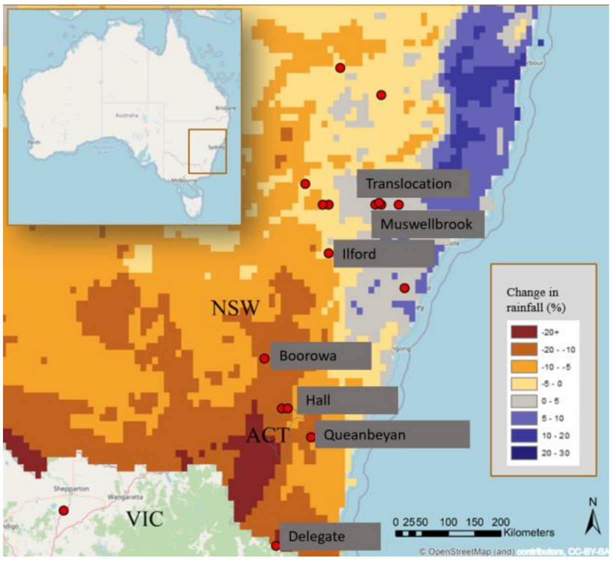
l) far future



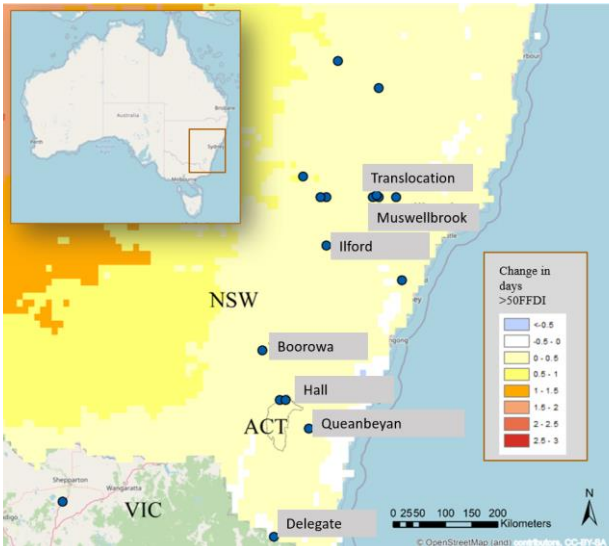
m) near future



n) far future



o) near future



p) far future

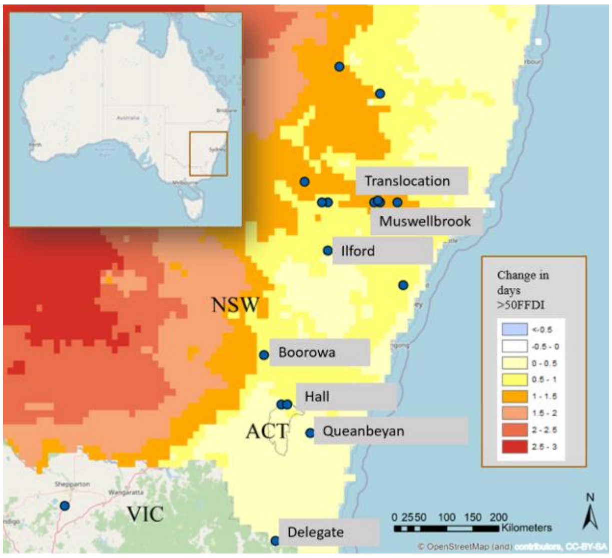


Fig. S3. Climate change projections for south-eastern Australia (NSW and ACT) for (a) and (b) mean annual change in average temperature, (c) and (d) mean annual change in maximum temperature, (e) and (f) mean change in hot (>35^o) days per year, (g) and (h) mean change in annual summer rainfall percentage, (i) and (j) mean change in annual autumn rainfall percentage, (k) and (l) mean change in annual winter rainfall percentage, (m) and (n) mean change in annual spring rainfall percentage, (o) and (p) mean change in number of severe fire weather days (FFDI>50) per year. Verified populations are labelled on each map and some unverified records are also shown. The population near Queanbeyan is no longer considered an extant population. Data sources: ALA 2020; OEH 2014b.

Workshop 1 materials

Table S3. Example format of questionnaire MS Excel spreadsheet provided to experts to complete

						In the near future (2020 - 2039)			In the far future (2060 - 2079)		
						Severity Score	**Certainty Score**	**Notes**	**Severity Score**	**Certainty Score**	**Notes**
Direct climate change impacts on *P. petilum* populations											
These climate factors may impact any component of the orchid ecology including seed set and recruitment, germination, emergence, flowering, genetic diversity, or growth period.											
1a.	The impact of	severe fire events in summer/spring			will impact *P. petilum* populations by:						
1b.	The impact of	increased number of hot days in all seasons			will impact *P. petilum* populations by:						
Impact of climate change on OMF to *P. petilum* populations											
OMF is an essential symbiont with P. petilum, assisting germination and exchanging nutrients (carbon) with the orchid roots.											
3d.	The impact of	severe fire events in summer/spring	on	OMF	will impact *P. petilum* populations by:						

Table S4. Potential threats to *P. petilum* populations. Experts were asked to estimate the severity of each threat to *P. petilum*.

Threat
1 Direct threats to populations
1a. severe fire events in summer/spring*
1b. increased number of hot days in all seasons*
1c. increased average and maximum temperature in all seasons*
1d. reduced winter/spring rainfall*
1e. habitat loss/degradation
1f. vegetative competition with weeds
1g. vegetative competition with native grasses
1h. grazing
2 Threats to pollinators
2a. severe fire events in summer/spring on pollinators*
2b. increased number of hot days in all seasons on pollinators*
2c. average and maximum temperature in all seasons on pollinators*
2d. shortened growth period on pollinators
2e. changed climate niche on pollinators*
3 Threats to OMF
3a. increased number of hot days in all seasons on OMF*
3b. average and maximum temperature in all seasons on OMF*
3c. reduced winter/spring rainfall on OMF*
3d. severe fire events in summer/spring on OMF*
3e. fertiliser runoff on OMF
4 Threats to habitat
4a. average and maximum temperature in all seasons on habitat quality*
4b. reduced winter/spring rainfall on habitat quality*
4c. increased summer/autumn rainfall on habitat quality*
4d. drought on habitat quality*
4e. severe fire events in summer/spring on habitat quality *
4f. changed climate niche on habitat quality*
4g. fertiliser runoff on habitat quality
4h. weed incursion on habitat quality
5 Threats to microenvironment
5a. severe fire events in summer/spring on microenvironment*
5b. increased number of hot days in all seasons on microenvironment*
5c. average and maximum temperature in all seasons on microenvironment *
5d. drought on microenvironment*
5e. reduced winter/spring rainfall on microenvironment*
5f. habitat loss/degradation on microenvironment
5g. weed incursion on microenvironment
6 Threats to weeds
6a. average and maximum temperature in all seasons on weeds*
6b. increased summer/autumn rainfall on weeds*

* Asterisks represent climate related threats.

Top 13 most severe threats in the far future

Table S5. Mean severity of the top 13 most severe threats in the far future, with the associated near future severity

Threat	Near future mean severity	Far future mean severity	P-value*
reduced winter/spring rainfall	3.125	3.75	<0.05
grazing	3.25	3.75	<0.1
drought on microenvironment	3	3.714285714	<0.05
habitat loss/degradation	3.375	3.625	=0.17
reduced winter/spring rainfall on microenvironment	3	3.571428571	<0.05
habitat loss/degradation on microenvironment	3.333333333	3.5	=0.5
drought on habitat quality	2.875	3.428571429	<0.1
reduced winter/spring rainfall on OMF	2.6	3.4	<0.05
changed climate niche on pollinators	2.6	3.4	<0.1
weed incursion on microenvironment	2.833333333	3.333333333	=0.19
vegetative competition with weeds	2.875	3.25	=0.19
increased summer/autumn rainfall on weeds	2.714285714	3.142857143	=0.19
weed incursion on habitat quality	2.625	3.125	<0.1

*Wilcoxon's signed-rank test using 'wilcox.test' function in R (R Core Team 2024). This test determined if the median difference is significantly larger than zero.

Workshop 2 Materials

Table S6. List of potential actions developed in Workshop 2, with descriptions of the action, the desired response of P. petilum from the actions, and the threats addressed by the actions.

Potential actions	Description and desired response	Threats addressed
Supplementary watering	Maintain optimal soil moisture, increased emergence and flowering	Reduced winter/spring rainfall on populations, OMF and microenvironment, drought
Fencing/exclosures	Protect patches or populations from grazing/browsing. Reduce damage, increase flowering, pollination and recruitment.	Grazing/browsing
Caging	Protect individuals or small patches from grazing/browsing. Reduce damage, increase flowering, pollination and recruitment.	Grazing/browsing
Mowing regime	Minimum height requirements, mowing restrictions during growth period. Reduce biomass and resource competition, increase germination and emergence, while reducing structural damage to individual plants	Site management, vegetative competition with weeds and natives
Controlled burns	Cool burns during the dormant seasons to reduce biomass and resource competition, increase germination and emergence	Vegetative competition with weeds and natives, increased summer/autumn rainfall on weeds
Grazing regime	Stock grazing during dormant season to reduce biomass and resource competition, increase germination and emergence	Vegetative competition with weeds and natives, increased summer/autumn rainfall on weeds
Translocation	Translocate ex situ propagated plants to new suitable locations. Establish new populations, increase wild population numbers	Habitat loss/degradation
Hand pollination	Increased seed production, increased wild and ex-situ seed bank, potentially increase wild population size.	Changed climate niche on pollinators
Restoration of habitat	Create suitable habitat for orchid translocations	Habitat loss/degradation on populations and microenvironment
Assisted gene flow between populations*	Mix different temperature adapted individuals	Increased max temperatures and hot days
Species distribution modelling*	SDM of current distribution to search for existing populations. Habitat and climate suitability modelling to determine suitable sites for new populations in the future.	Reduced winter/spring rainfall
Ex-situ climate threshold trials*	Inform suitable locations for translocations, identify future at-risk populations	Reduced winter/spring rainfall, increased max temperatures
Map OMF distribution*	Inform suitable locations for translocations	

Pollinator ID and ecology*	Inform suitable locations for translocations. Understand impact of climate change on pollinator phenology and orchid association.	Changed climate niche on pollinators, fire on pollinators
Monitoring and analysis*	Analyse existing rainfall and temperature data with population data to further understand components of climate impact on populations. Modelling. Analyse controlled burn data to determine impact of fire on flowering and emergence.	Reduced winter/spring rainfall on microenvironment, drought

*Research actions are marked with an asterisk

Table S7. Example format of questionnaire MS Excel spreadsheet provided to workshop participants in workshop 2.

	ACT		**South-eastern region**		**Northern region**		
Potential Actions	*Benefit*	*Feasibility*	*Benefit*	*Feasibility*	*Benefit*	*Feasibility*	*Notes (e.g. reasons for score, beneficial interactions with other actions)*
Supplementary watering							
Fencing/exclosures							

Feasibility and benefit

Feasibility Benefit

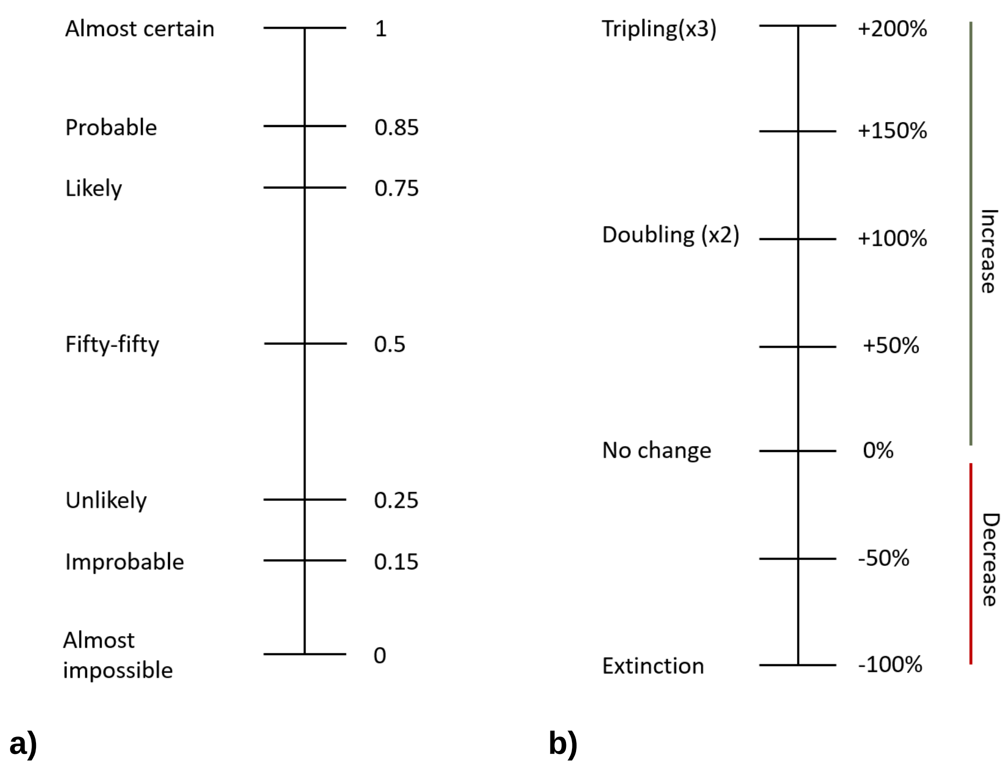


Fig. S4. Scales utilised by experts to estimate (a) feasibility (adapted from Carwardine et al. 2012) and (b) benefit (adapted from Rout and Walshe 2021), measured as percentage change in the population, of each action.

Severity and certainty of threats to *P. petilum* over the near and far future

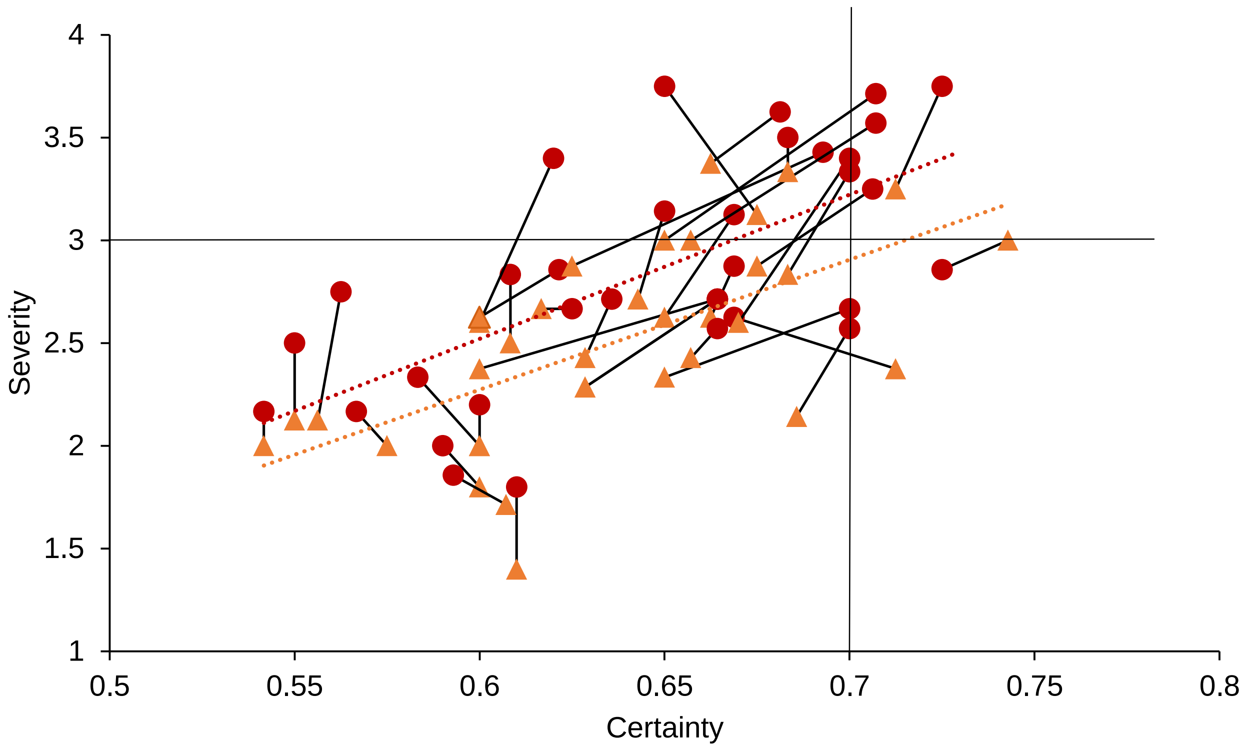
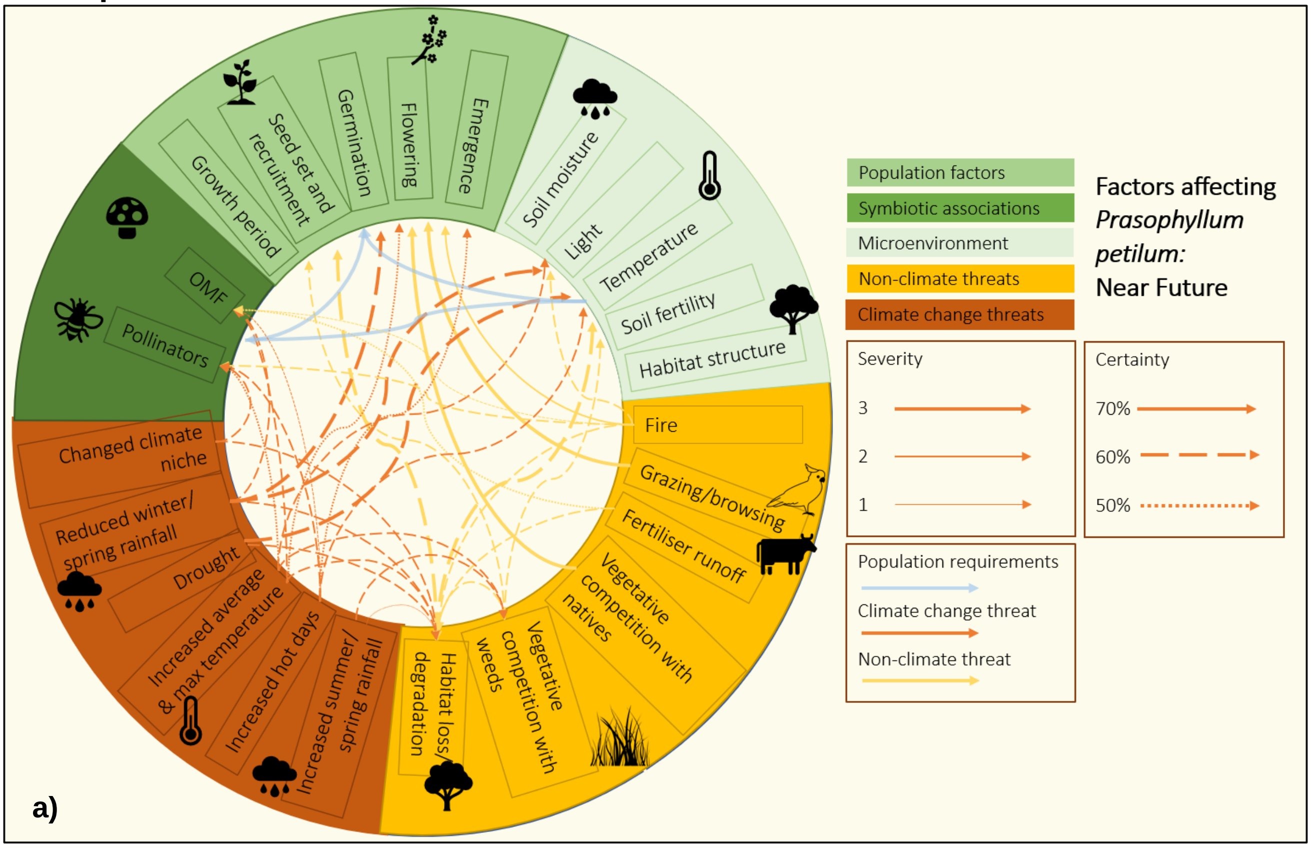


Fig. S5. Mean severity versus certainty of each threat to *P. petilum* estimated for the near (orange triangles) and far future (red circles). The same threats are connected by a black line indicating the change in severity and certainty.

Conceptual Models



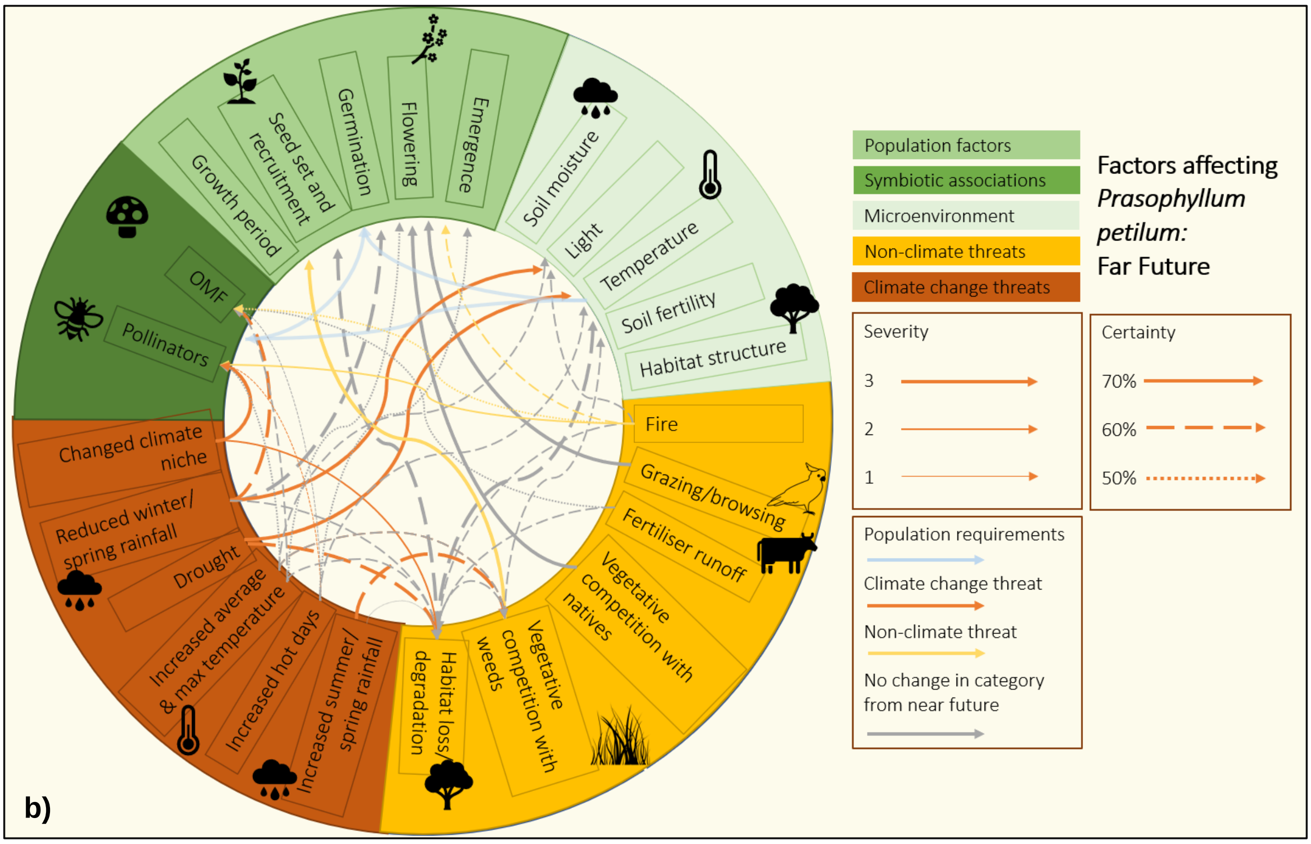
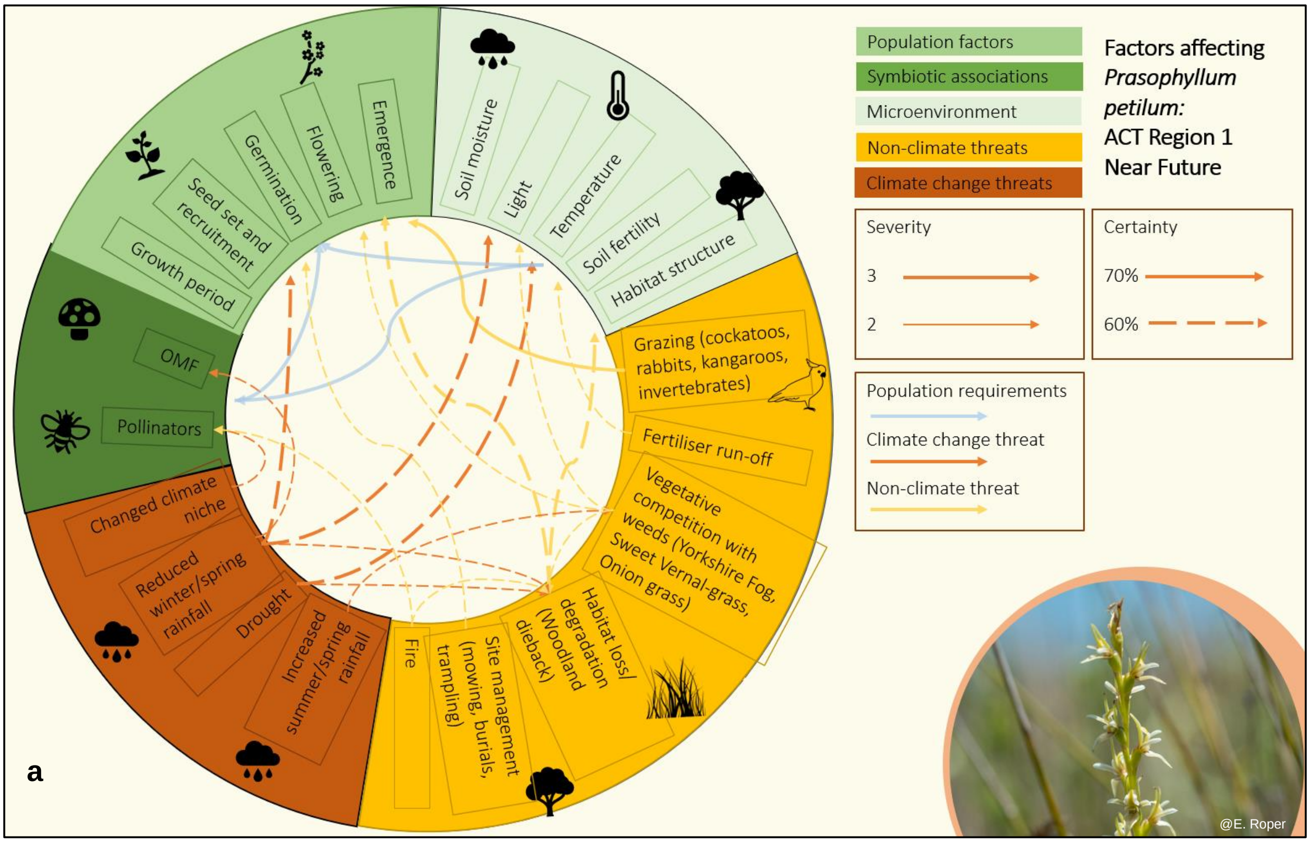


Fig. S6 The updated conceptual model incorporated expert estimates of threat severity and certainty for *P. petilum* in (a) the near future (2020 – 2039) and (b) the far future (2060 – 2079). Greyed lines in 6b indicate no change in threat or certainty category between near and far future. Lines arrows that do not connect with individual factors (boxes) indicate the threat may impact the suite of factors in that section. This model summarises threats to all populations (Supplementary Material, Table S4). Regional conceptual models are found in Fig. S7, S8 and S9

Regional conceptual models



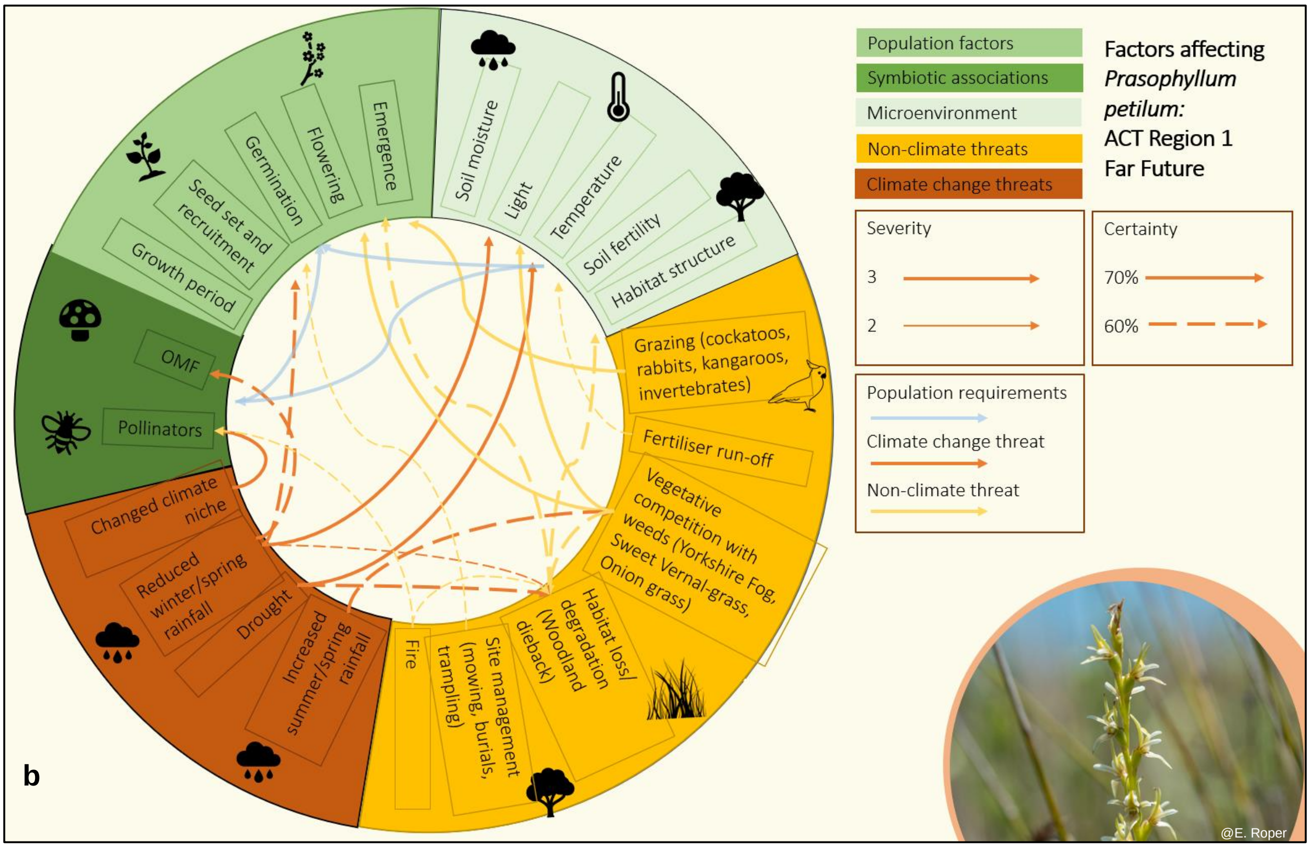


Fig. S7. Conceptual model of threats affecting the ACT *P. petilum* population in the (a) near future and (b) far future. Weeds detailed here are Yorkshire Fog (*Holcus lanatus*), Sweet Vernal-grass (*Anthoxanthum odoratum*) and Onion Grass (*Romulea rosea*).

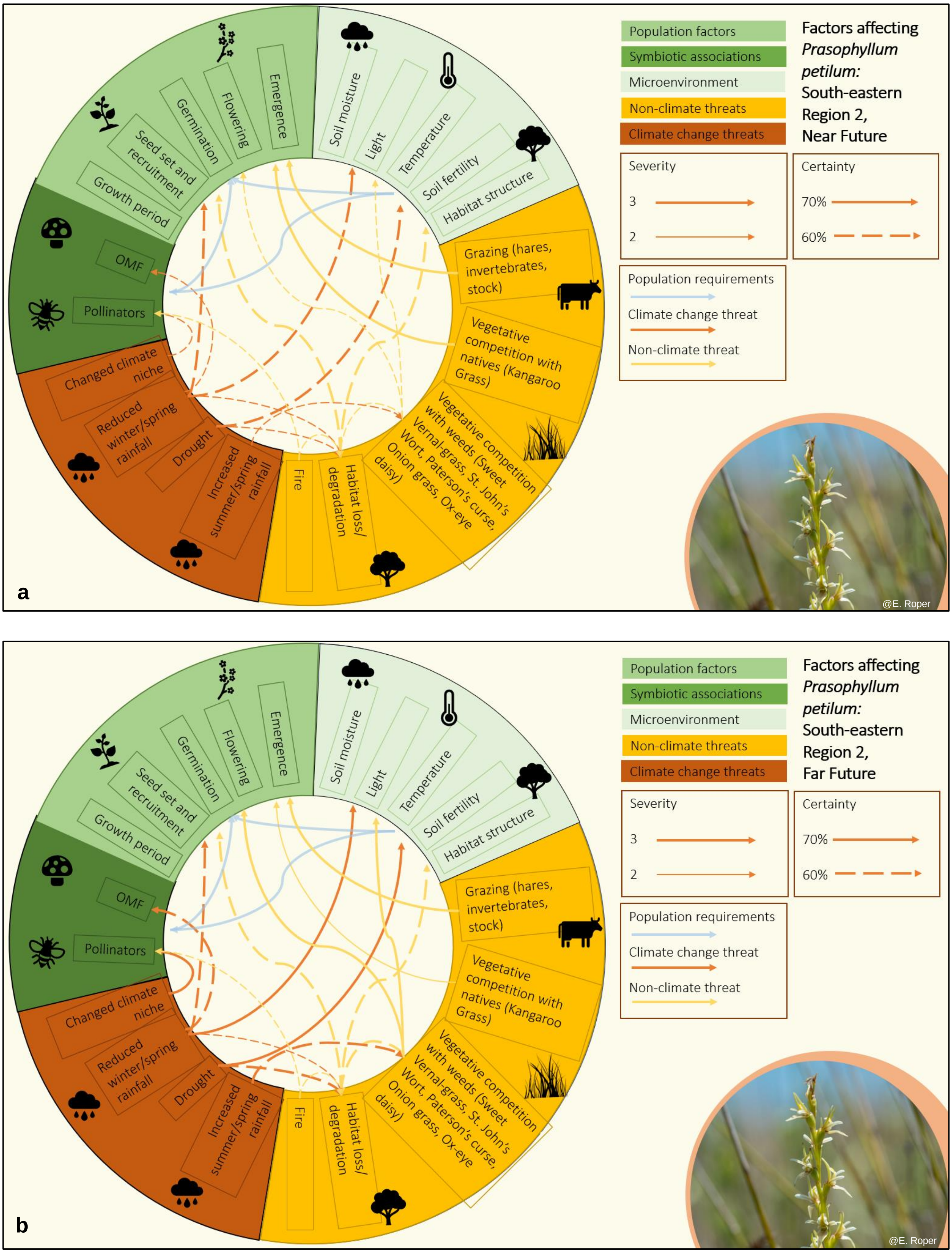


Fig. S8. Conceptual model of threats affecting South-eastern *P. petilum* populations in the (a) near future and (b) far future. Weeds detailed here are Sweet Vernal-grass (*Anthoxanthum odoratum*), Onion Grass (*Romulea rosea*), St John's Wort (*Hypericum perforatum*), Paterson's curse (*Echium plantagineum*), Ox-eye daisy (*Leucanthemum vulgare*). Only Delegate is grazed by stock.

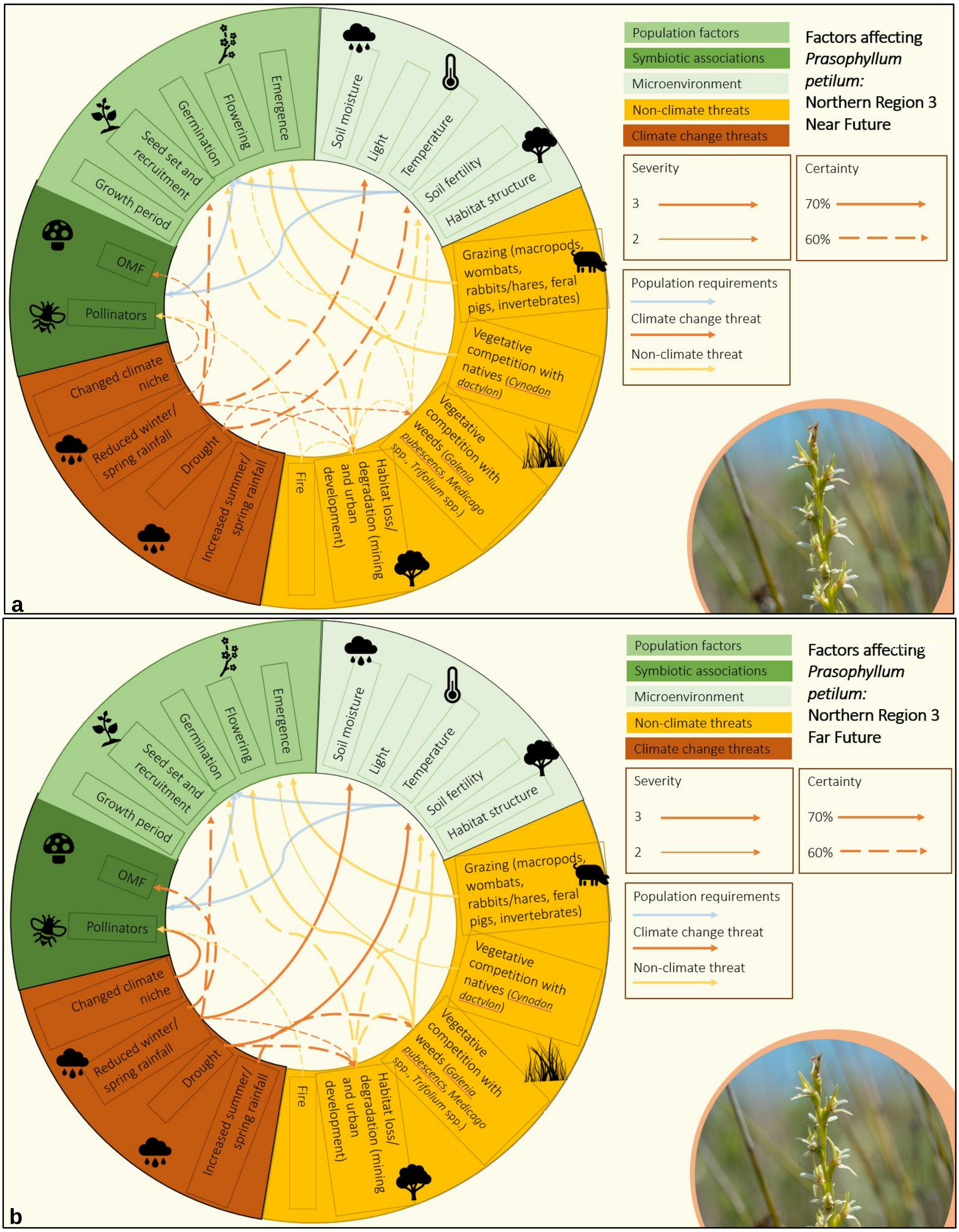


Fig. S9. Conceptual model of threats affecting Northern *P. petilum* populations in the (a) near future and (b) far future. These populations are small and scattered amongst cemeteries and mining sites and include a large translocation site in the Hunter Valley (Bell, 2020). Winter rainfall will increase in the far future for most northern locations, though spring rainfall will still decrease. Summer rain will initially decrease for these locations (near future) but will increase by the far future.

Workshop 2 terminology

Table S8. Definitions of terminology used in management elicitation

Terminology	
Feasibility	Probability of an action being successfully implemented, from 0 to 1, with 0 being an action that is impossible to achieve and 1 being an action that is certain to be achieved. Feasibility may account for social, economic, political, knowledge and logistical constraints (Carwardine et al. 2012; Cross et al. 2012)
Benefit	Impact of an action to the species, based on percentage change in population size (Rout and Walshe 2021).
Successful implementation	Implemented to the point that the maximum potential benefit has been attained

Estimated decline in population

Table S9. Estimated percentage change in the ACT *P. petilum* population/management region by the far future (2060 – 2079) under different management paradigms. The range of responses are shown in parentheses.

	Mean percentage change in population size*
If all management ceased, what would the trajectory for *Prasophyllum petilum* populations be?	-92% (-75 - 100%)
If we continue with current management, what is the trajectory for *Prasophyllum petilum* populations?	-20% (0 - -50%)

* Managers estimated a decline in both scenarios, with a larger decline if all management ceased ($P < 0.05$; paired one-tailed t-test using 't.test' function in R (R Core Team 2024).

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