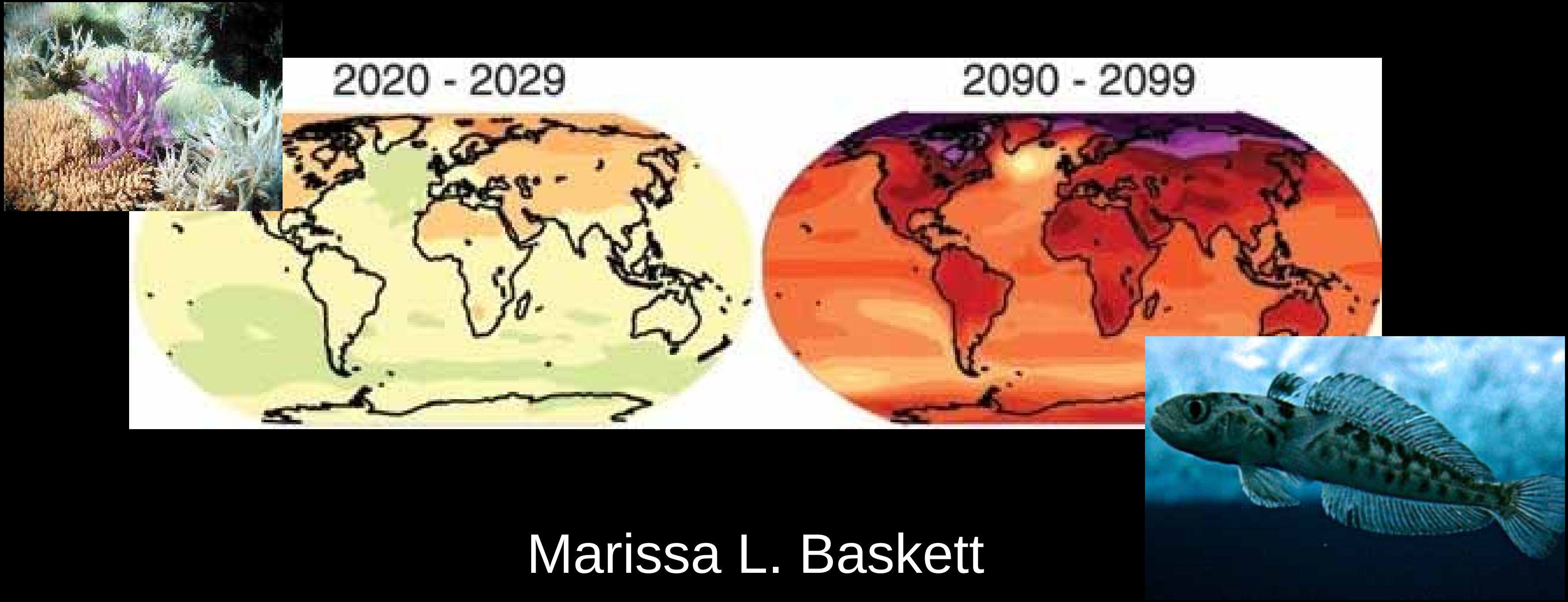
Ecological and rapid evolutionary responses to climate change: Implications for marine management



Marissa L. Baskett

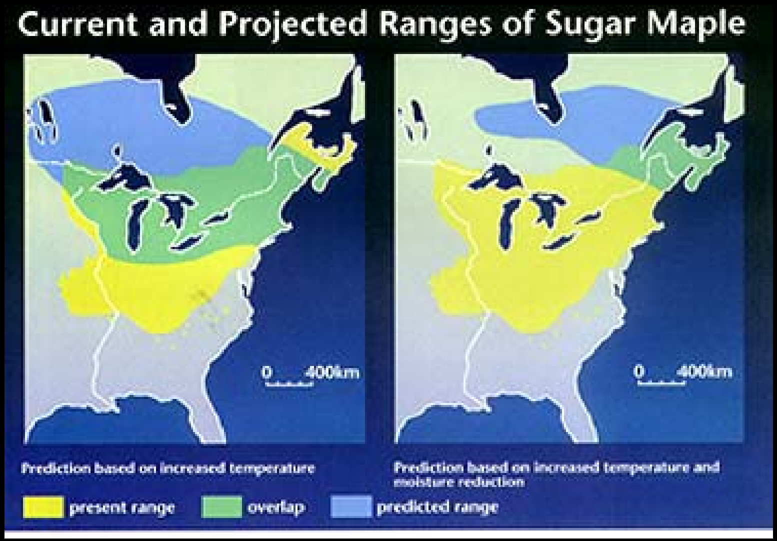
National Center for Ecological Analysis and Synthesis,
University of California, Santa Barbara

Effects of Climate Change on the World’s Oceans, Gijón, Spain
May 23rd, 2008

Responses to climate change

Holt 1990
McCarty 2001

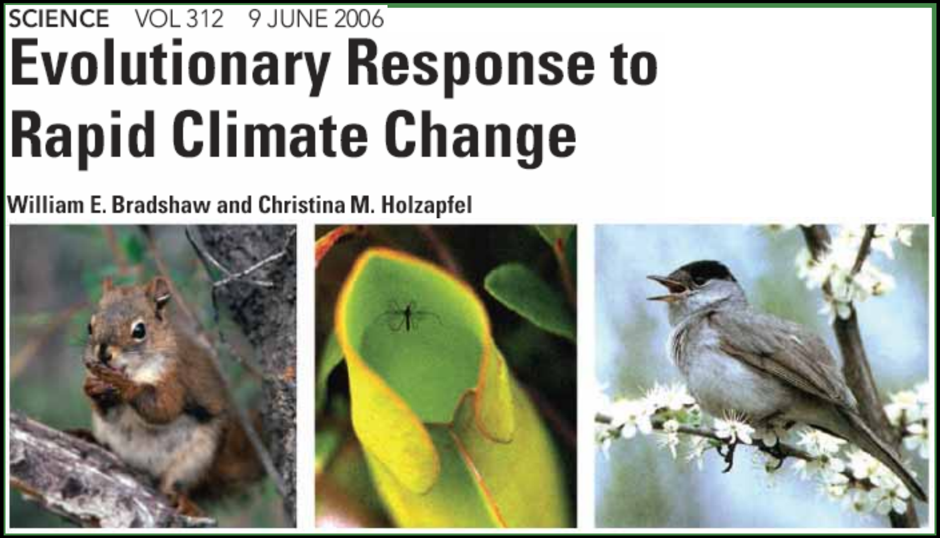
- Movement
- Acclimatization
- Genetic adaptation



Current and Projected Ranges of Sugar Maple

Prediction based on increased temperature

Prediction based on increased temperature and moisture reduction



SCIENCE VOL 312 9 JUNE 2006

Evolutionary Response to Rapid Climate Change

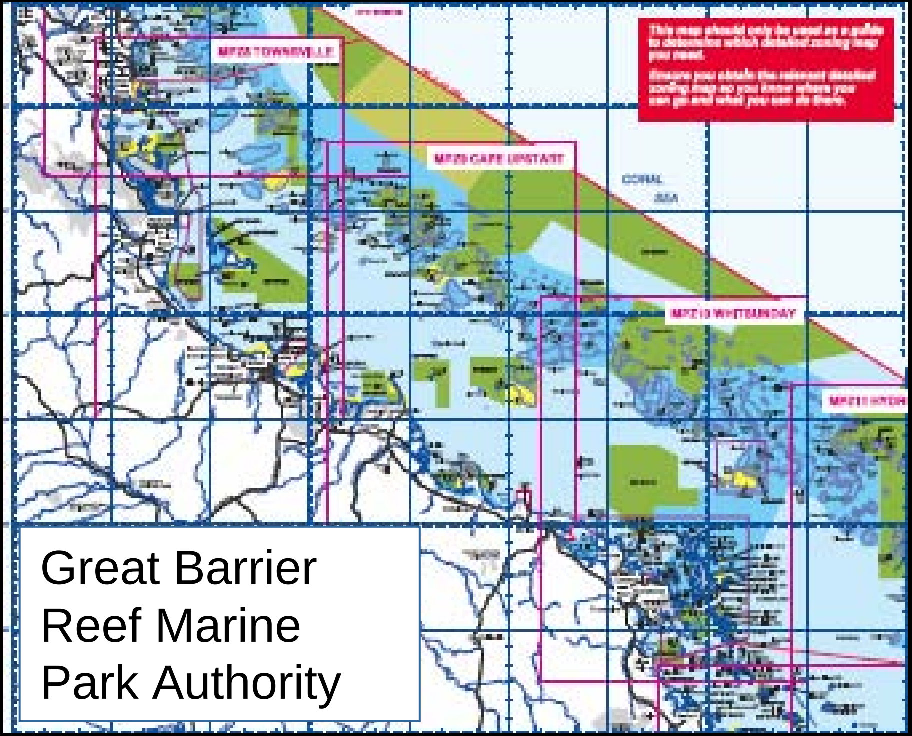
William E. Bradshaw and Christina M. Holzapfel

🟨 Present range
🟦 Predicted range
🟩 Overlap

Management in a changing climate

- Movement
- Acclimatization
- Genetic adaptation

Protect response capacity



Great Barrier Reef Marine Park Authority

1. Protect locations with greater response capacity

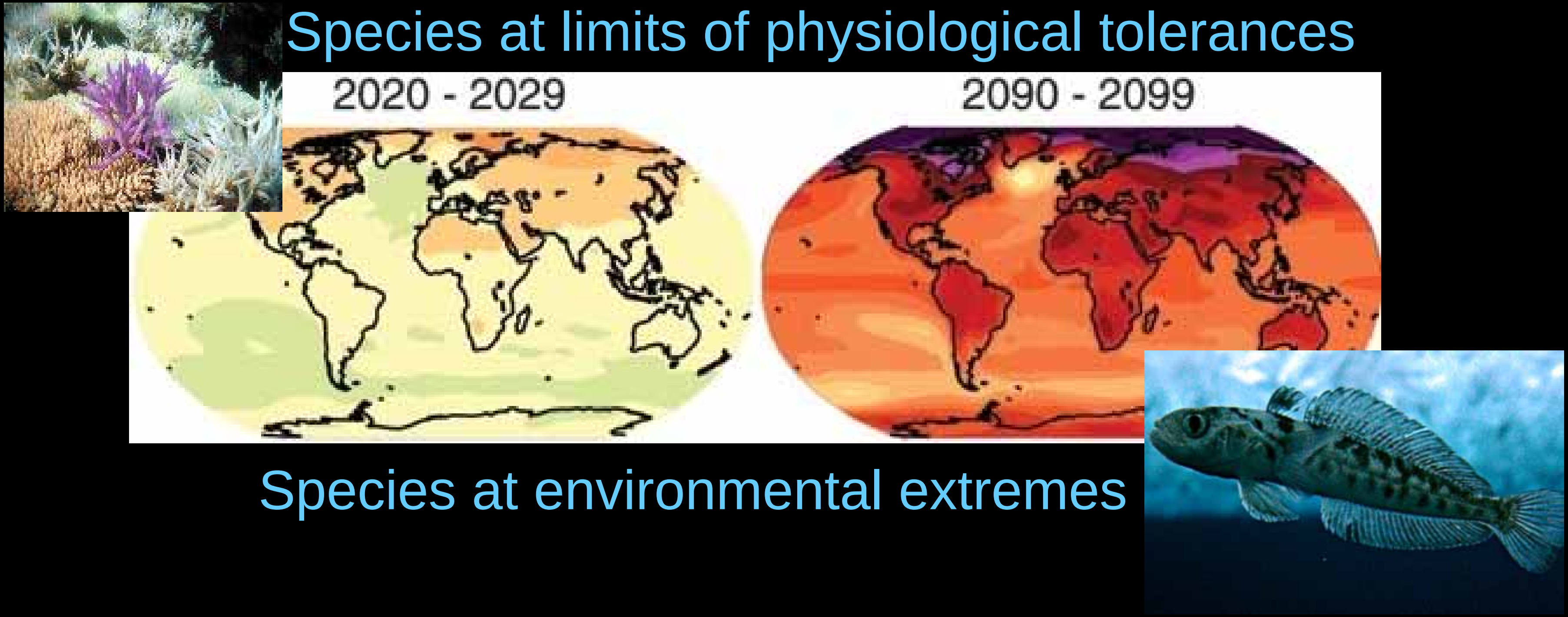
2. Protect against local impacts that may reduce response capacity

Critical species

Parmesan 2006

- ~~Movement~~
- ~~Acclimatization~~
- Genetic adaptation

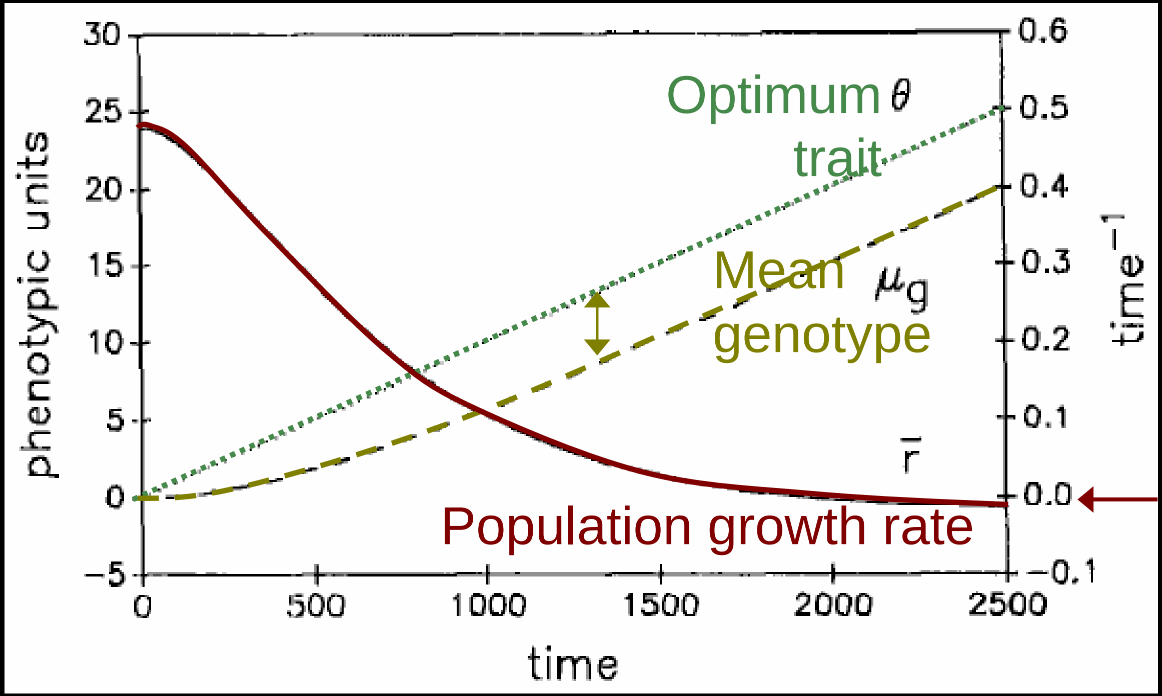
Protect response capacity



Species at limits of physiological tolerances

Species at environmental extremes

Genetic adaptation: theory



Lynch et al. 1991, Lynch 1996

Heritability

Phenotypic variation

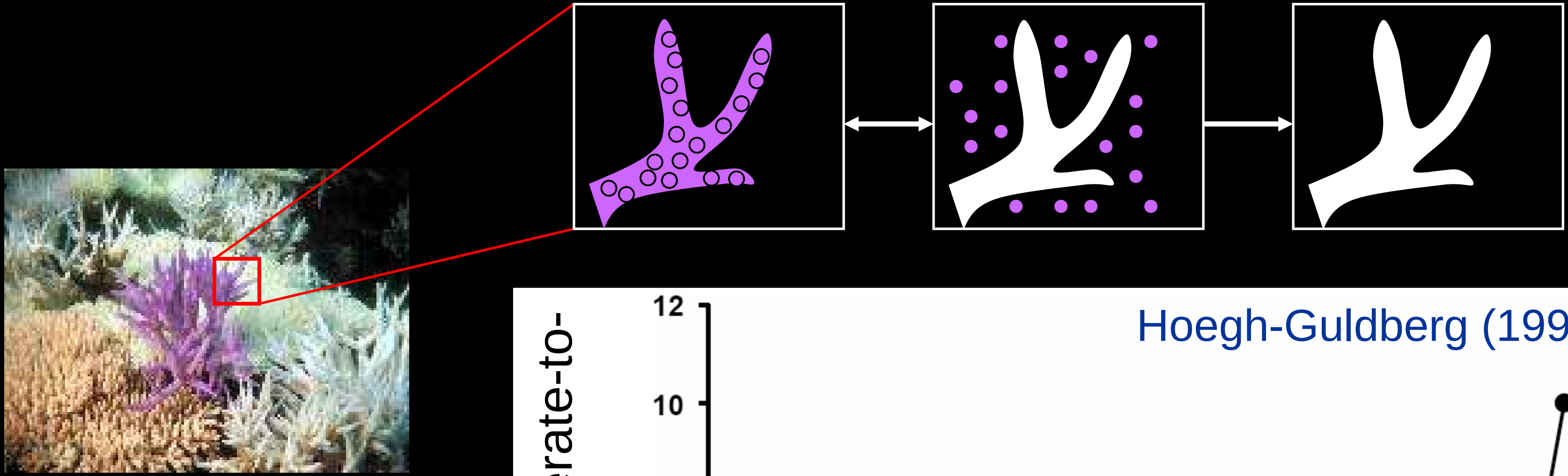
Max. pop growth rate

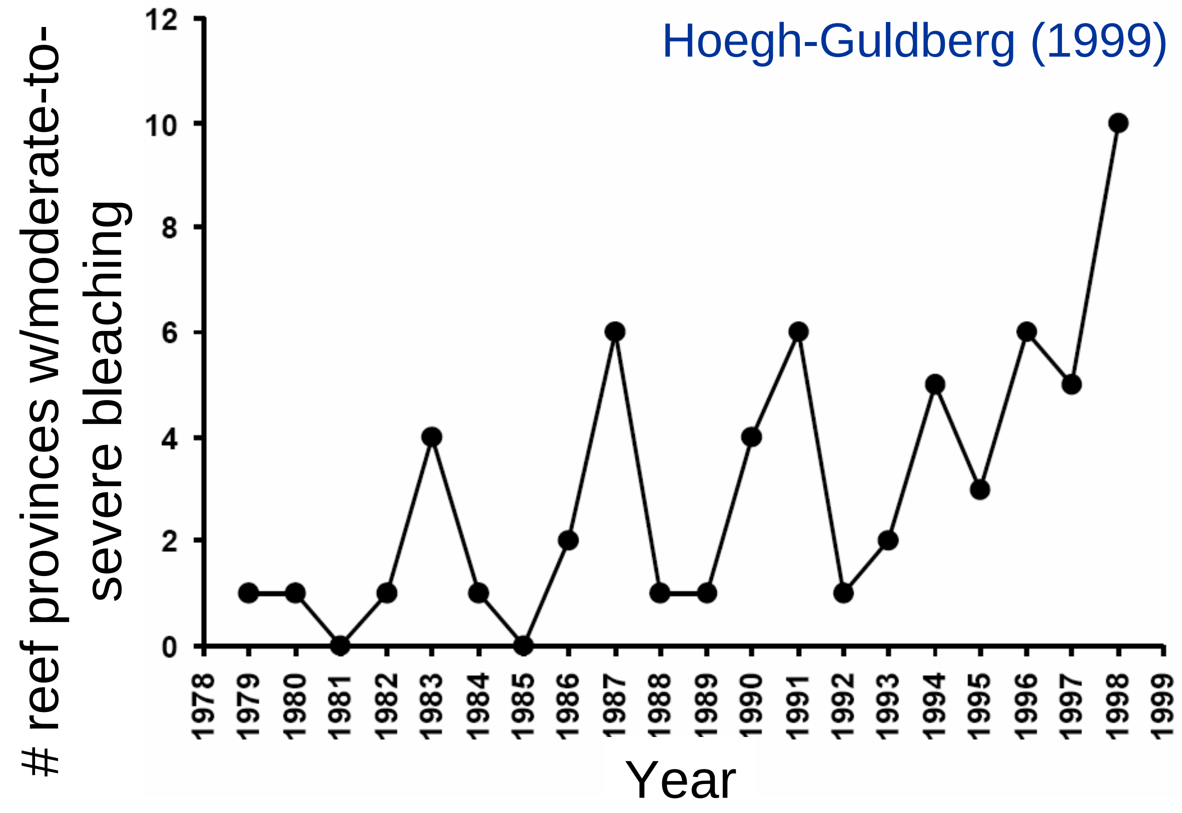
Critical rate of change $= \frac{h^2\,\sigma_z}{\sigma_w}\left(2\,r_{max} - \frac{1}{2\,N_e}\right)^{1/2}$

Selection strength

Effective pop size

Example: coral bleaching

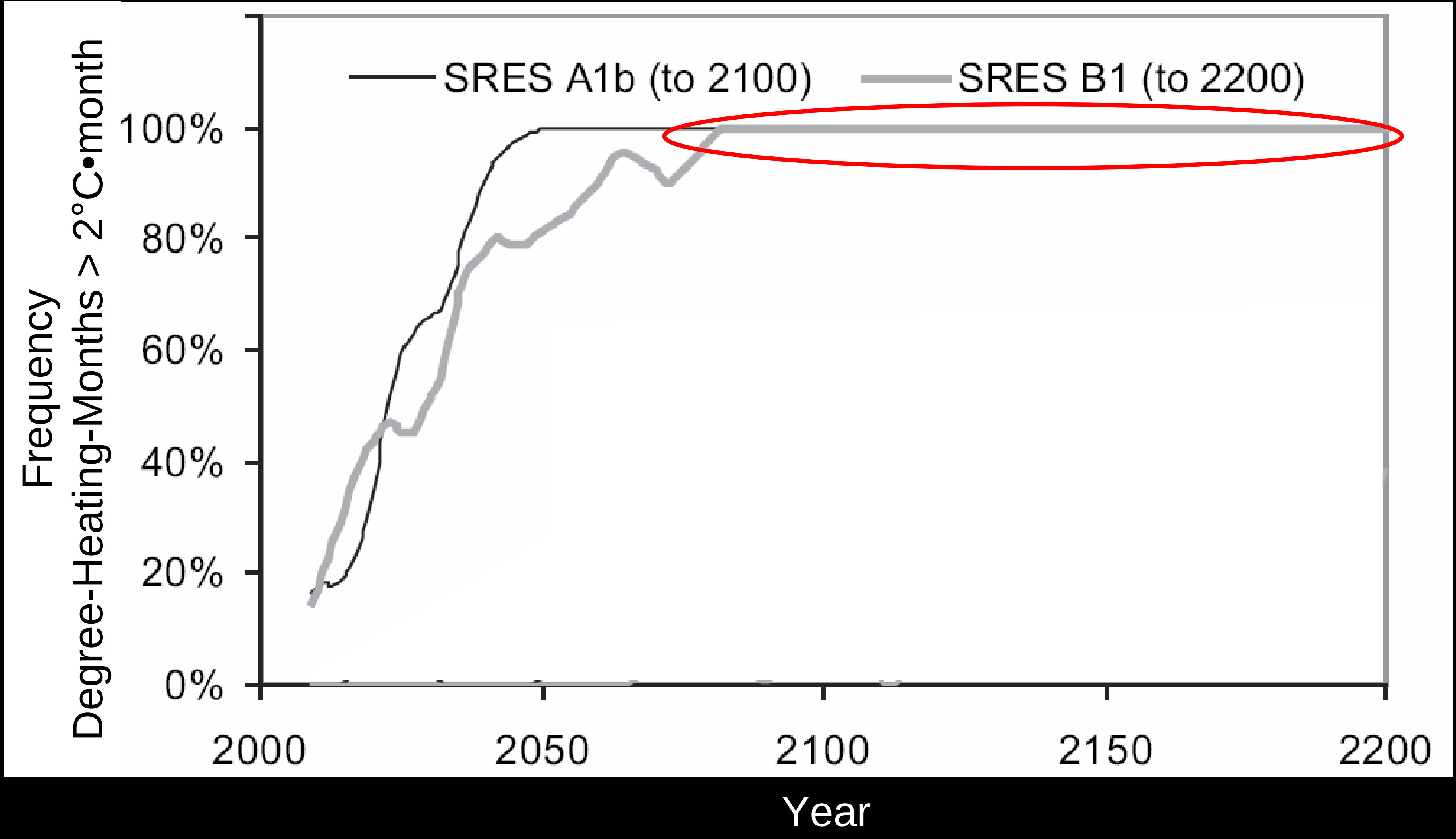



Hoegh-Guldberg (1999)

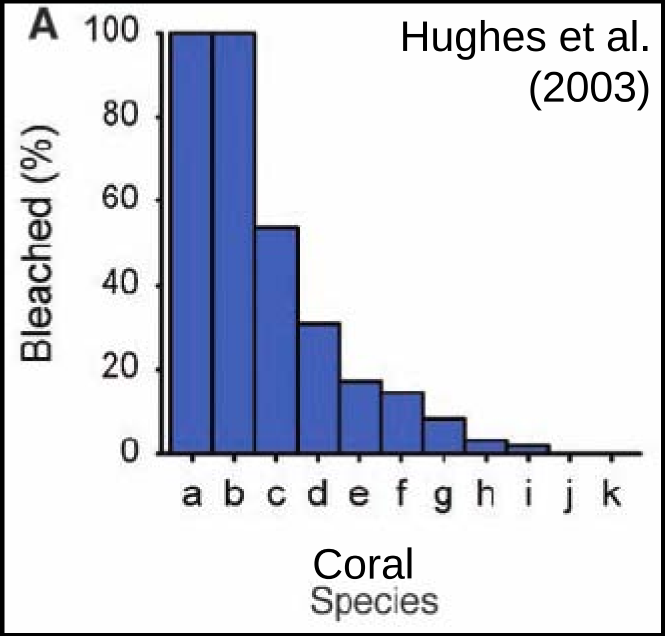
Coral bleaching: future threat

Cumulative-thermal-stress-based

Donner et al. (2007)

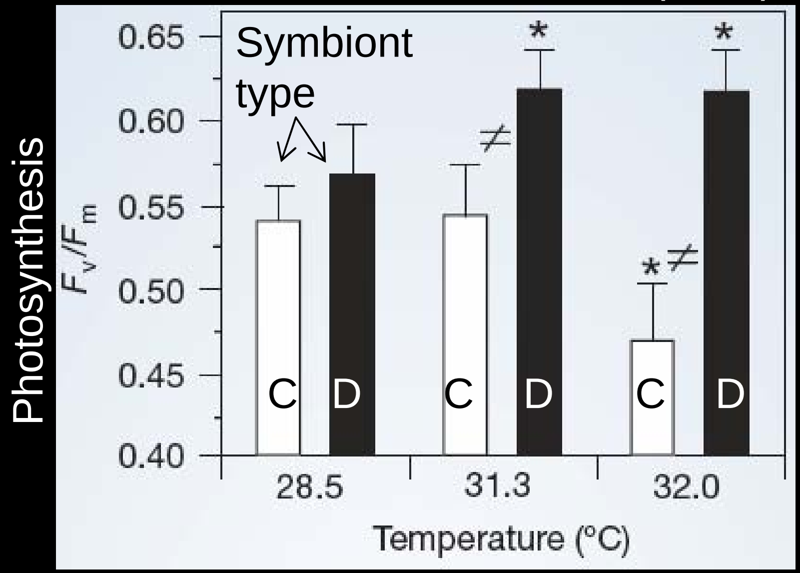


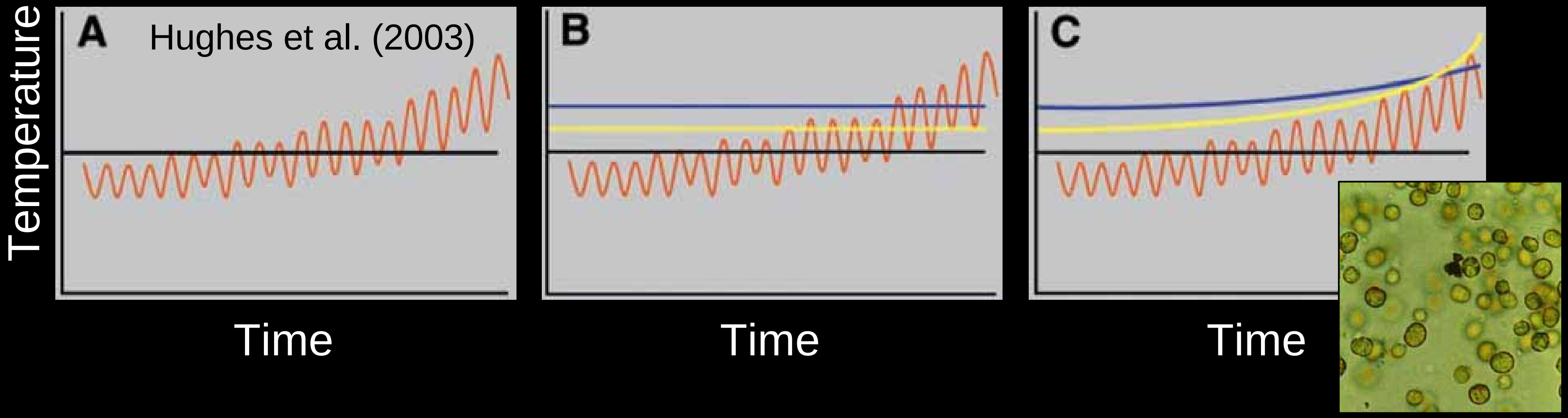
Potential for coral response



Hughes et al. (2003)

Rowan (2004)



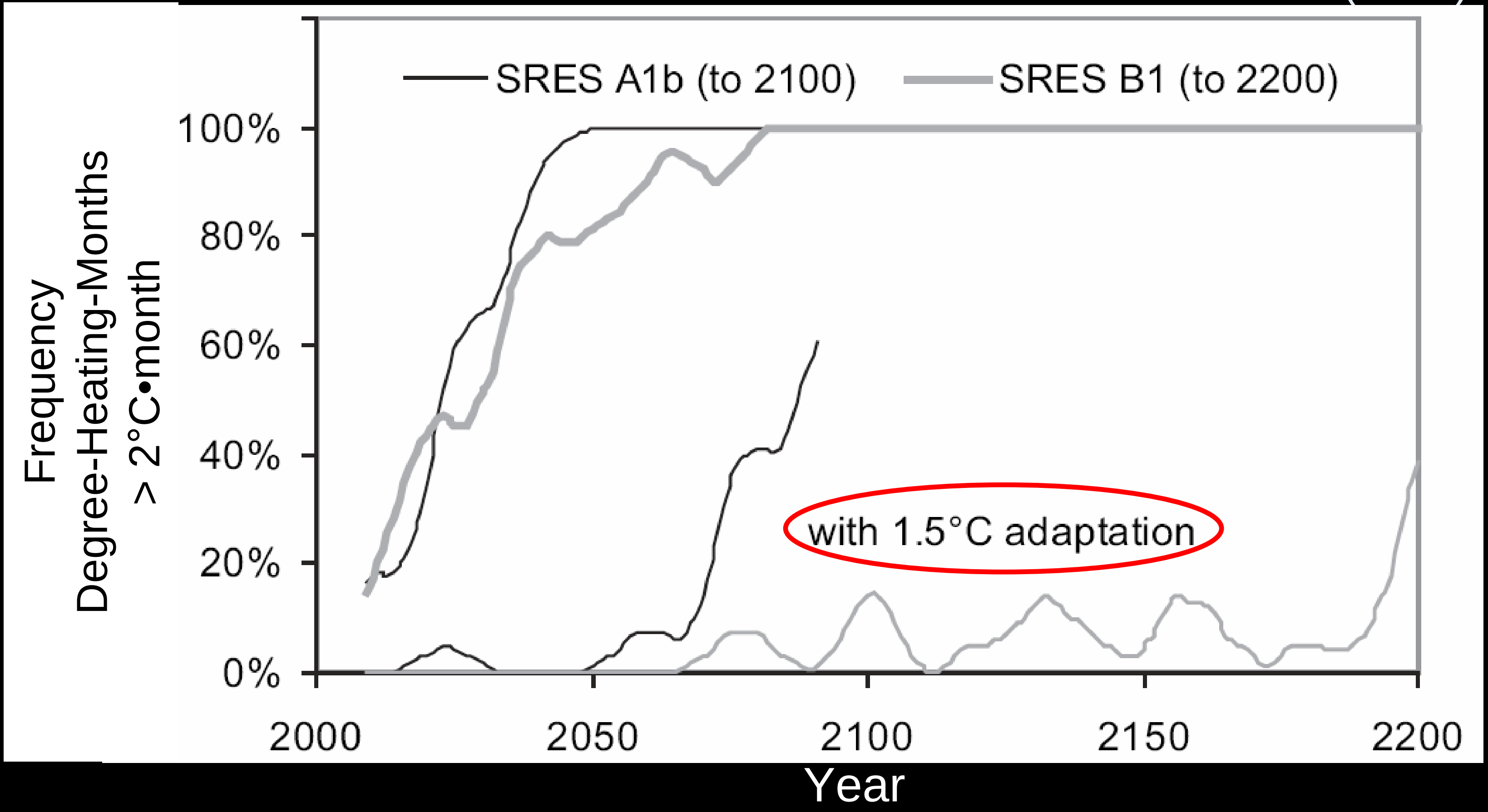


Hughes et al. (2003)

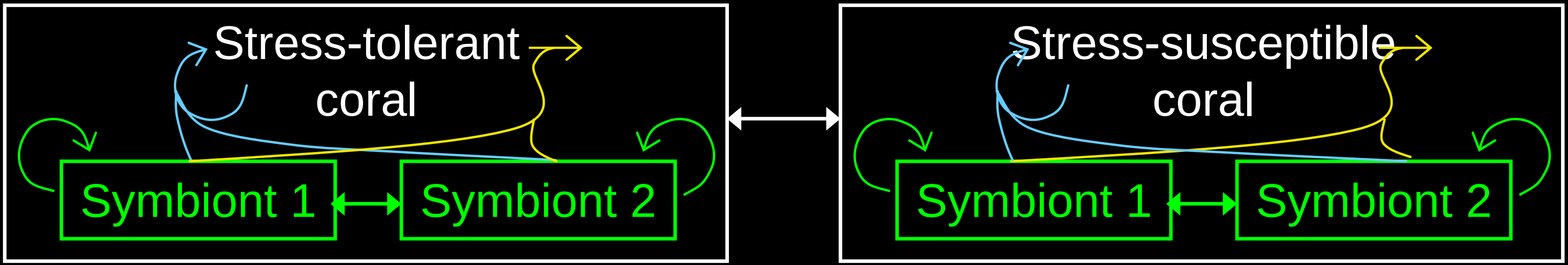
Central question: rate of response

Can coral reefs respond to climate change via genetic adaptation & community shifts?

Donner et al. (2007)



Model: population dynamics



Stress-tolerant coral

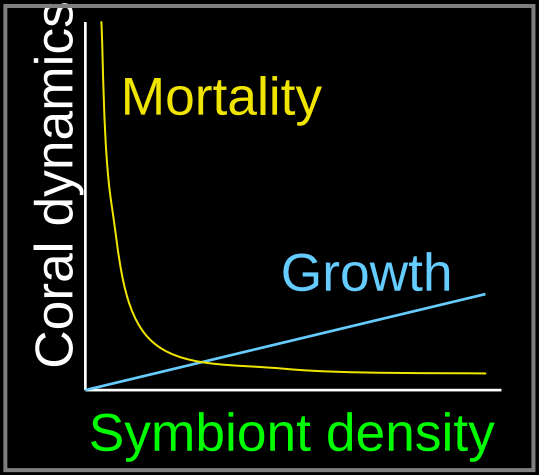
Symbiont 1

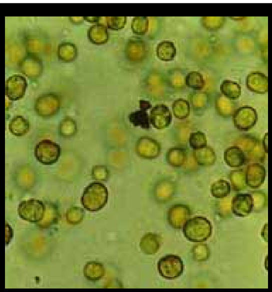
Symbiont 2

Stress-susceptible coral

Symbiont 1

Symbiont 2

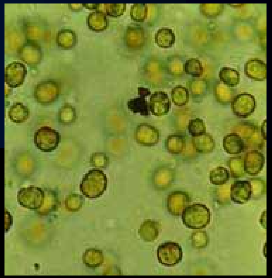




$$\frac{dC_m}{dt} = C_m \left(\frac{\gamma_m \sum S_{im}}{K_{Sm} C_m} \bullet \frac{K_{Cm} - \alpha_{mn} \sum C_n}{K_{Cm}} - \frac{\mu_m}{1 + u_m \sum S_{im} / K_{Sm} C_m} \right)$$

$$\frac{dS_{im}}{dt} = \frac{S_{im}}{K_{Sm} C_m} \left(K_{Sm} C_m r_{im} - \hat{r}(t) \sum S_{jm} \right)$$

Model: genetic dynamics

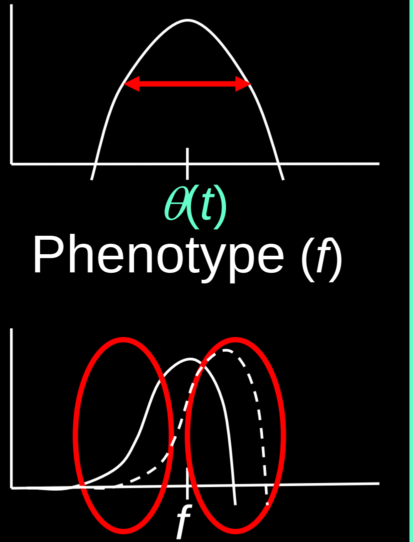


Population growth rate

Density dependence

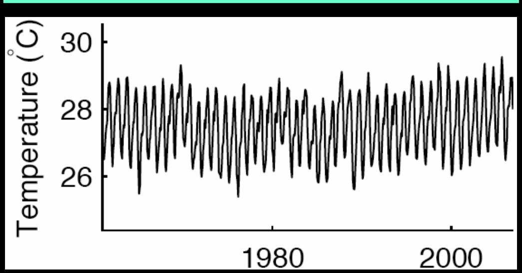
Asymptotic growth rate

Fitness



Phenotype (f)

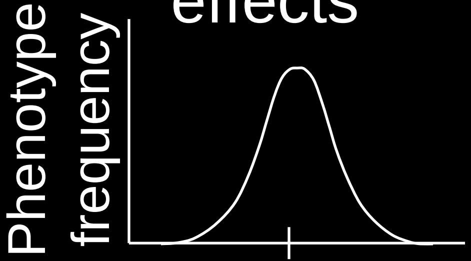
Temperature ($\theta(t)$)



Phenotype distribution

Genotype distribution

Environmental effects



Phenotype (f)

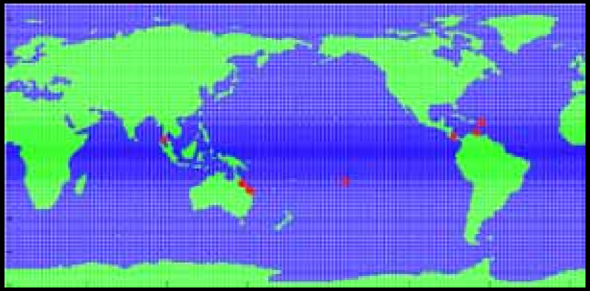
$$r_{im} = \left(1 - \frac{\sigma^2_{gim} + \sigma^2_{e} + [\,\theta(t) - g_{im}]^2}{2\sigma^2_{wm}}\right) ae^{b\theta(t)}$$

$$\frac{dg_{im}}{dt} = \frac{\sigma^2_{gim}[\,\theta(t) - g_{im}]}{\sigma^2_{wm}} ae^{b\theta(t)}$$

$$\frac{d\sigma^2_{gim}}{dt} = \sigma^2_{M} - \frac{\sigma^4_{gim}}{\sigma^2_{wm}} ae^{b\theta(t)}$$

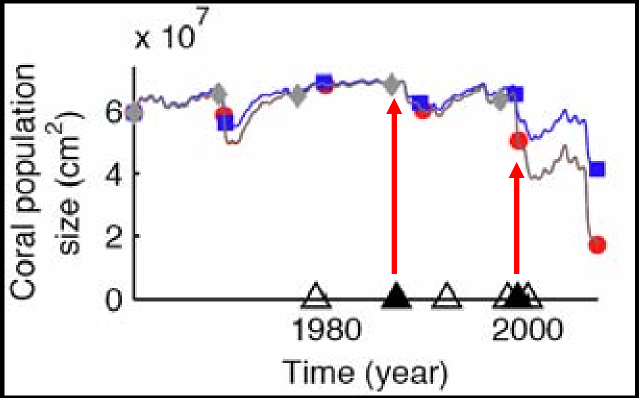
Adapted from Lynch et al. (1991)

Model tests



- Multiple locations
- Multiple climate models & scenarios

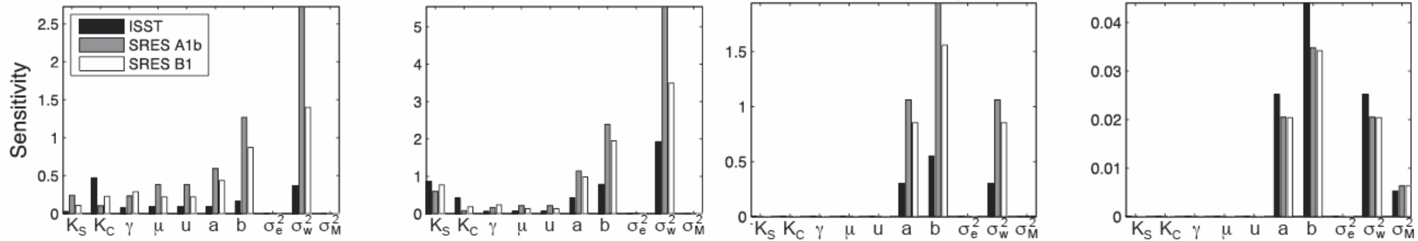
HadCM3, GFDL 2.1



- Predictions with past temperatures
- Sensitivity to model assumptions

Try with: open symbiont dynamics, coral heterotrophy, coral size structure

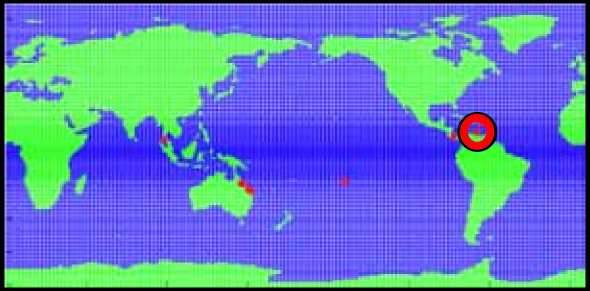
- Sensitivity to parameter values



Chancerelle (2000)
Mumby (2006)
Langmead & Sheppard (2004)
Huston (1985)
McClanahan et al. (2001)
Fitt et al. (2000)
Muscatine et al. (1984)
Eppley (1972)
Mousseau and Roff (1987)

Model tests

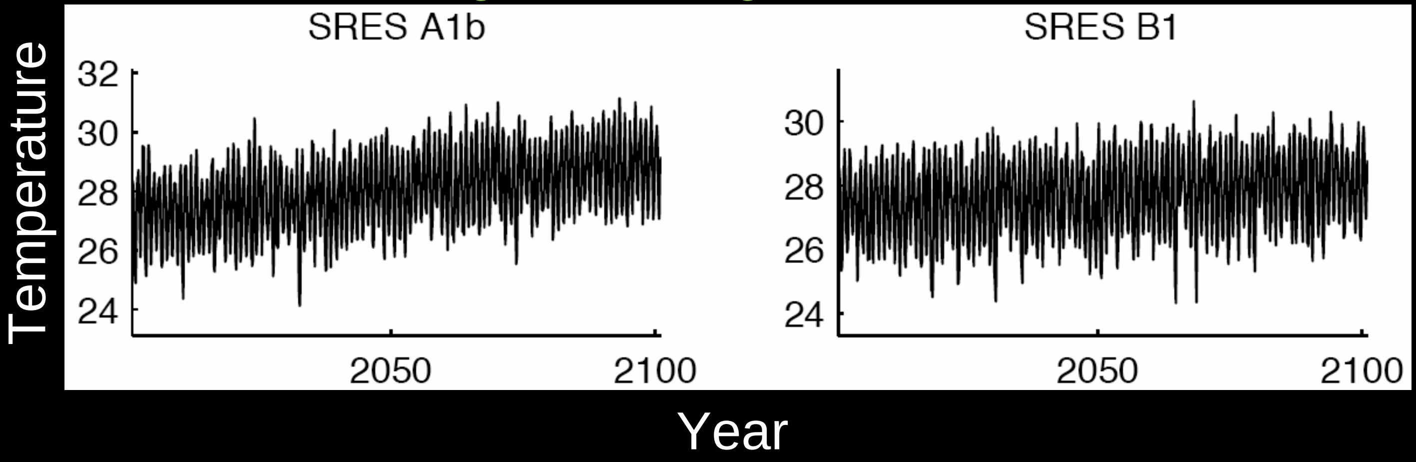
- Multiple locations



- Multiple climate models & scenarios

HadCM3, GFDL 2.1

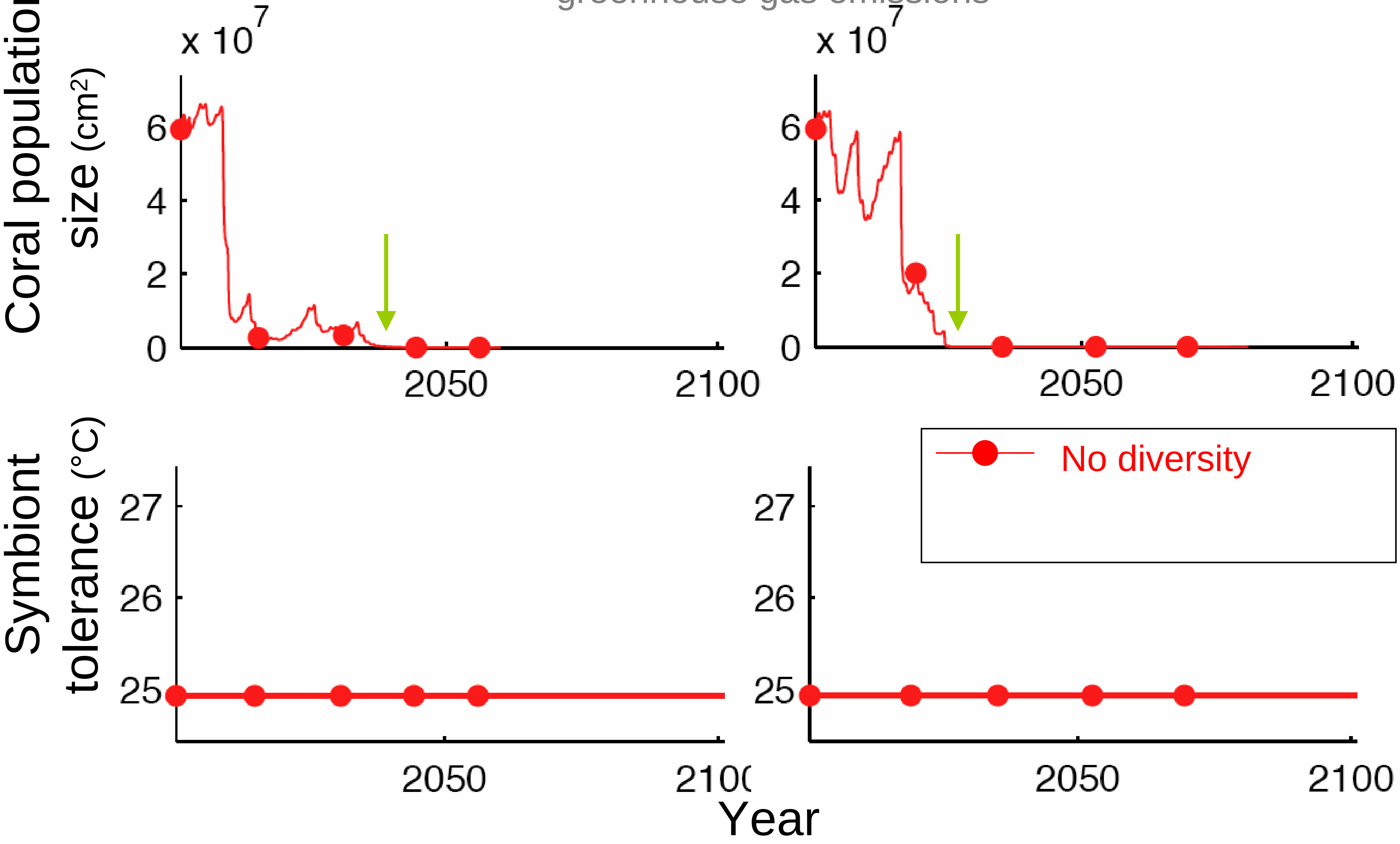
higher lower
greenhouse gas emissions



Baskett, Gaines, & Nisbet, in revision, *Ecol Appl*

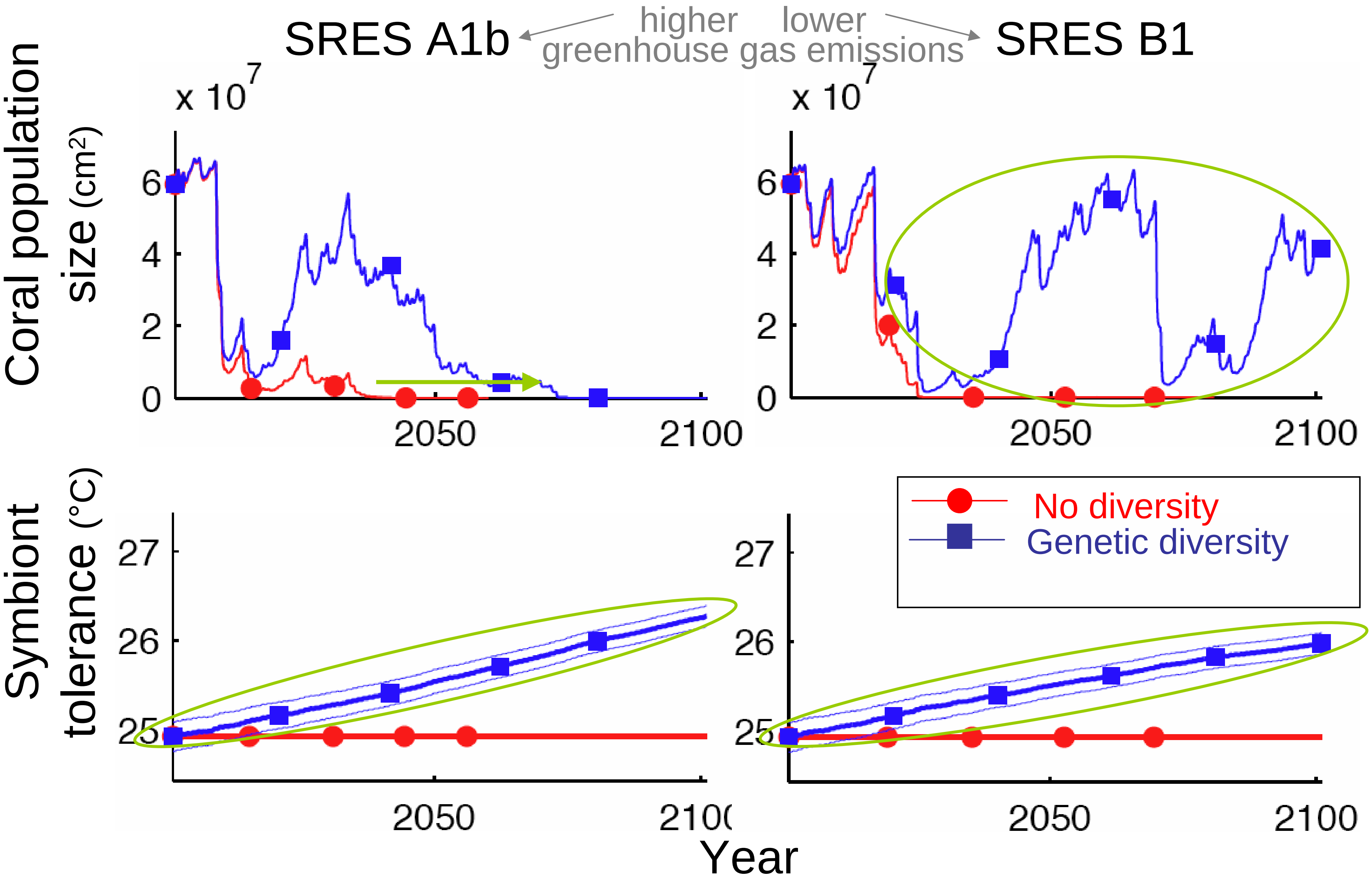
Symbiont diversity

SRES A1b ← higher lower → SRES B1
greenhouse gas emissions



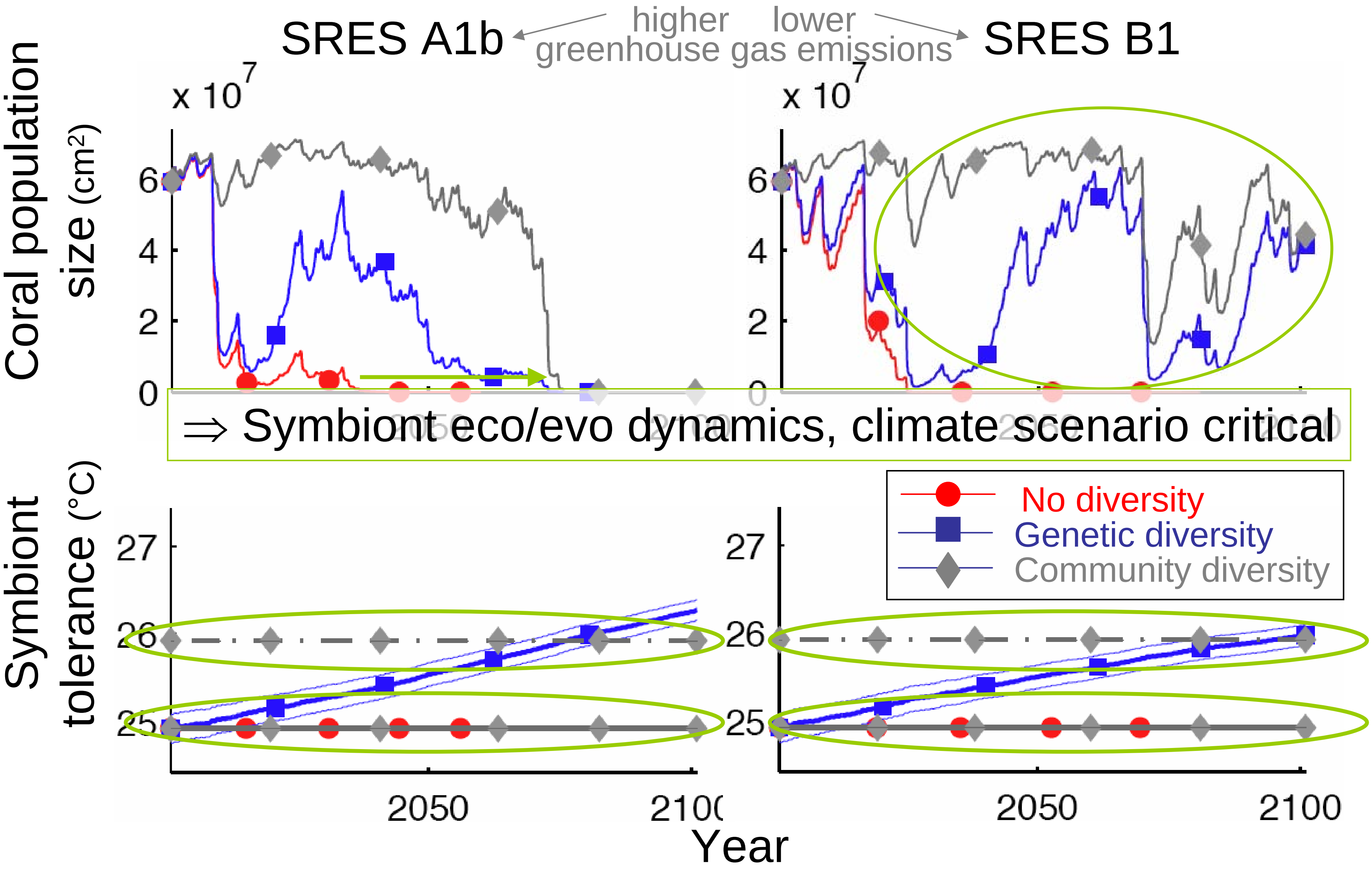
Baskett, Gaines, & Nisbet, in revision, *Ecol Appl*

Symbiont diversity



Baskett, Gaines, & Nisbet, in revision, *Ecol Appl*

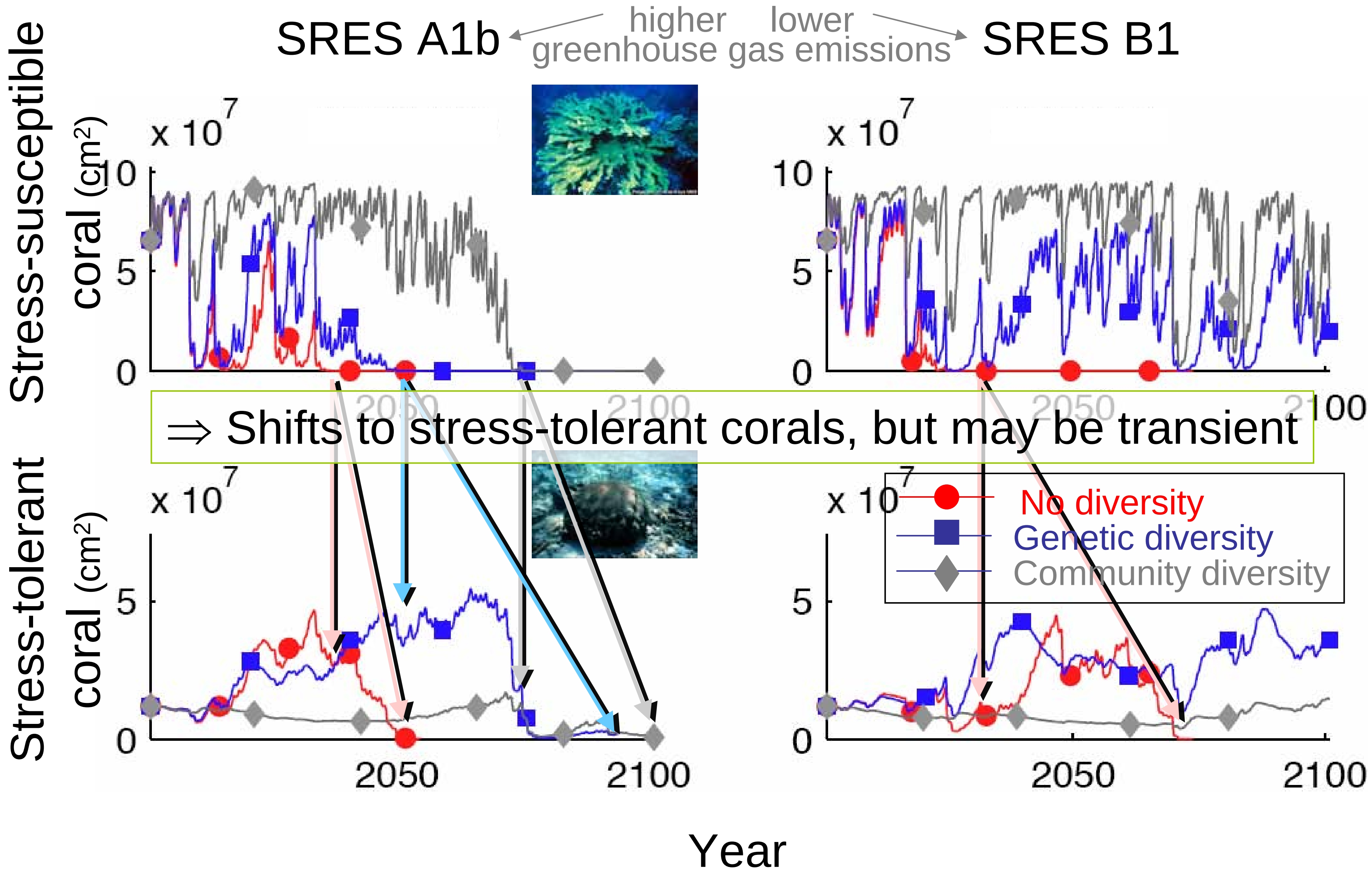
Symbiont diversity



⇒ Symbiont eco/evo dynamics, climate scenario critical

Baskett, Gaines, & Nisbet, in revision, *Ecol Appl*

Coral diversity

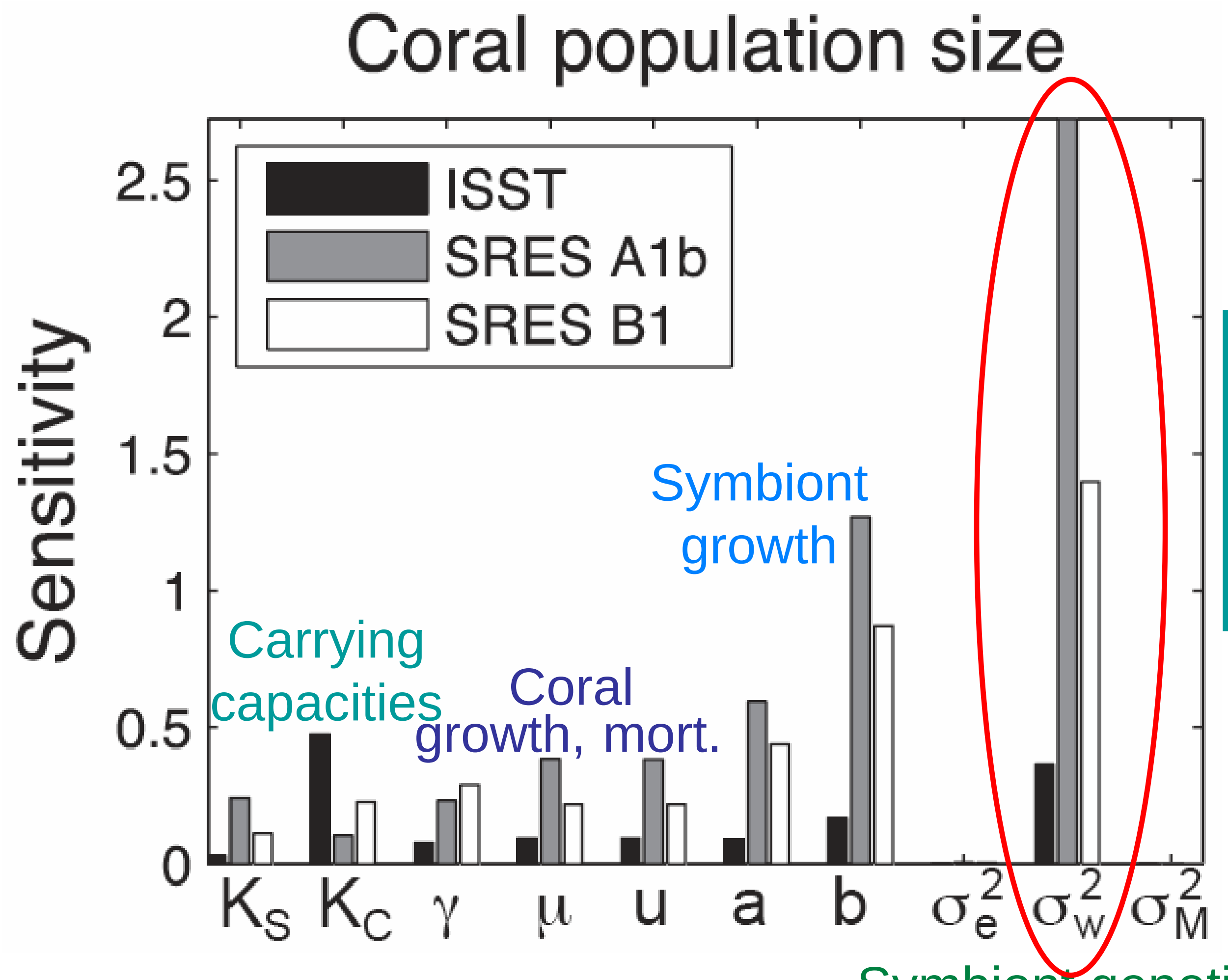


SRES A1b ← higher greenhouse gas emissions lower → SRES B1

⇒ Shifts to stress-tolerant corals, but may be transient

Baskett, Gaines, & Nisbet, in revision, *Ecol Appl*

Sensitivity analysis

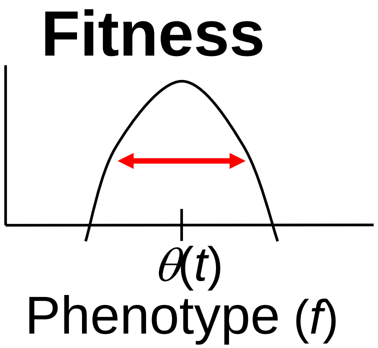


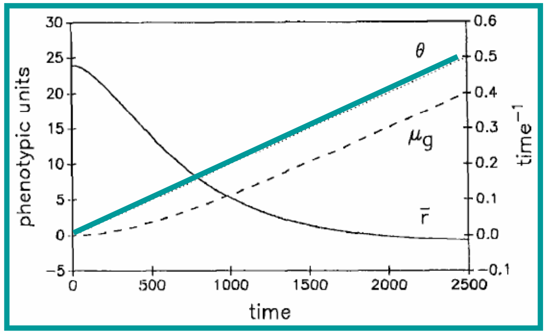
Carrying capacities

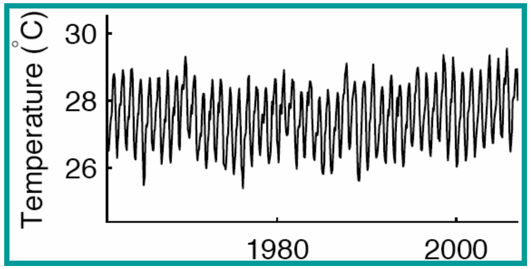
Coral growth, mort.

Symbiont growth

Symbiont genetics







Conclusions: coral bleaching

Accounting for biological variation and dynamics reveals importance of future climate scenario to coral persistence

Protecting response capacity

- Which reefs to protect?
  High diversity, low stress levels (with connectivity)

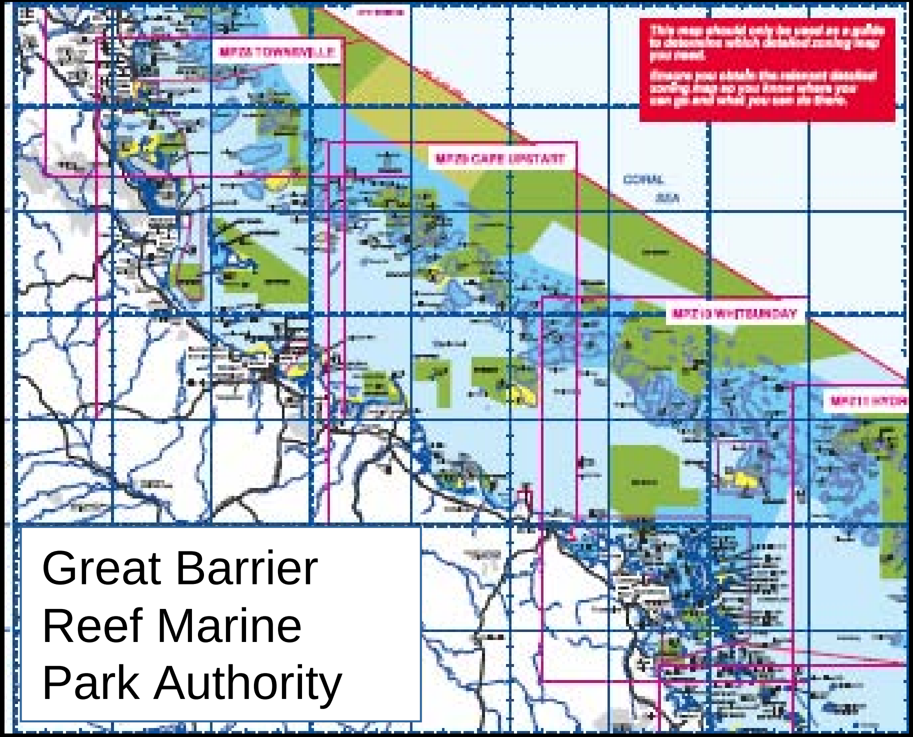
- Which additional impacts to protect against?
  Reduce algal competition, impacts on coral mortality and recruitment (vs. coral growth, fragmentation)

Baskett, Nisbet, Kappel, Mumby, & Gaines, in prep; West & Salm 2003; Bellwood et al. 2004

Management in a changing climate

- Movement
- Acclimatization
- Genetic adaptation

Protect response capacity



Great Barrier Reef Marine Park Authority

1. Protect locations with greater response capacity

2. Protect against local impacts that may reduce response capacity

Acknowledgements

collaborators:
Steve Gaines, Roger Nisbet

also:
Drew Allen, Troy Day, Simon Donner, Ruth Gates, Alan Hastings, Pete Edmunds, Carrie Kappel, Nancy Knowlton, Sally Holbrook, Jim Leichter, Monica Medina, Pete Mumby, Ben Santer, Russ Schmitt, Jen Smith, Mark Urban, Madeleine van Oppen

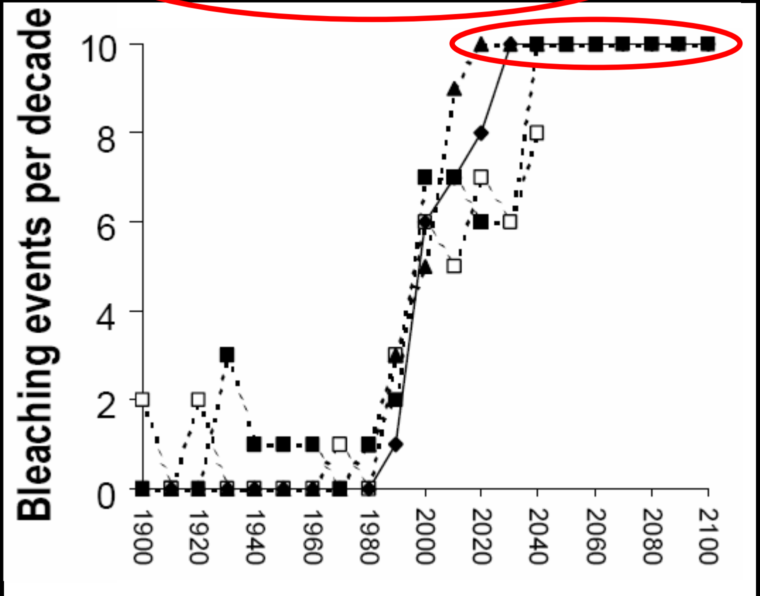
funding:

NSF NCEAS LTER Moorea

Photos: reefbase.org

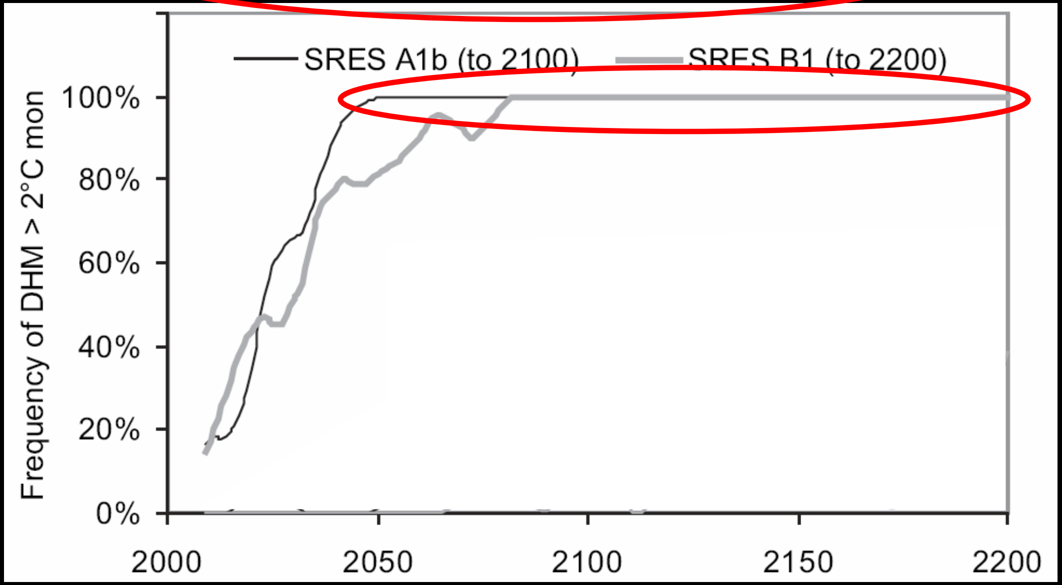
Coral bleaching: future threat

Temperature-based



Hoegh-Guldberg (1999)

Cumulative-thermal-stress-based



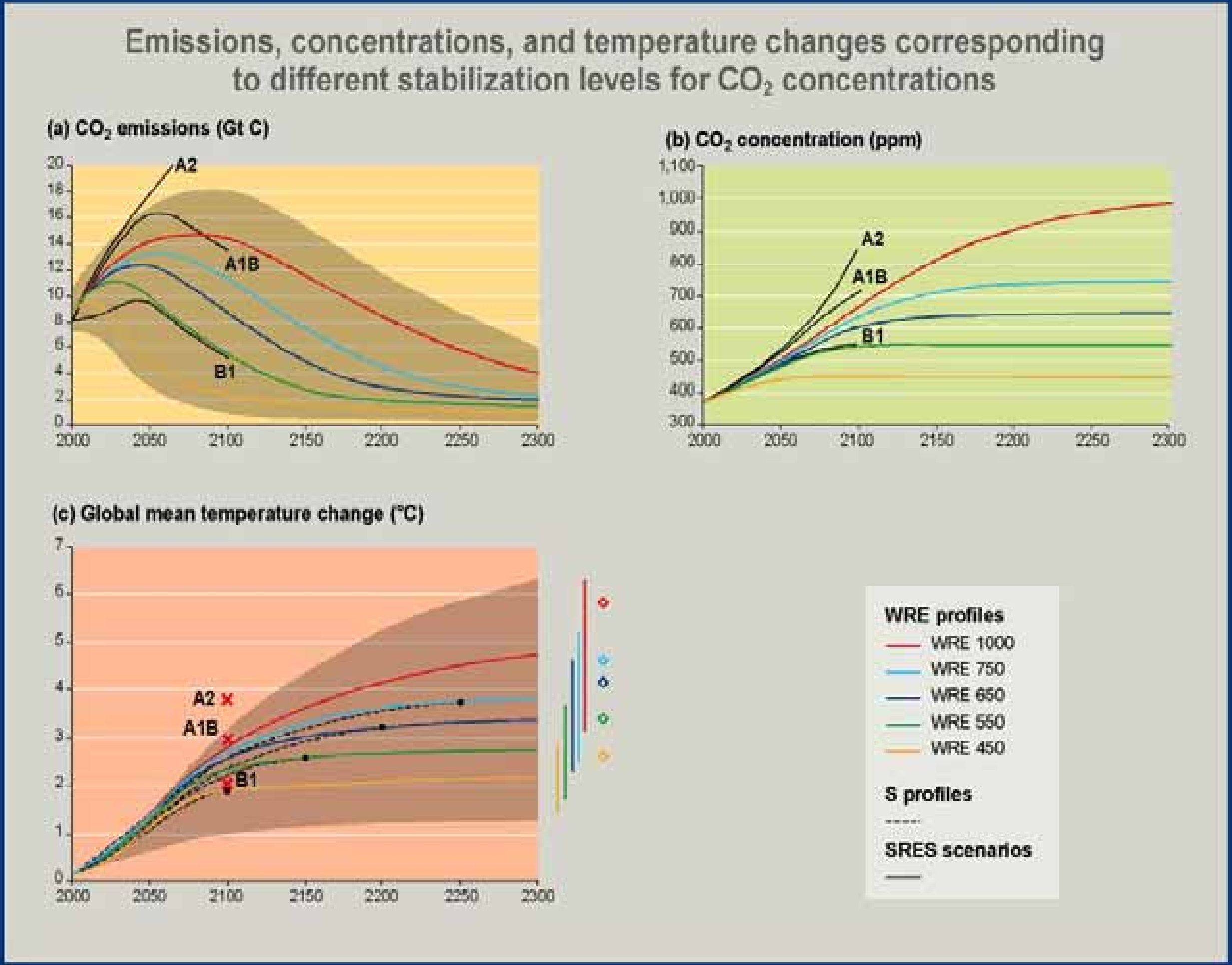
Donner et al. (2007)

Corals: multiple human impacts

Jackson et al. 2001

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Emissions scenarios



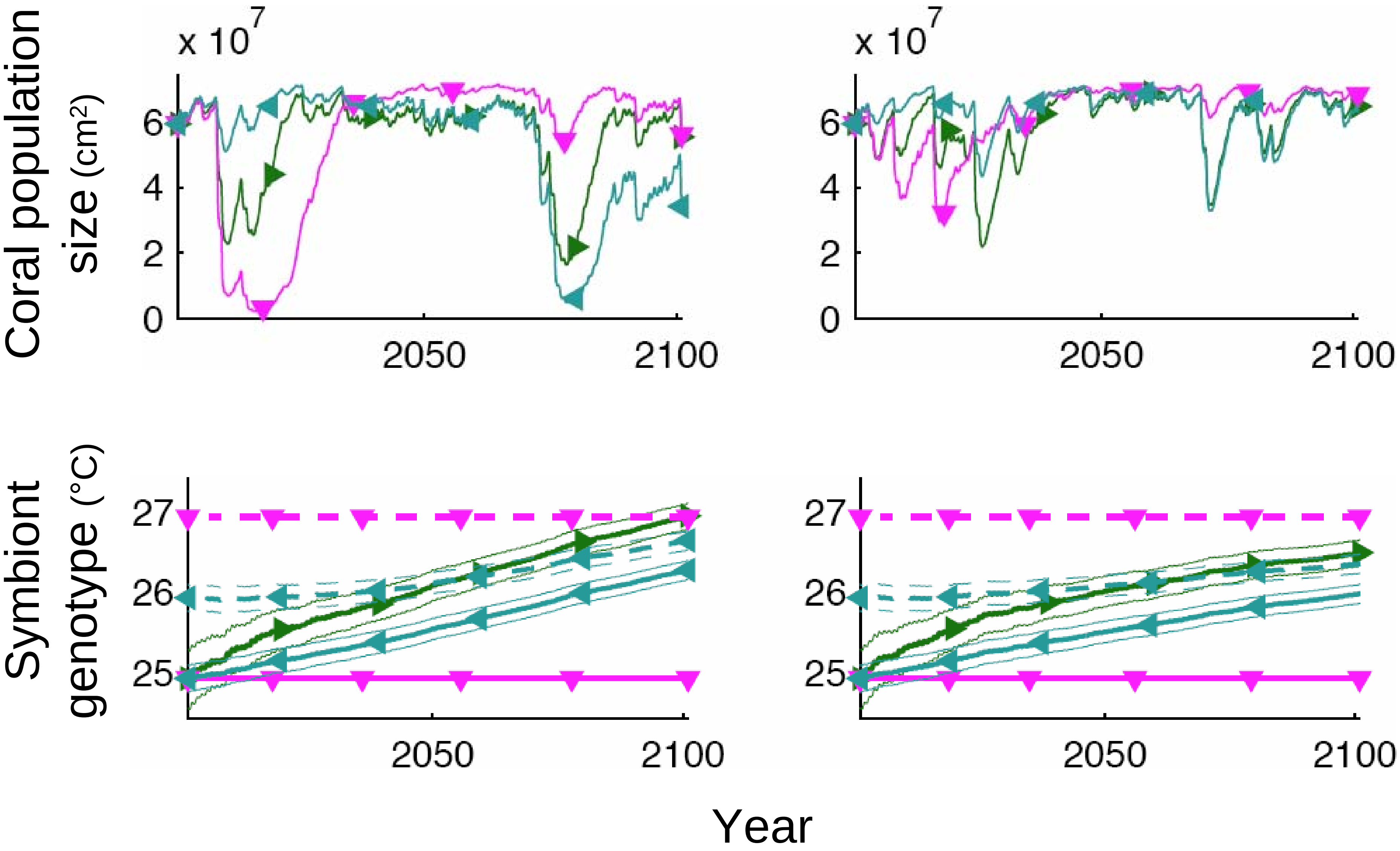
Emissions, concentrations, and temperature changes corresponding to different stabilization levels for CO_2 concentrations

SYR - FIGURE 6-1

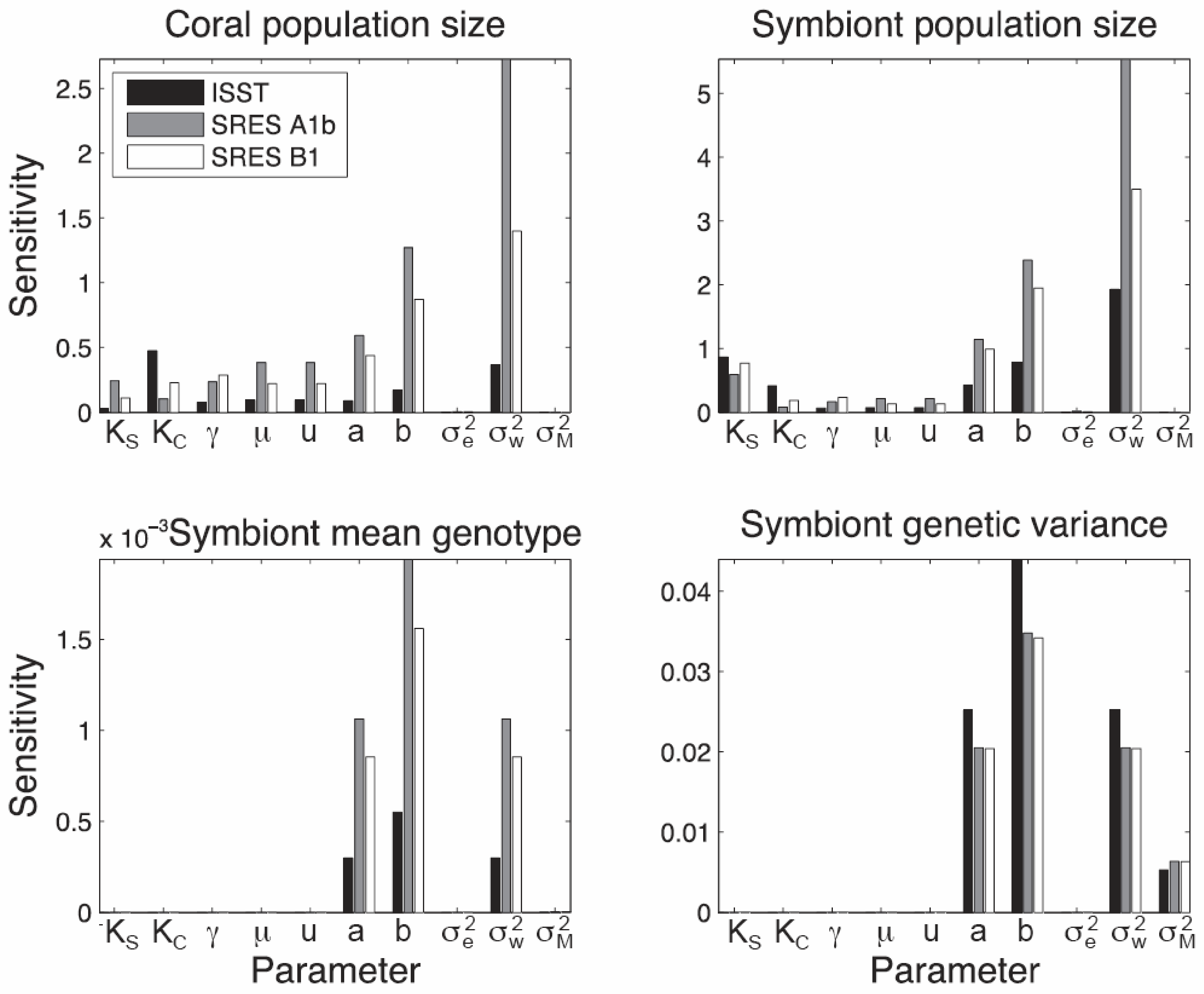
Results: more symbiont diversity

SRES A1b ← higher lower → SRES B1

greenhouse gas emissions



Results: sensitivity analysis



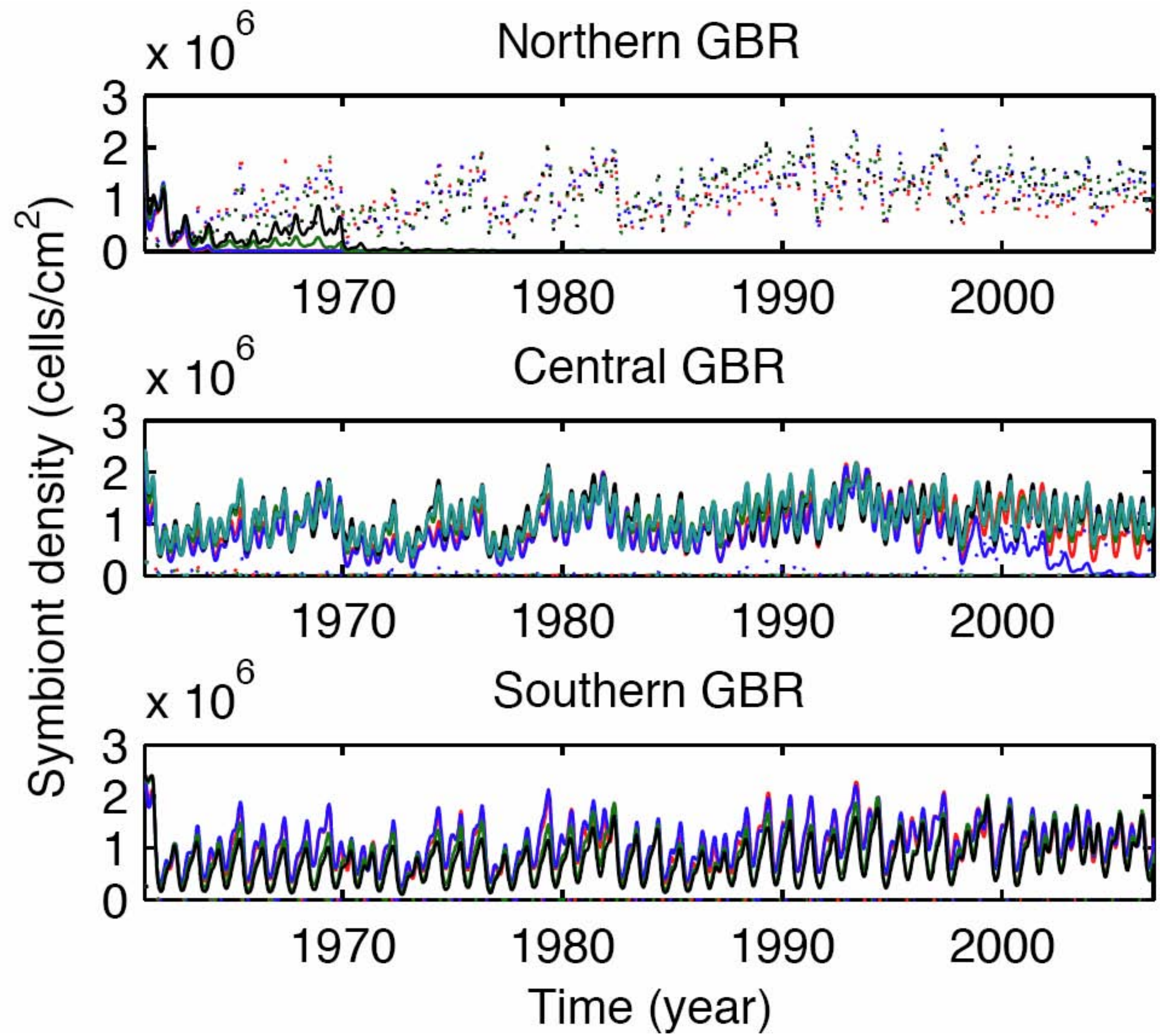
Coral population size

Symbiont population size

Symbiont mean genotype

Symbiont genetic variance

Results: latitudinal gradient



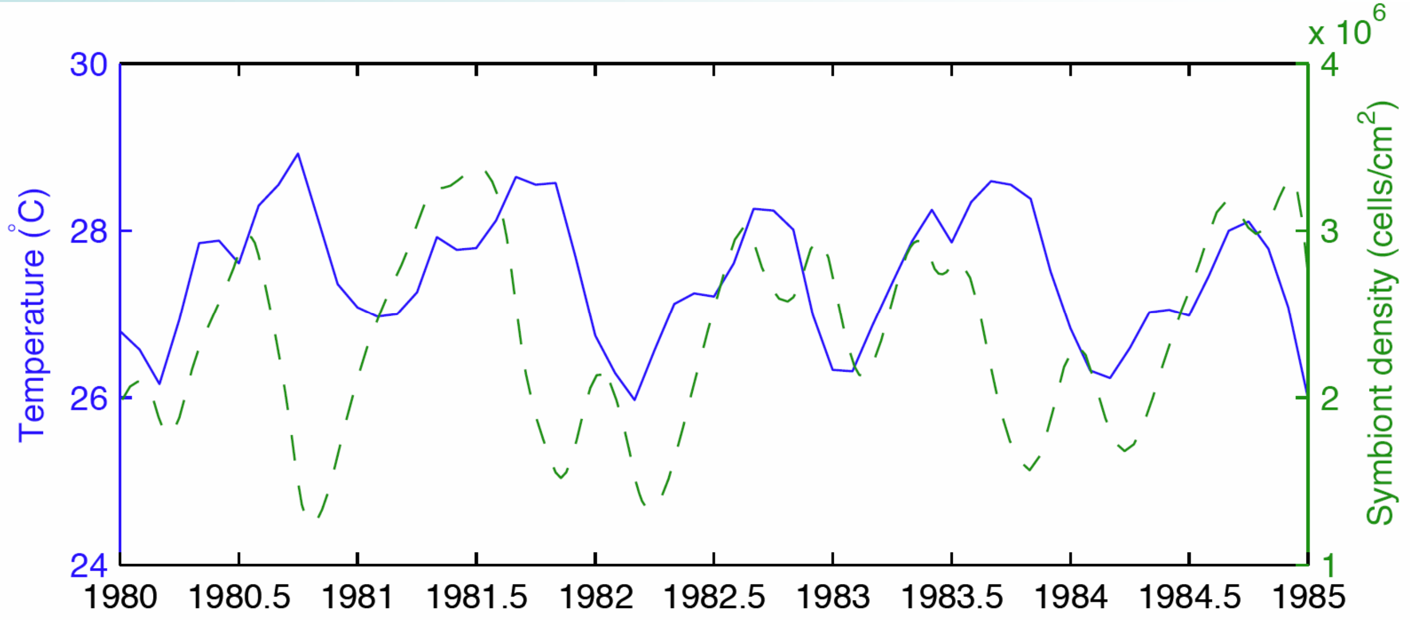
Observed
<u>dominant symbiont</u>

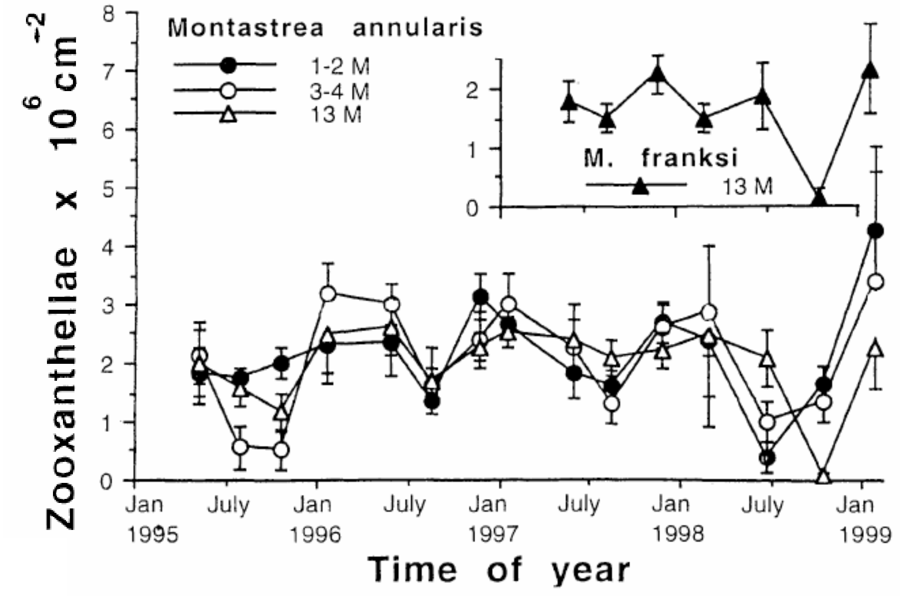
Symbiodinium D

Symbiodinium C

Symbiodinium C

Results: symbiont fluctuations



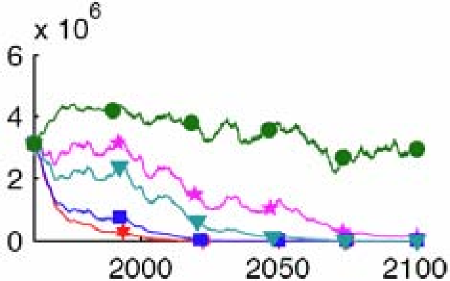


Fitt et al. (2000)

Conclusions

Accounting for biological variation and dynamics reveals importance of future climate scenario to coral persistence

Protecting response capacity



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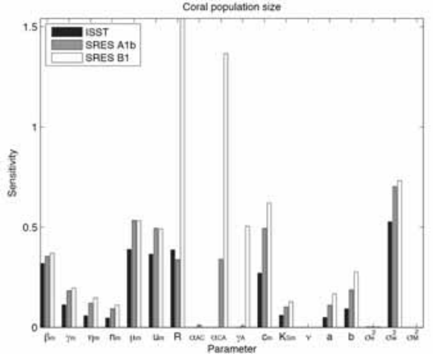
  High diversity, low stress levels (with connectivity)

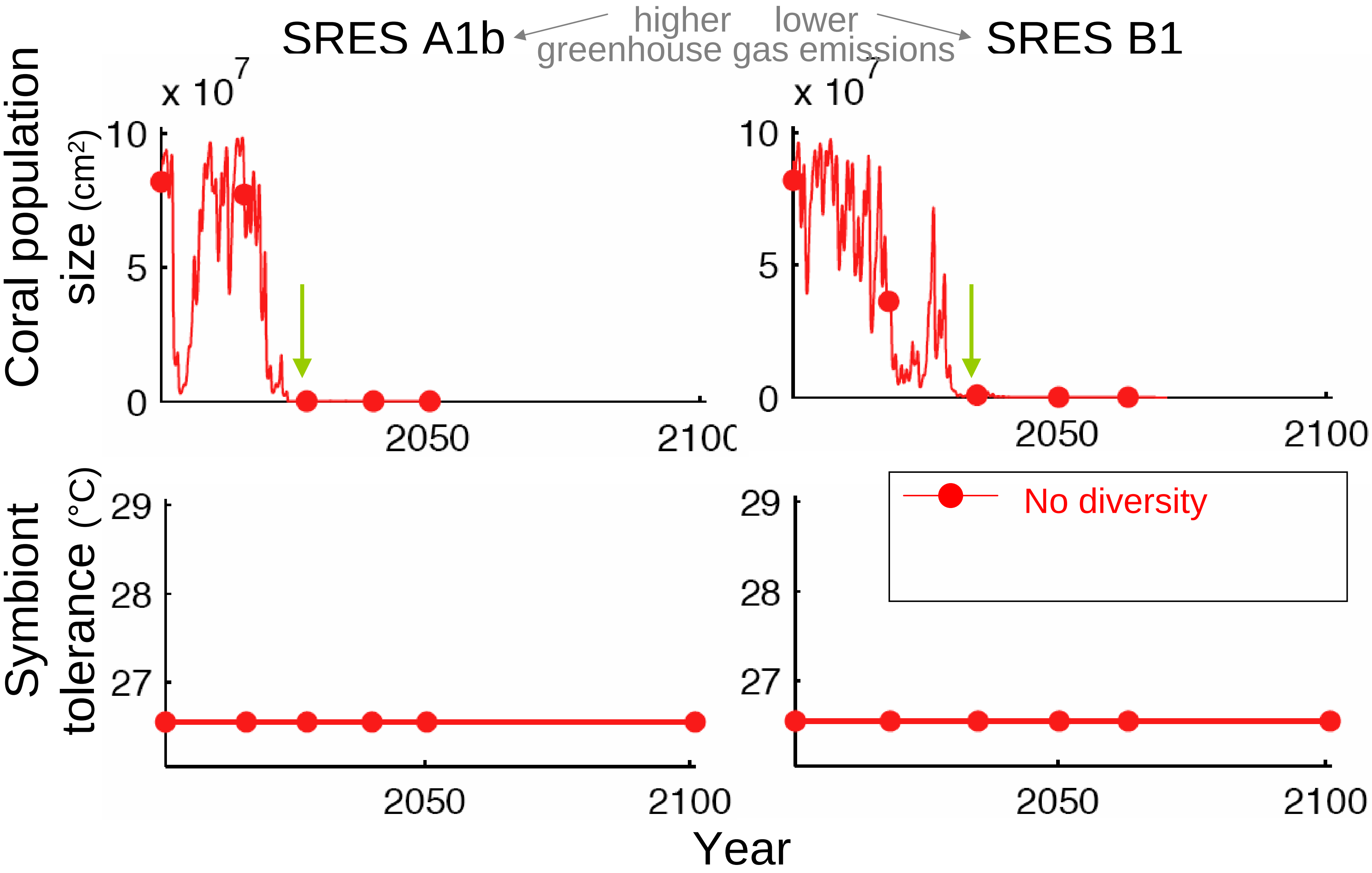


- Which additional impacts to protect against?

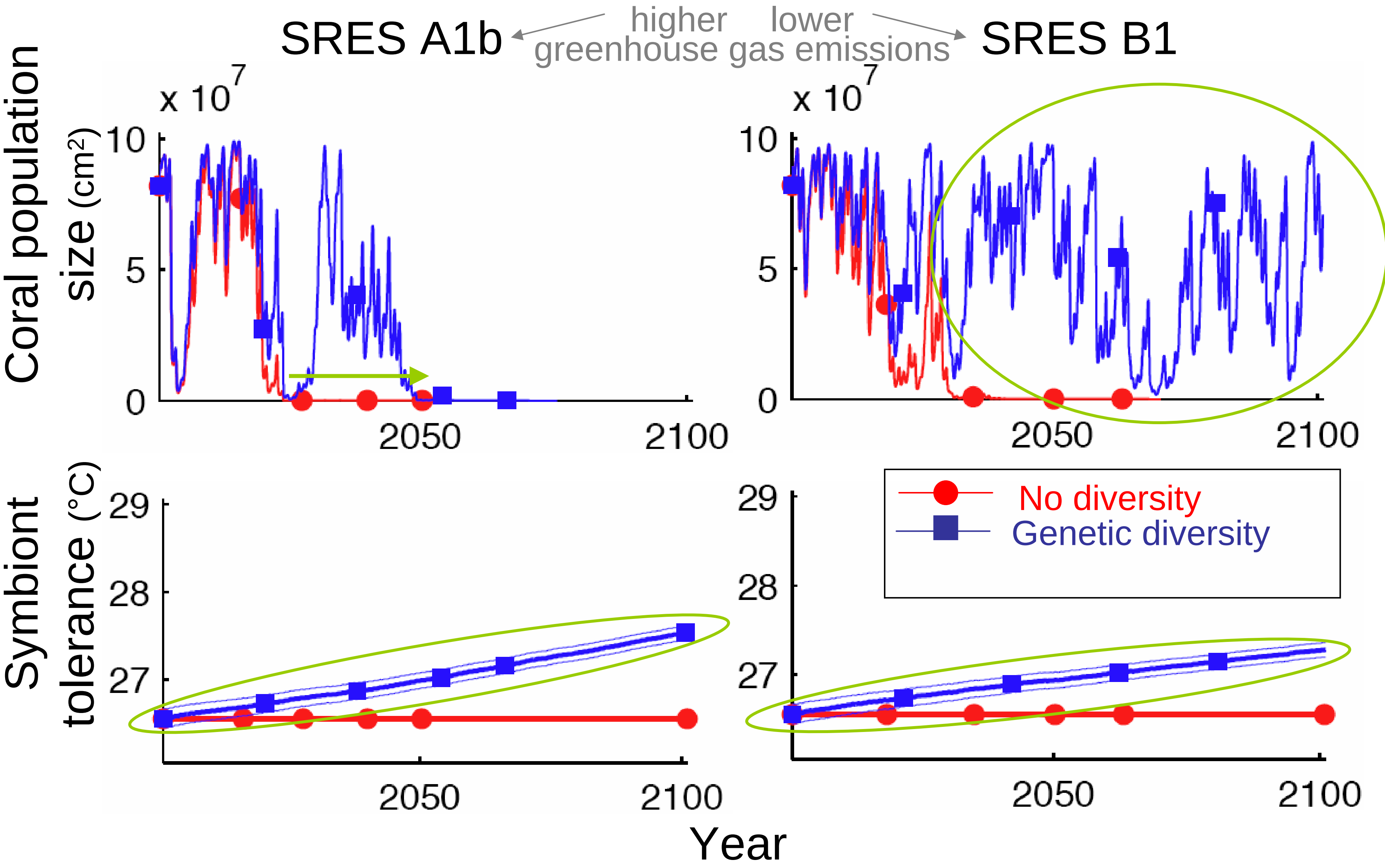
  Reduce algal competition, impacts on coral mortality and recruitment (vs. coral growth, shrinkage)


------- Pacific results -------

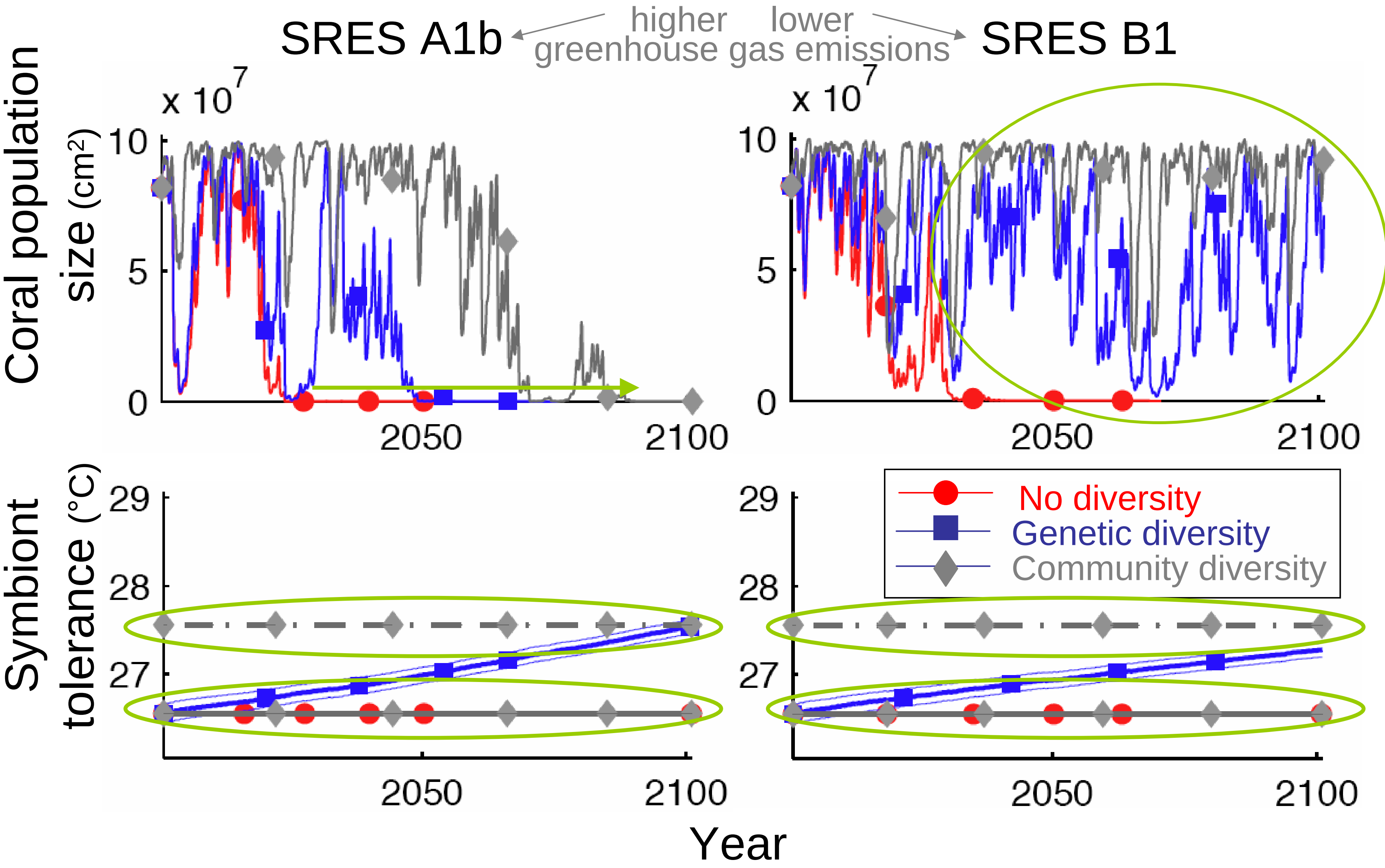
Results: symbiont diversity



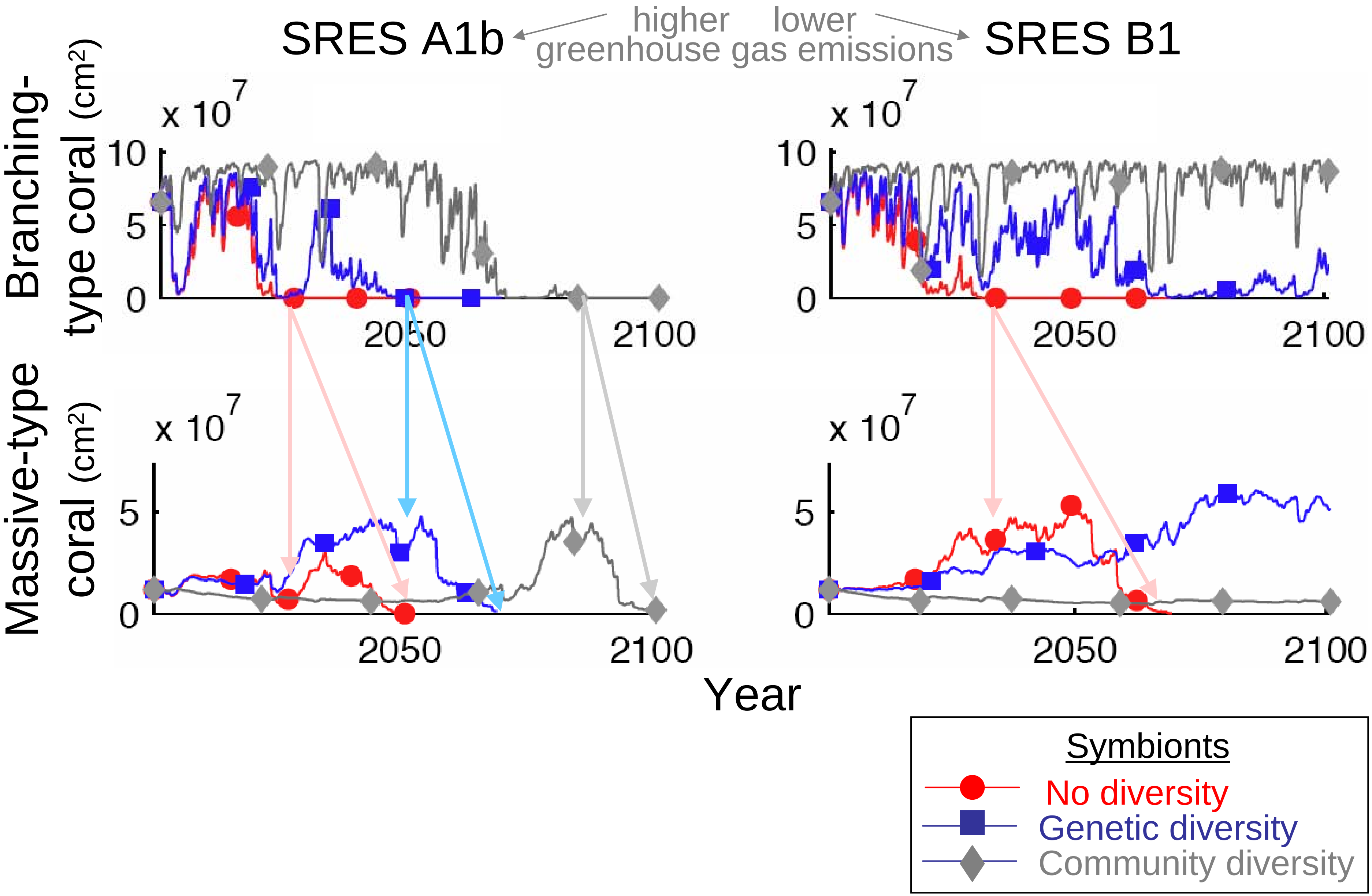
Results: symbiont diversity



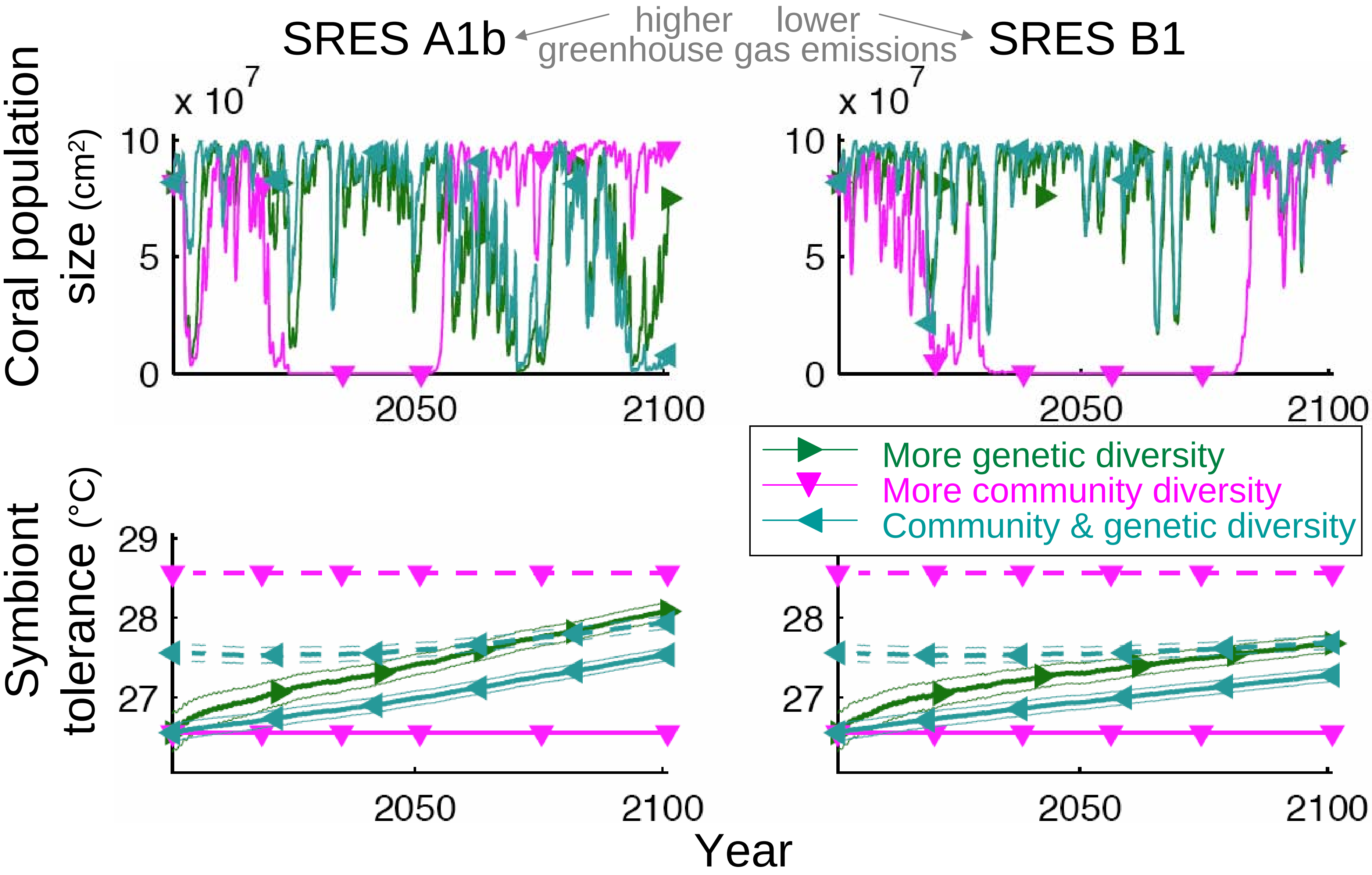
Results: symbiont diversity



Results: coral diversity



Results: more symbiont diversity



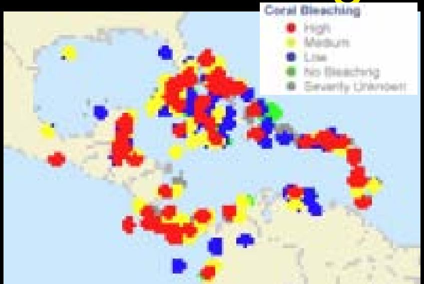
SRES A1b ← higher lower → SRES B1
greenhouse gas emissions

------- Size-structured results -------

Conservation priorities

1. Can coral reefs respond to climate change via genetic adaptation & community shifts?

2. How do we protect corals more likely to survive climate change?



(a) Which reefs to protect?

- Diversity vs. more stress-tolerant species/types
- Locations w/low stress vs. selection for stress-tolerance
- Connectivity → enhance recruitment or input of malapdapteds

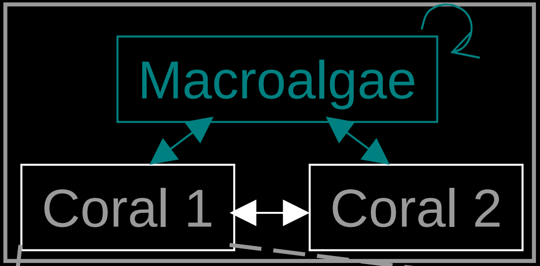
(b) Which additional human impacts to protect against?

- Locally: Sedimentation, eutrophication, herbivore overfishing, COTS
- Globally: Ocean acidification, storm intensity, disease

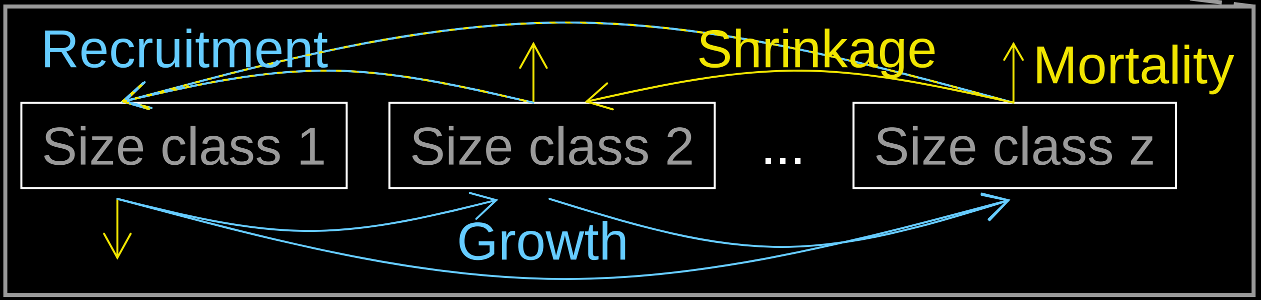
Differentially affect coral growth/recruitment/shrinkage/mortality/competition w/macroalgae

Model dynamics: added biological detail

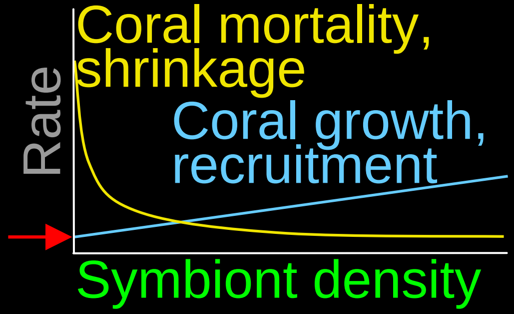
1. Macroalgae dynamics



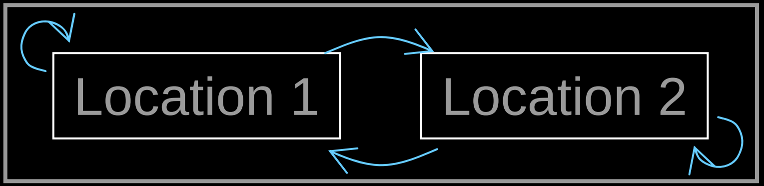
2. Size structure



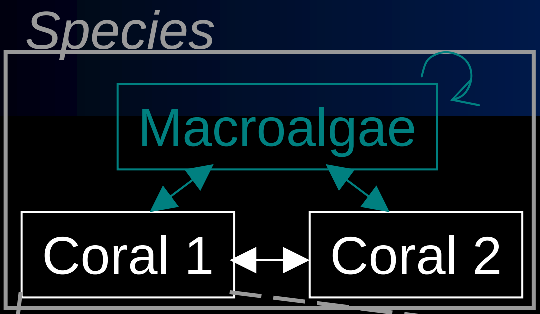
3. Heterotrophic energy acquisition



4. Spatial structure



Size-structured model



Species

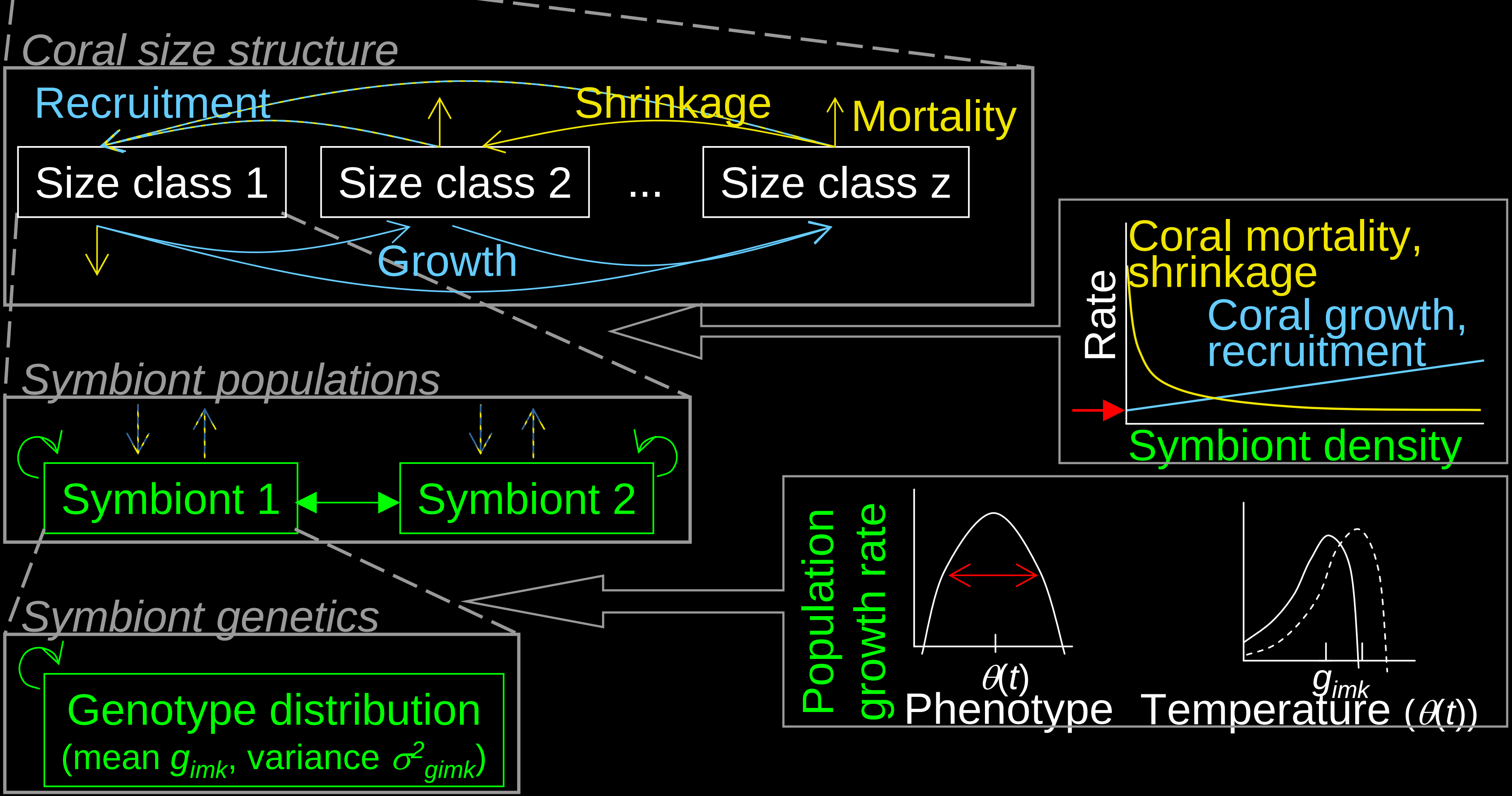
Macroalgae

Coral 1

Coral 2

<

<



Coral size structure

Recruitment

Shrinkage

Mortality

Size class 1

Size class 2

...

Size class z

Growth

Rate

Coral mortality, shrinkage

Coral growth, recruitment

Symbiont density

Symbiont populations

Symbiont 1

Symbiont 2

Symbiont genetics

Genotype distribution

(mean g_{imk}, variance $\sigma^2{}_{gimk}$)

Population growth rate

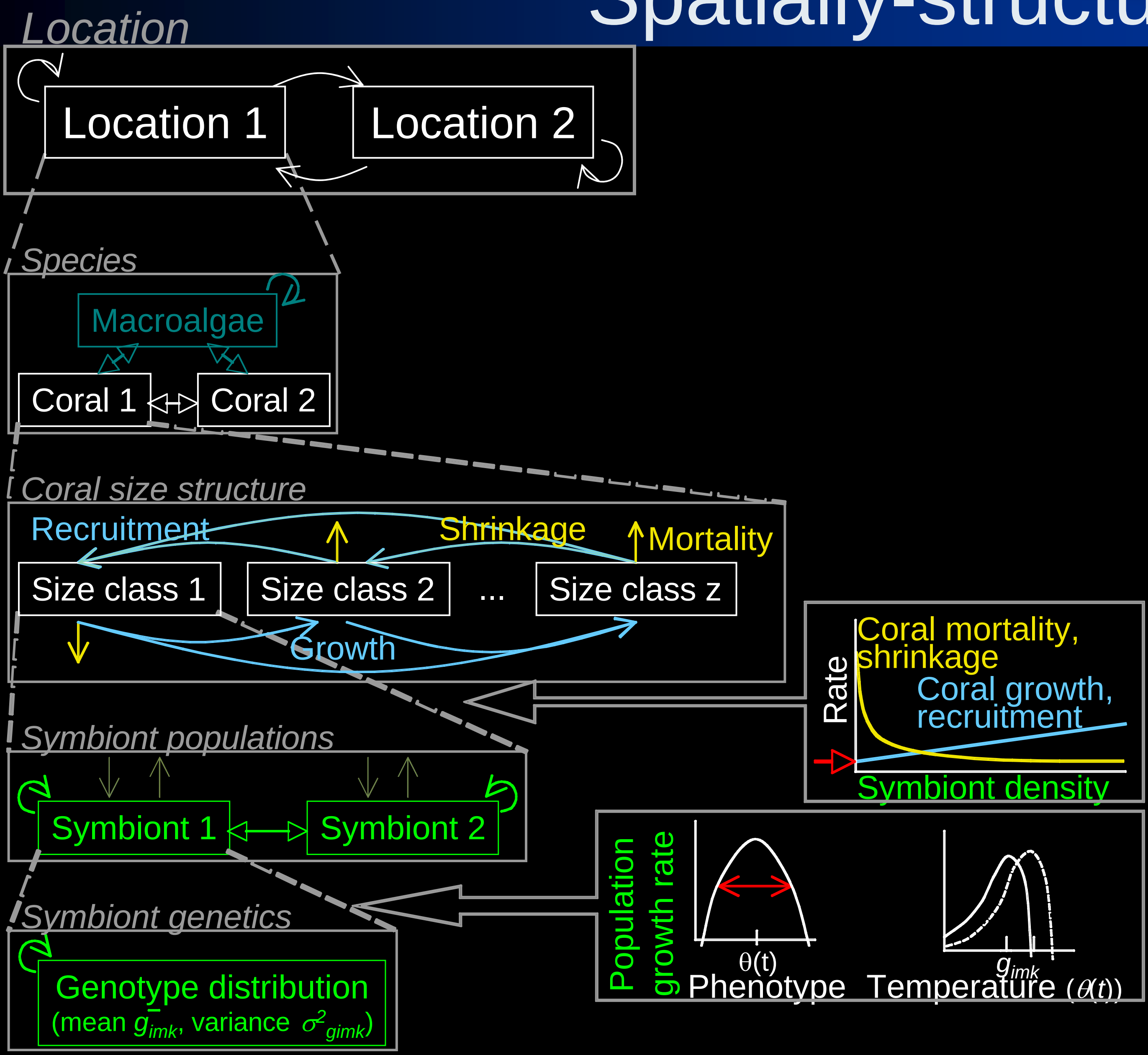
$\theta(t)$

Phenotype

g_{imk}

Temperature ($\theta(t)$)

Spatially-structured model



Location

Location 1

Location 2

Species

Macroalgae

Coral 1

Coral 2

Coral size structure

Recruitment

Shrinkage

Mortality

Size class 1

Size class 2

...

Size class z

Growth

Symbiont populations

Symbiont 1

Symbiont 2

Symbiont genetics

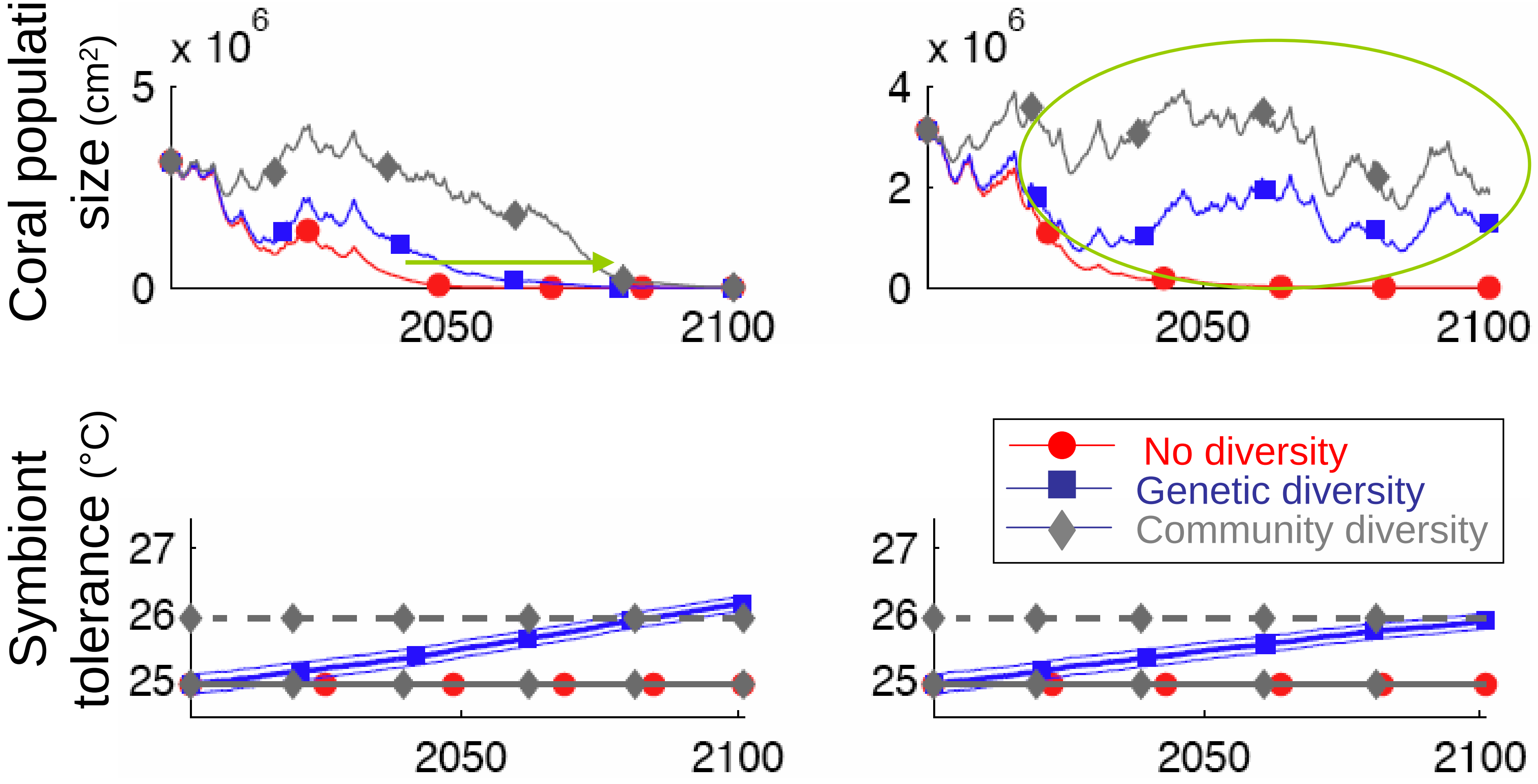
Genotype distribution

(mean $\bar{g}_{imk}$, variance σ^2_{gimk})

Size-structured model: symbiont diversity

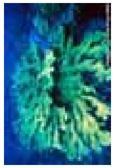
SRES A1b ← higher lower → SRES B1

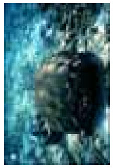
greenhouse gas emissions

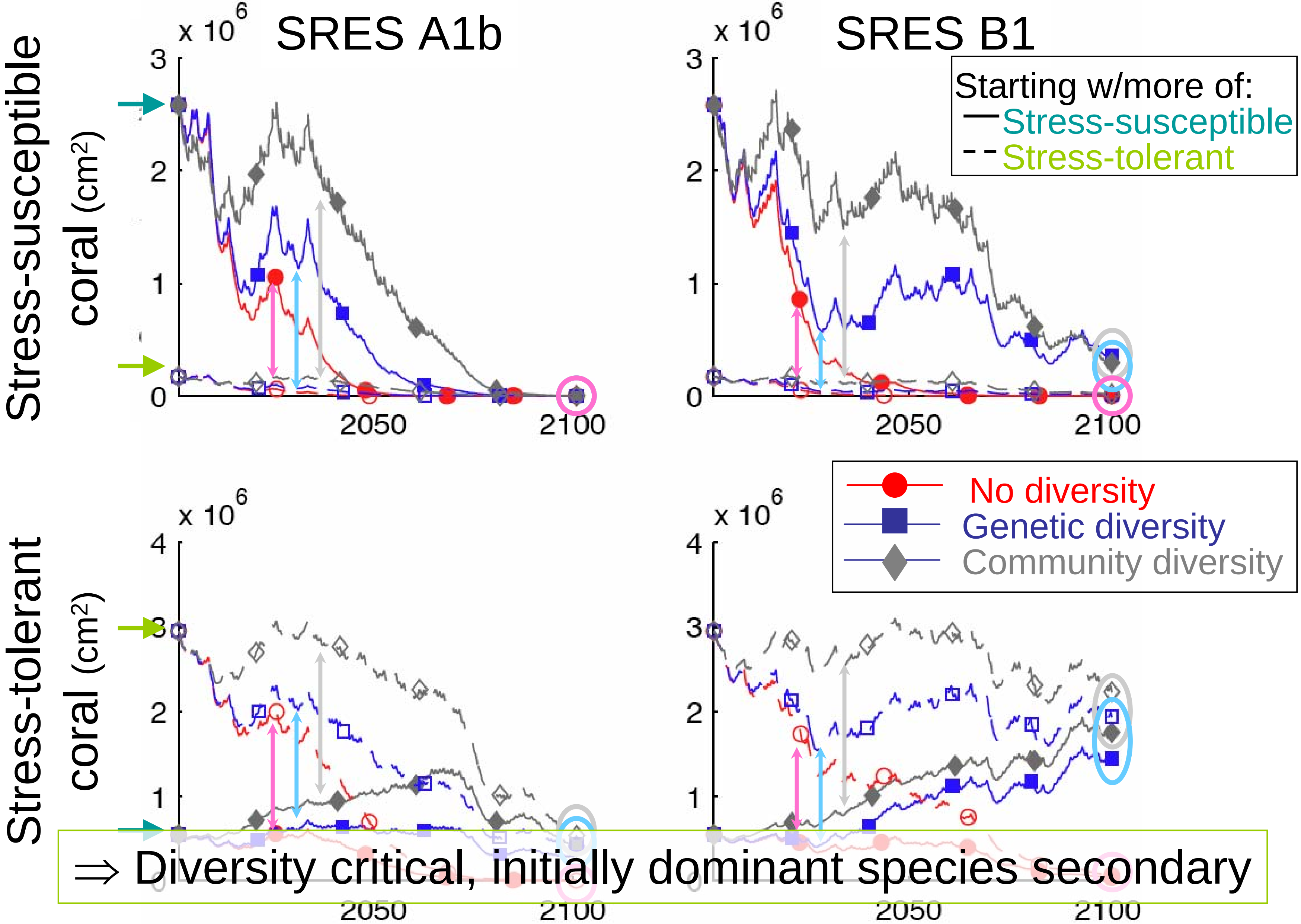


⇒ Symbiont eco/evo dynamics, climate scenario critical

Two corals: initial conditions



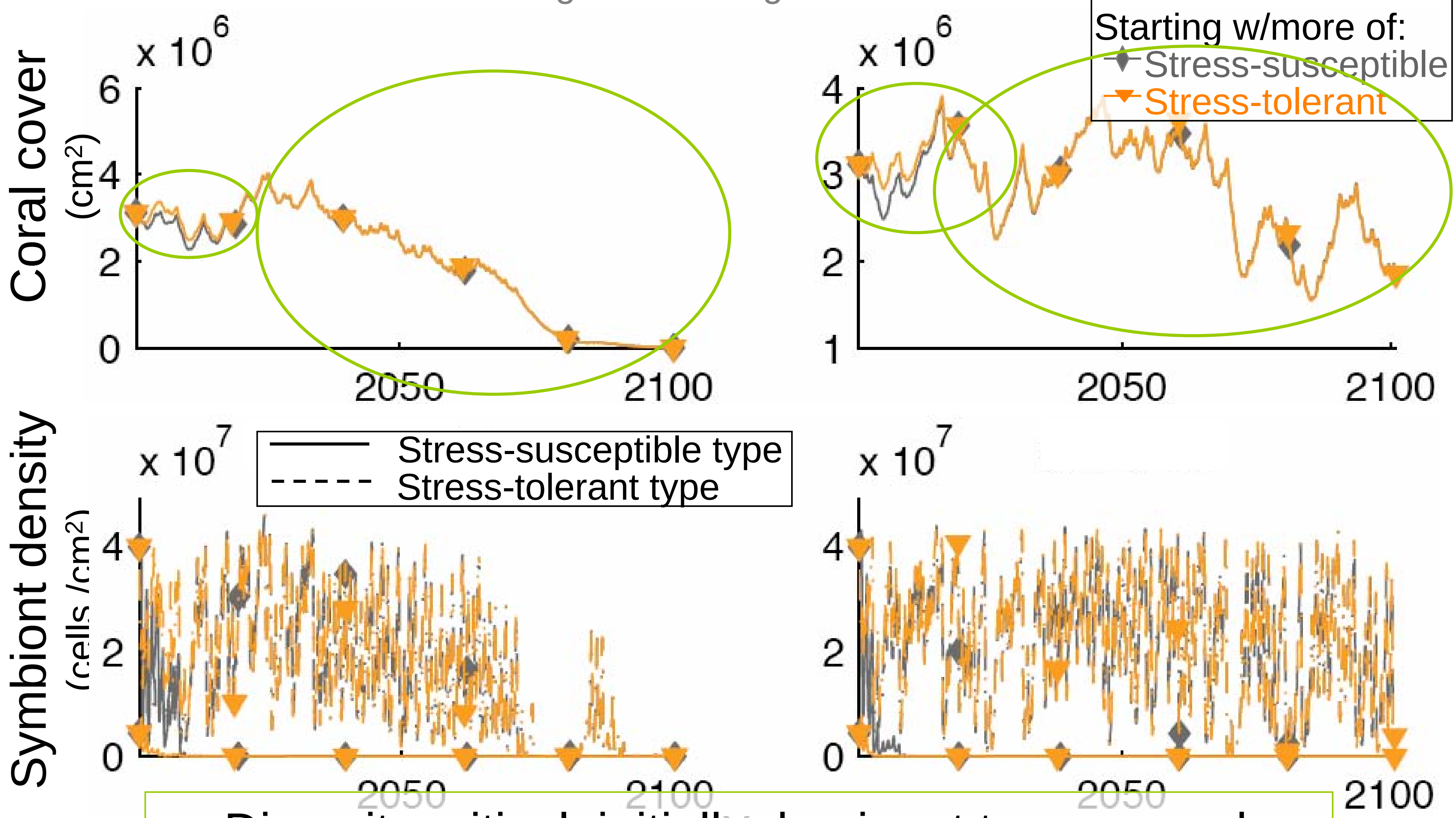




⇒ Diversity critical, initially dominant species secondary

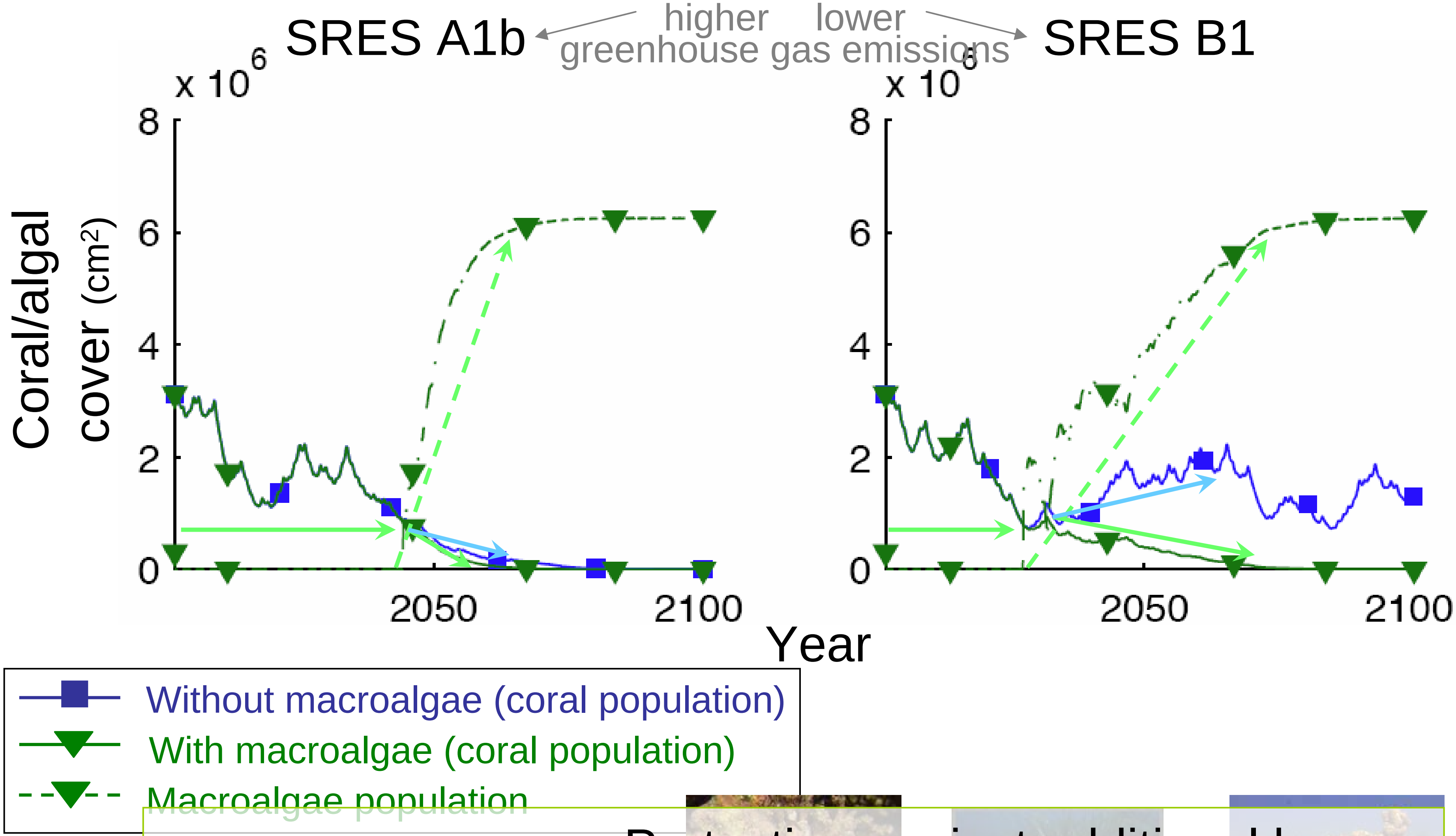
Two symbionts: initial conditions

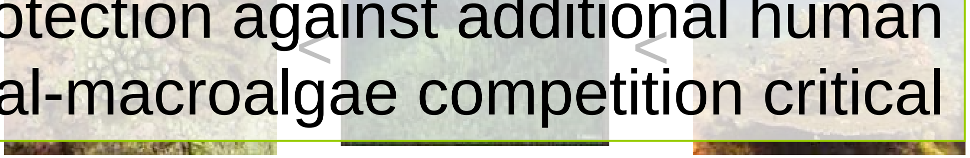
SRES A1b ← higher greenhouse gas emissions | lower greenhouse gas emissions → SRES B1



⇒ Diversity critical, initially dominant type secondary

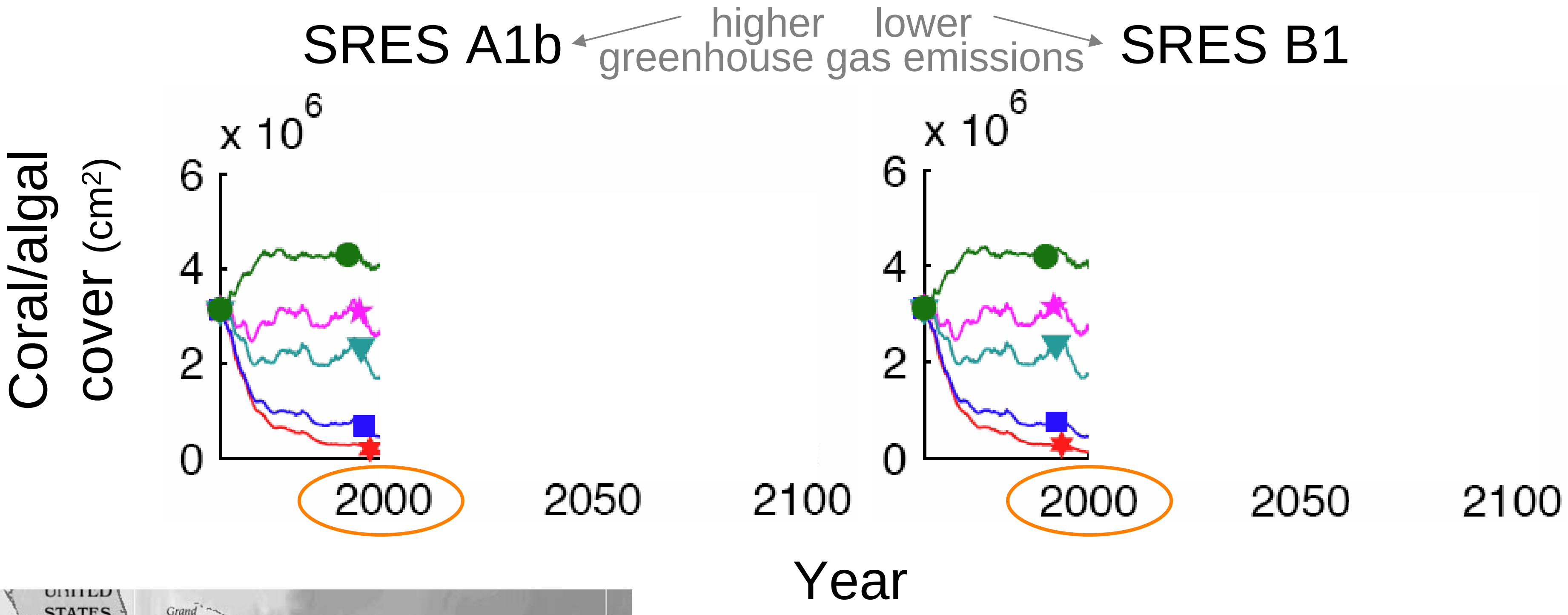
Coral-macroalgae competition

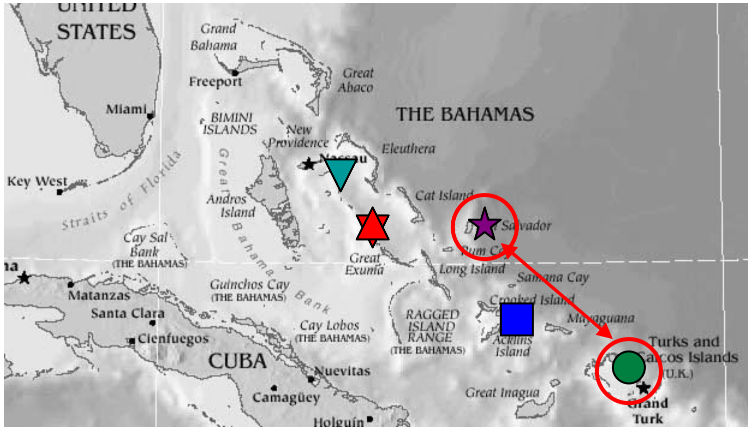




⇒ Protection against additional human impacts on coral-macroalgae competition critical

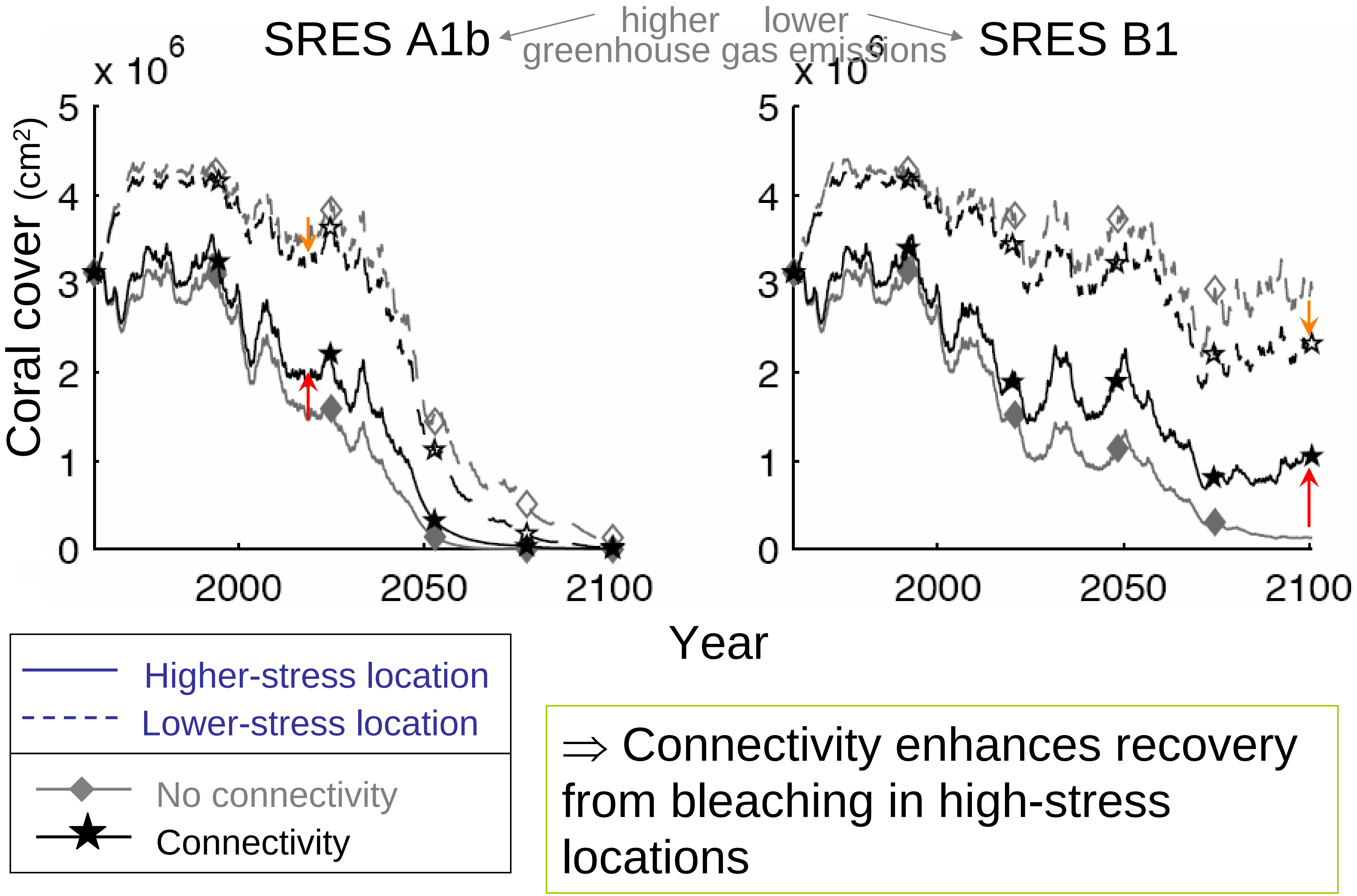
Multiple locations with varying stress





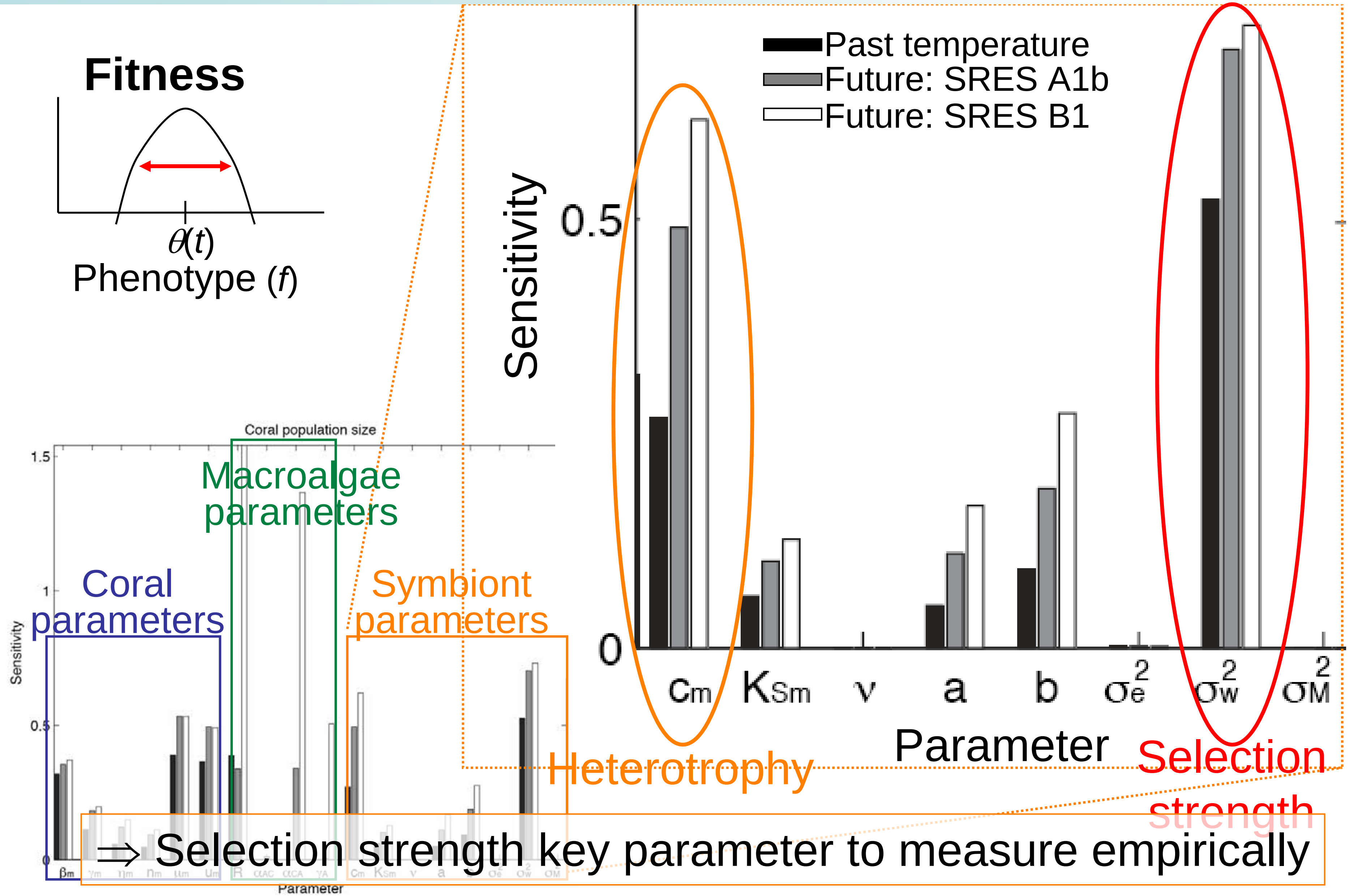
⇒ Past high stress indicator of high future stress on coarse spatial scales

Connectivity between two locations



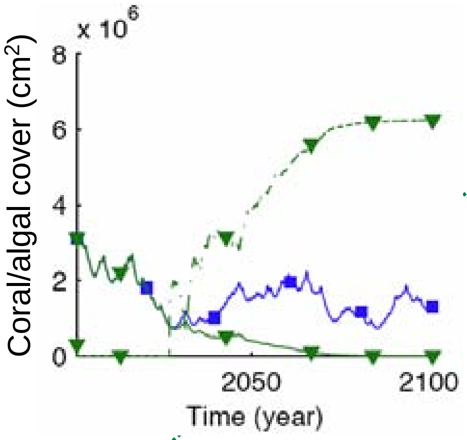
⇒ Connectivity enhances recovery from bleaching in high-stress locations

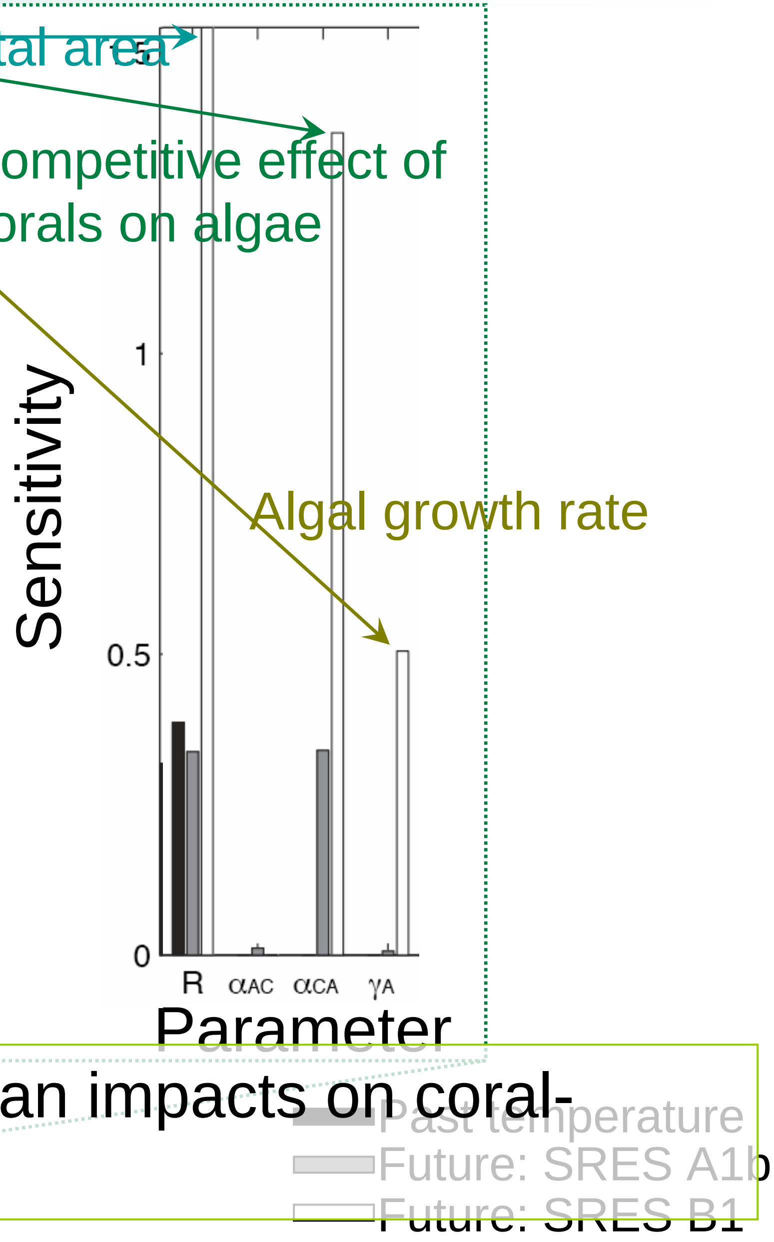
Sensitivity analysis：symbiont parameters



⇒ Selection strength key parameter to measure empirically

Sensitivity analysis: macroalgae parameters

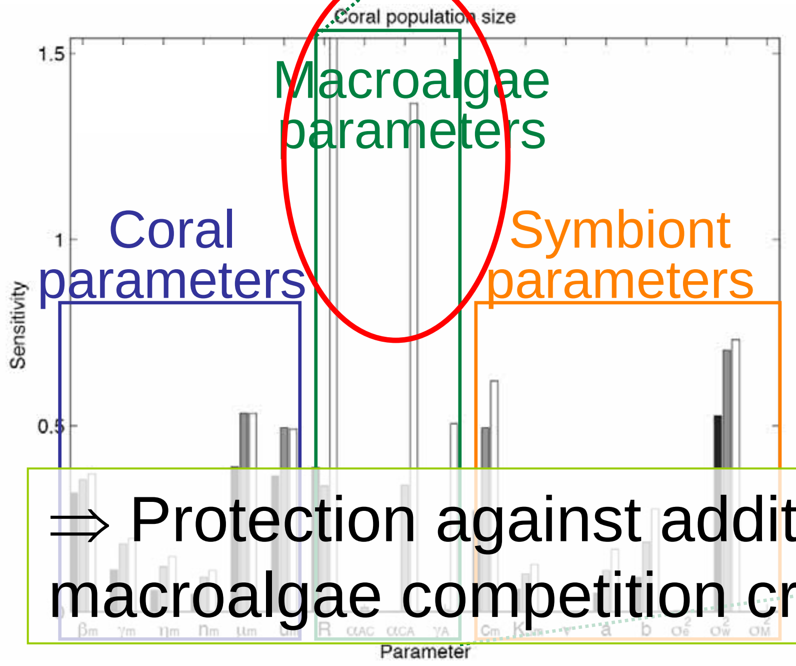




Total area

Competitive effect of corals on algae

Algal growth rate



Macroalgae parameters

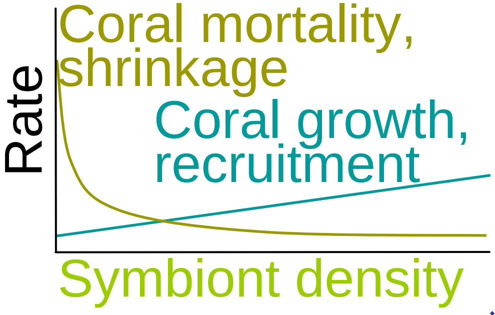
Coral parameters

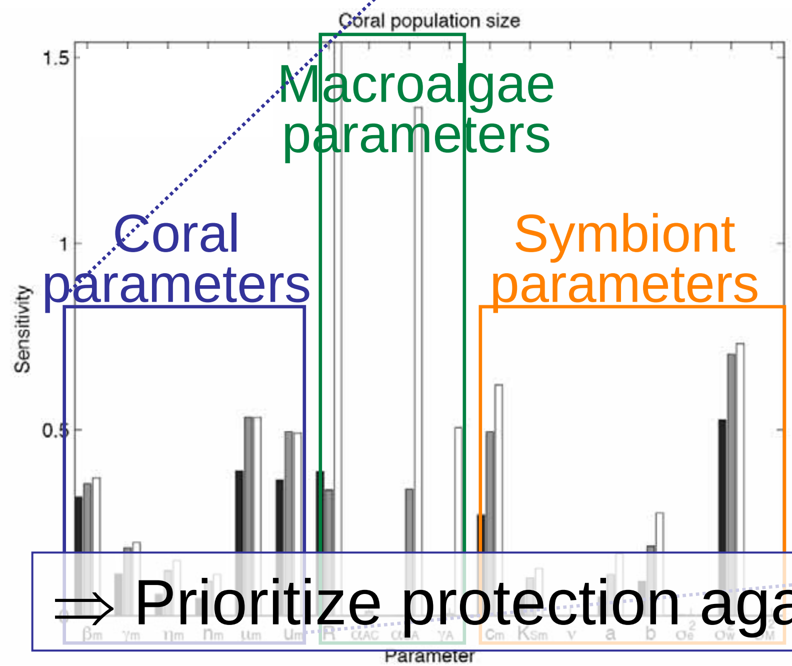
Symbiont parameters

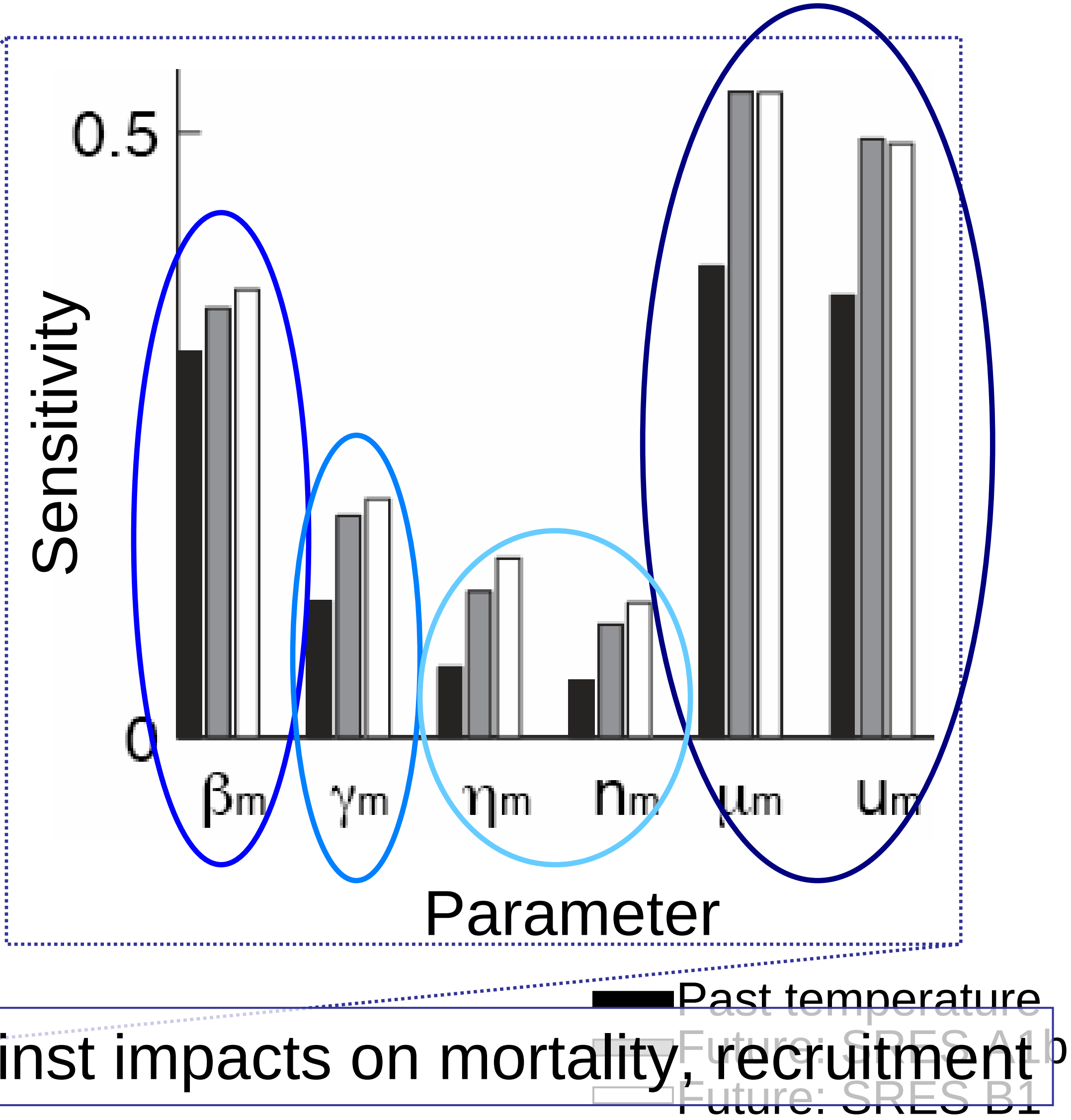
⇒ Protection against additional human impacts on coral-macroalgae competition critical

Sensitivity analysis: coral parameters

Shrinkage < Growth < Recruitment < Mortality







⇒ Prioritize protection against impacts on mortality, recruitment

Conclusions (part 2)

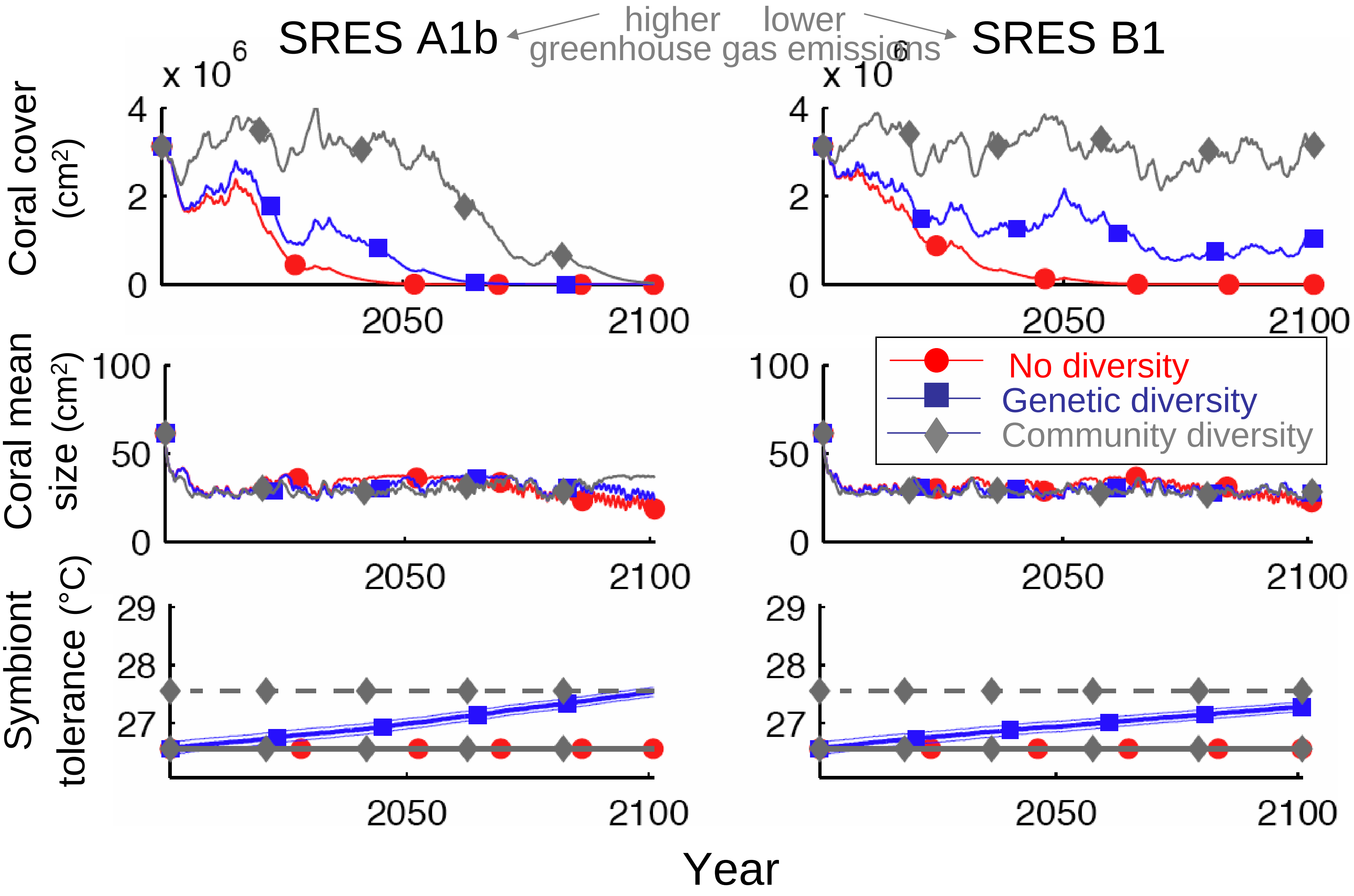
- Genetic and community variation in symbiont thermal tolerance may allow coral response to climate change

- Accounting for biological variation and dynamics reveals importance of future climate scenario to coral persistence

- Conservation priorities
  - High diversity
  - Low-stress locations (with connectivity)
  - Reduce algal competition, impacts on coral mortality and recruitment

Photos: reefbase.org

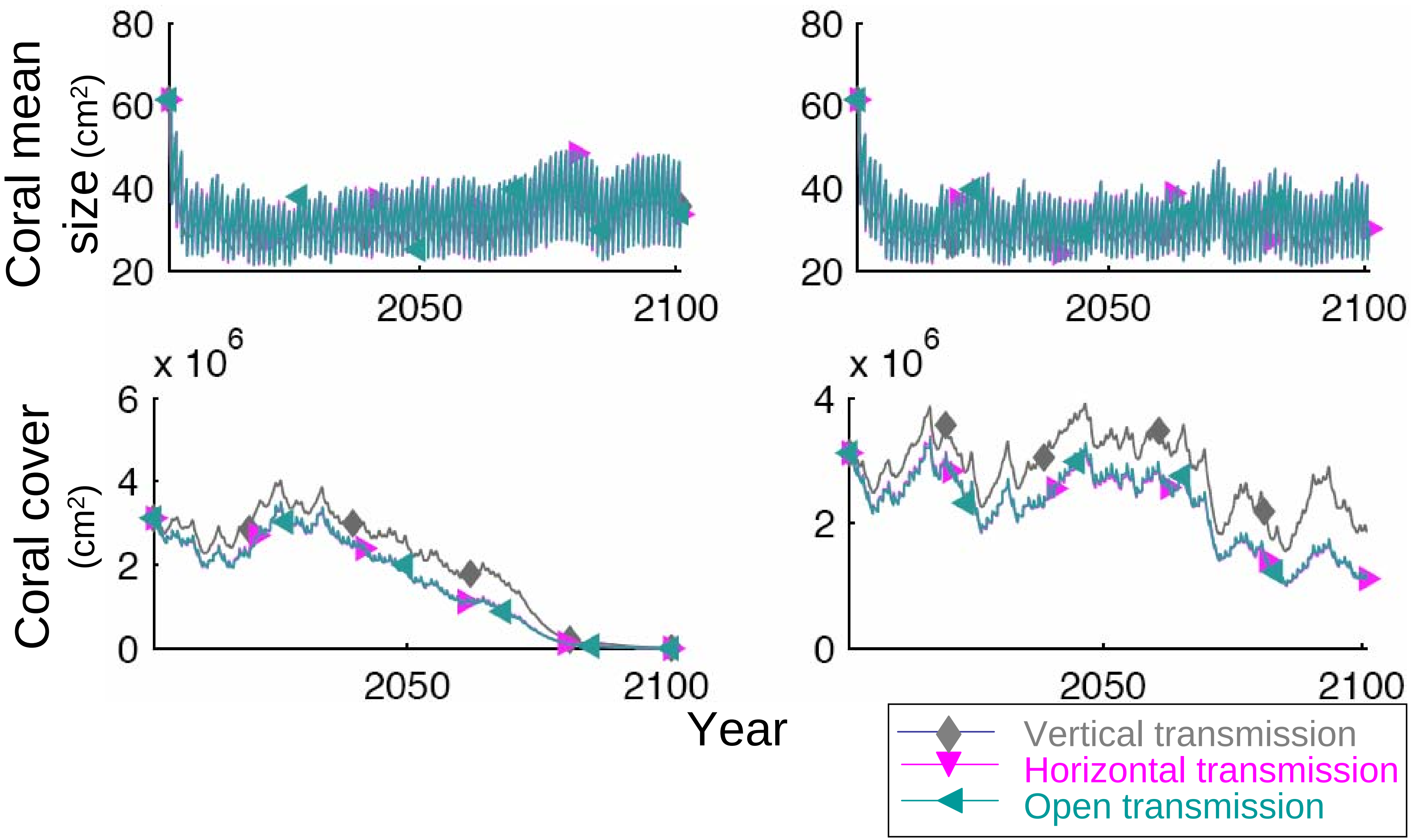
Results: size-structured model



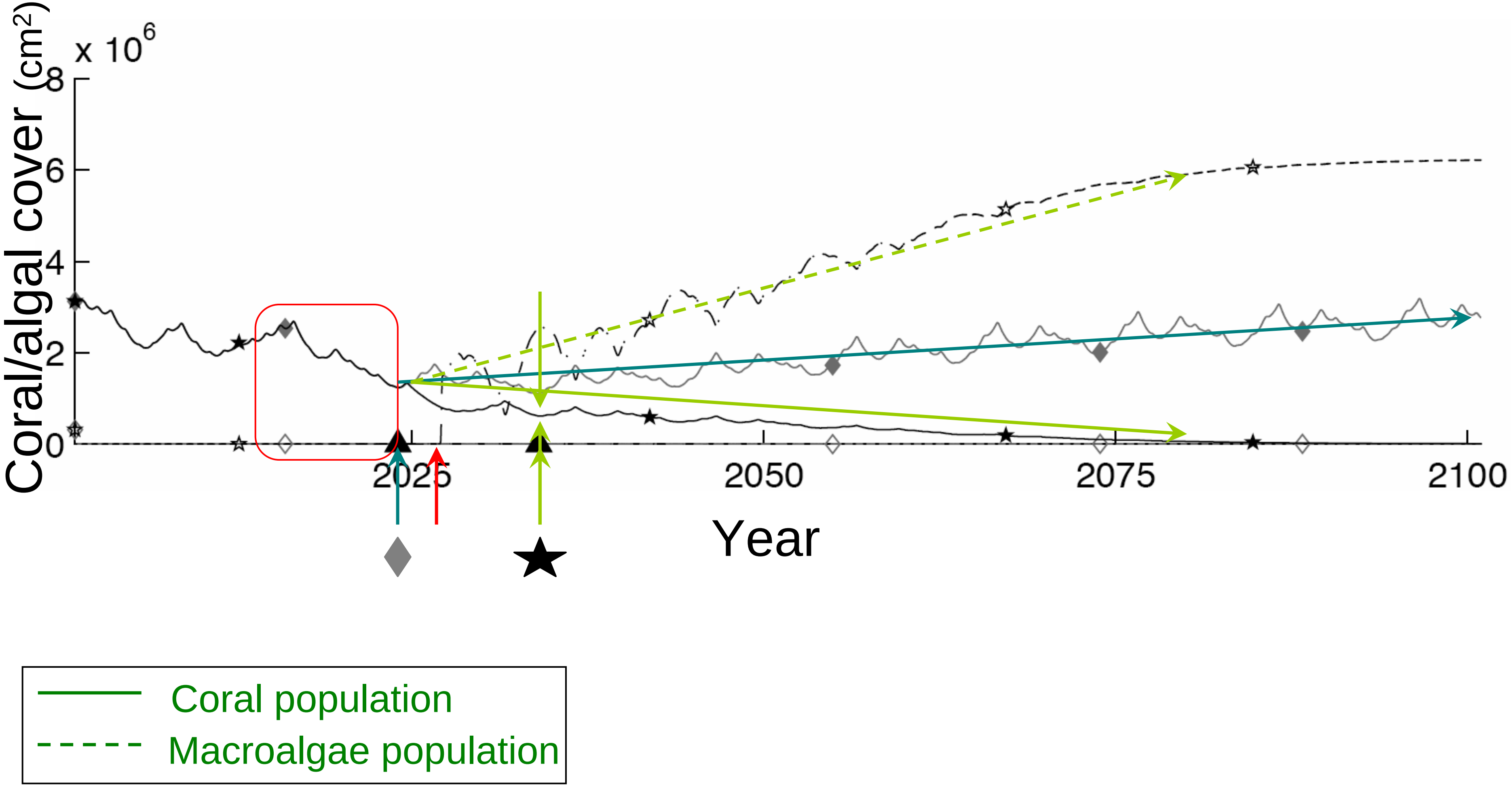
SRES A1b ← higher greenhouse gas emissions lower → SRES B1

Size-structured model: transmission type

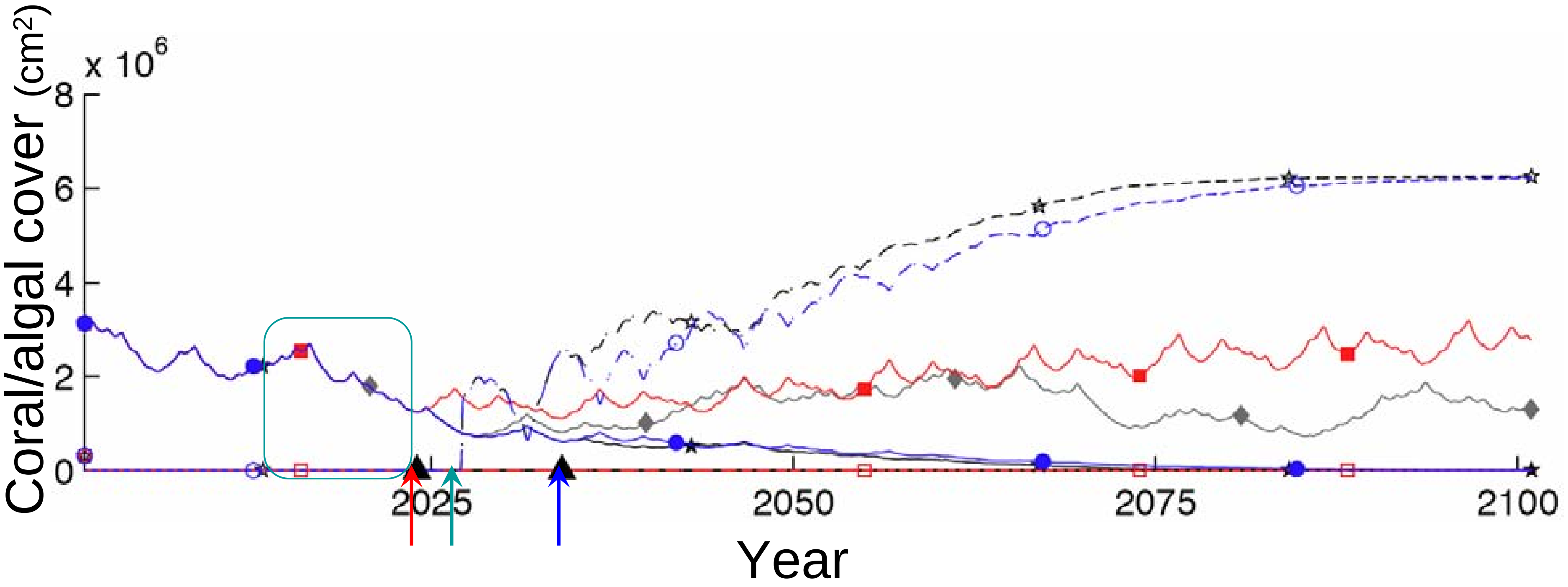
SRES A1b ← higher lower → SRES B1
greenhouse gas emissions



Size-structured model: hysteresis point



Size-structured model: hysteresis point



Coral population

Macroalgae population

Repeat after macroalgae increases

Repeat before macroalgae increases

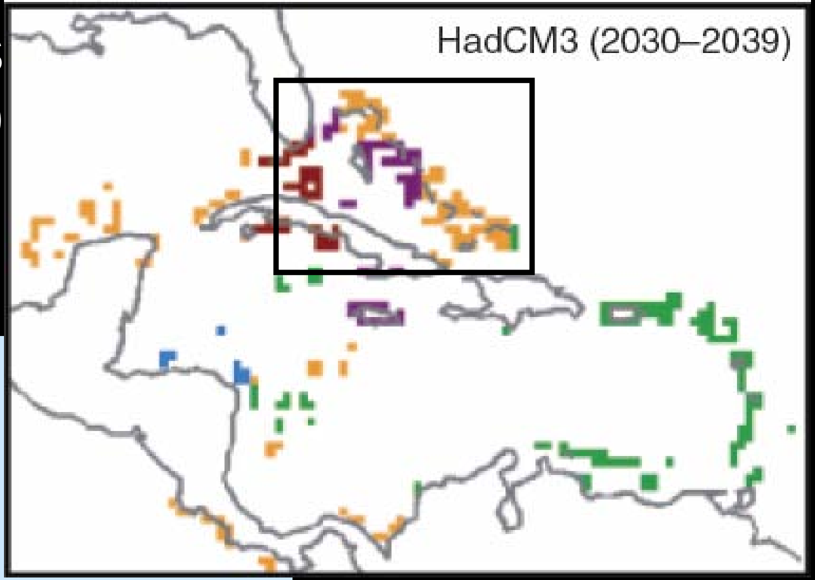
Actual temperature data

No macroalgae (actual temp. data)

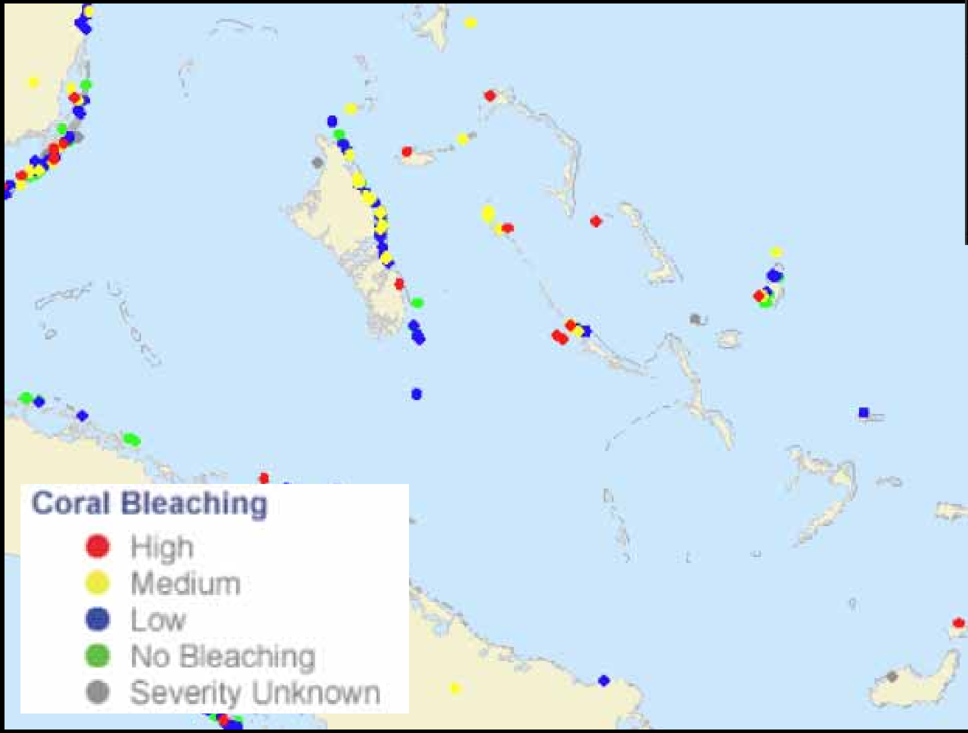
Past and future stress: multiple locations

Future stress

(Donner et al. 2005)

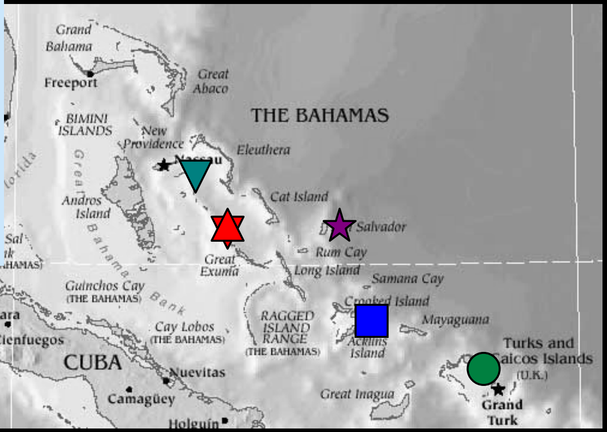


Past stress (reefbase.org)

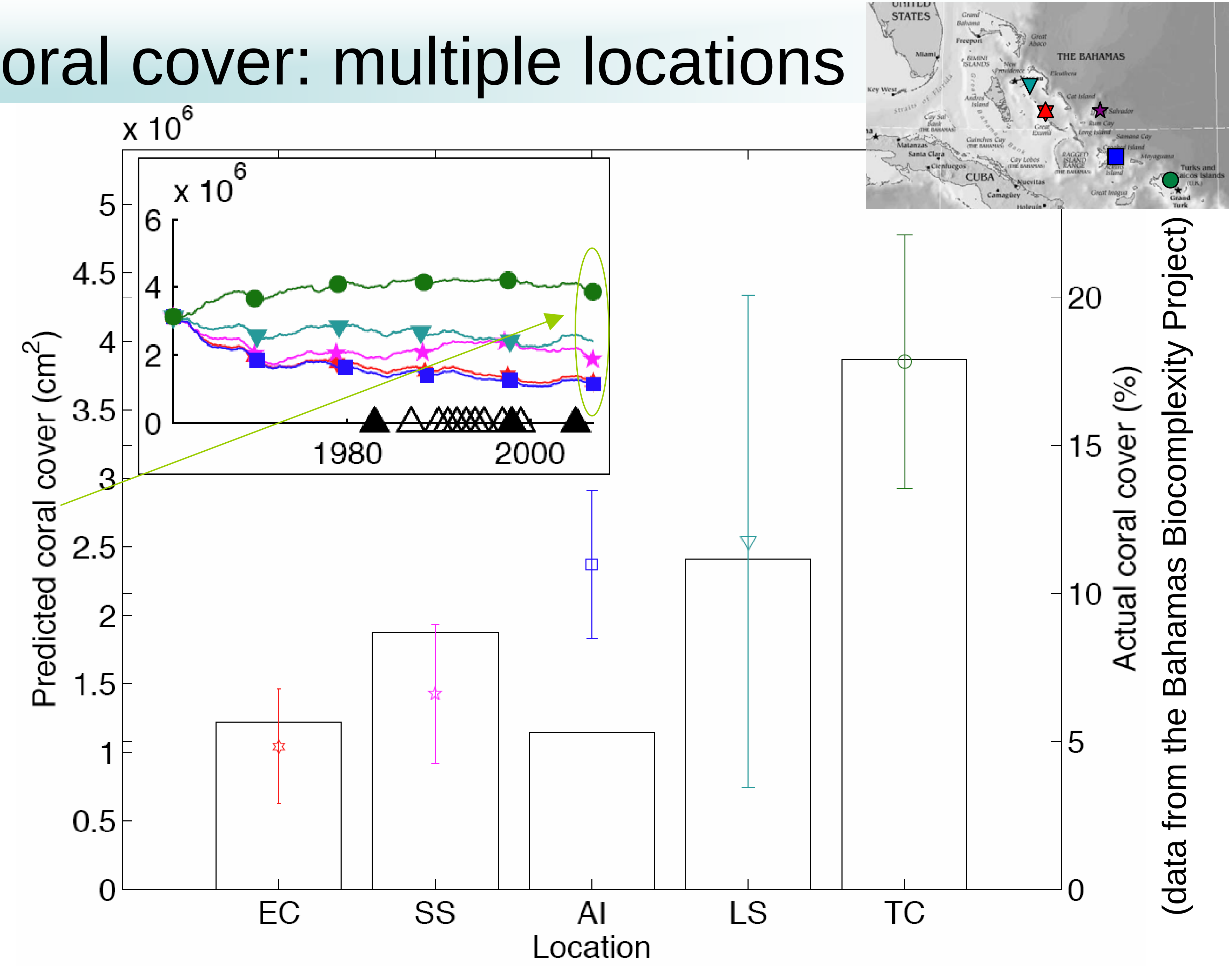


Coral Bleaching

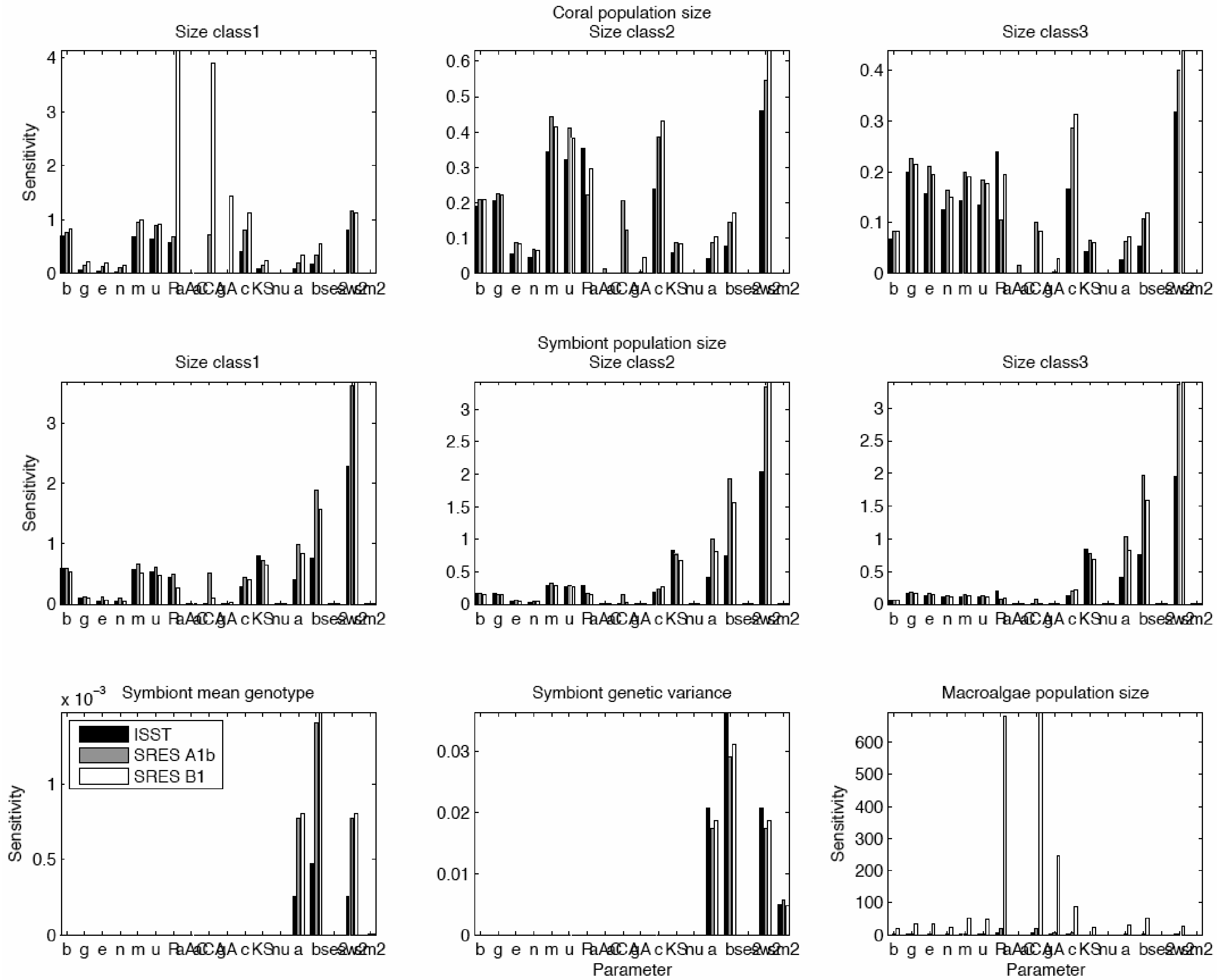
- 🔴 High
- 🟡 Medium
- 🔵 Low
- 🟢 No Bleaching
- ⚪ Severity Unknown



Coral cover: multiple locations



Sensitivity: all state variables



Runoff effects

	Dissolved inorg. nutr.	POM	Light reduction	Sedimentation
Fecundity	↓		↓	↓
Fertilization	⬇	↓	—	—
Embryo develop./ larval surv.	⬇	🡓	—	—
Settlement / metamorphosis	↓	↓	⬇	⬇
Recruit survival			🡓	⬇
Juvenile growth / survival			🡓	🡓

	Dissolved inorg. nutr.	POM*	Light reduction	Sedimentation
Crustose coralline algae	↓			⬇
Bioeroders	↑	⬆		↓
Macroalgae	⬆	↑	⬇	↓
Heterotrophic filter feeders		⬆	⬆	↓
Coral diseases	↑			↑
Coral predators		⬆		

	DIN	DIP	POM	Light reduction	Sedimentation
Calcification	↓	↓	↑	⬇	⬇
Tissue thickness	—	—	🡑	🡓	⬇
Zooxanthellae density	⬆	—	↑	↑	🡓
Photosynthesis	🡑	🡑	🡑	⬇	⬇
Adult colony survival	—	—	🡑	🡓	⬇

Fabricius (2005)