Climatic controls on ecosystem resilience: combining hierarchical modelling with space borne monitoring of past fire plant biomass accumulation

Adam M. Wilson, Ph.D.

August 6, 2014

YALE *Climate & Energy Institute*

"Fires in fynbos are frequent, spectacular, and alarming"

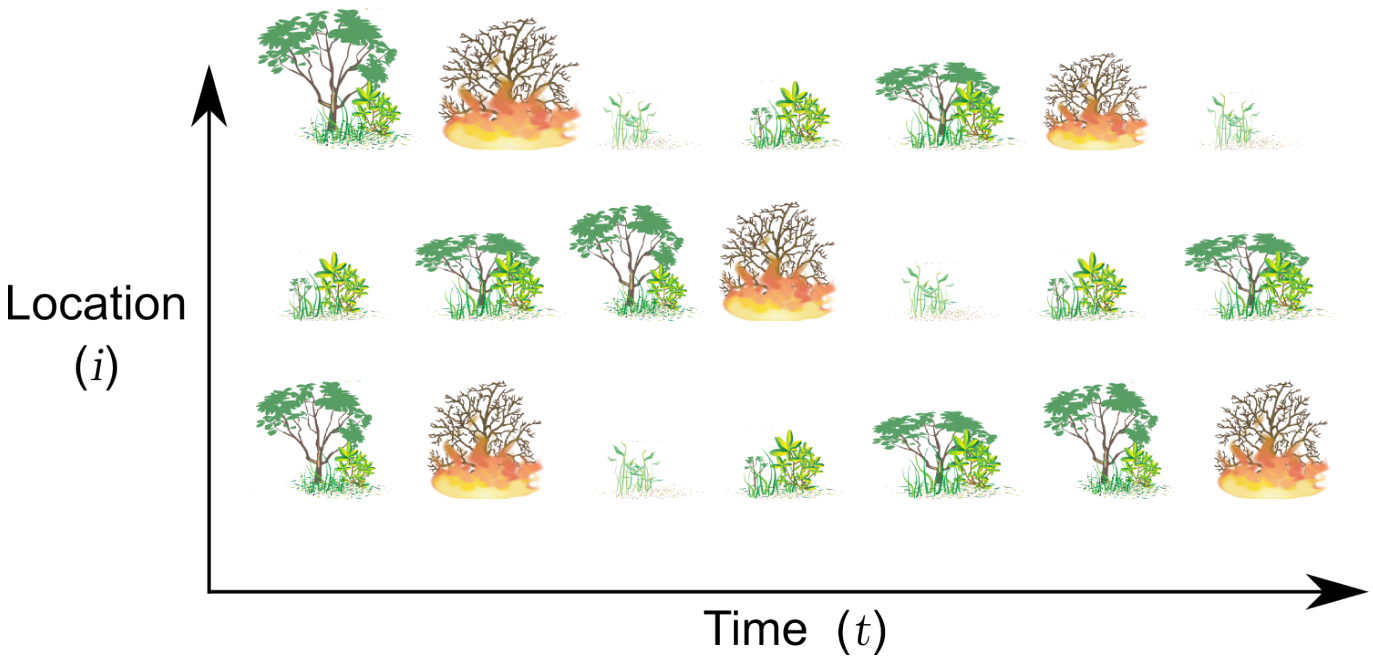
test

2011 Kogelberg Fire near Cape Town

Booysen & Tainton (1984), Timelapse courtesy of Eric Nathan (http://ericnathan.com/)

Analysis of Historical Fire Data: 1980-2000

Data: Burned area from field & satellite with gridded daily weather
Model: Bayesian spatio-temporal survival analysis



Wilson, Latimer, Silander, Gelfand, & deKlerk *Ecological Modelling* (2010)
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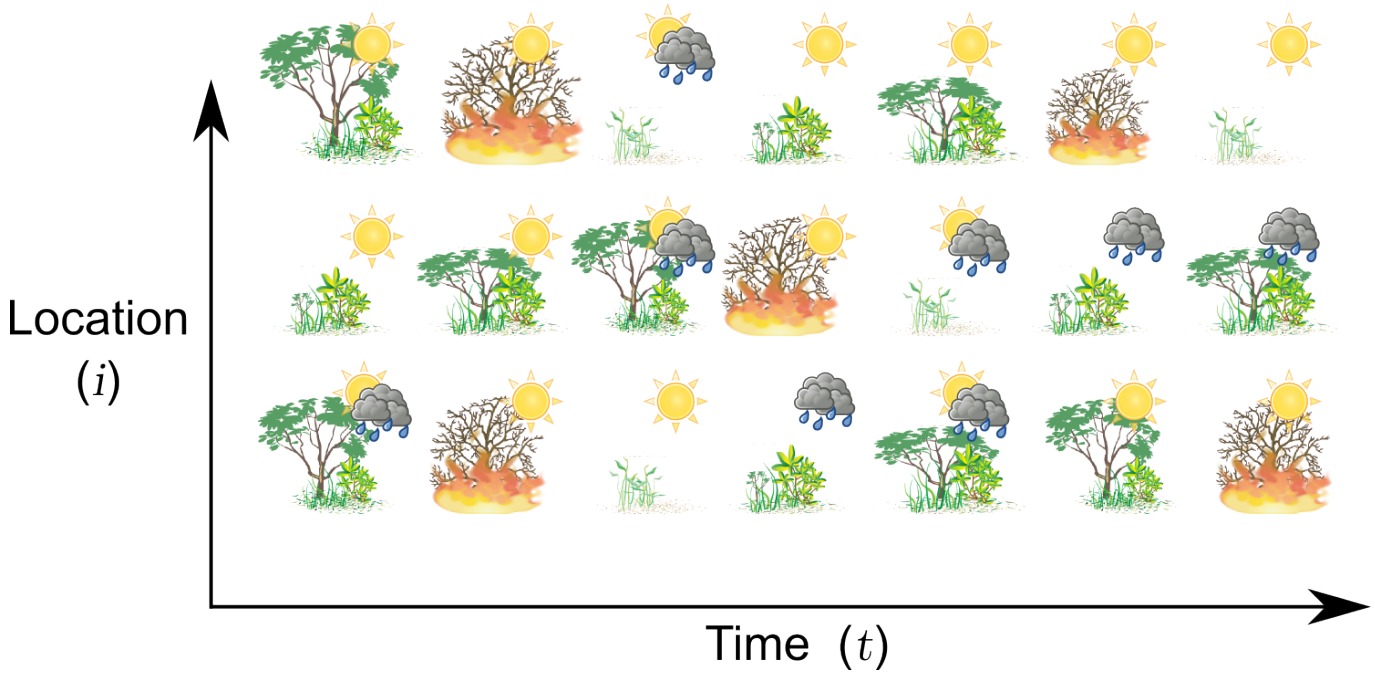

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Fire, Weather, &...

- Estimate fire return times have decreased **≈4 years (17%) since 1950**

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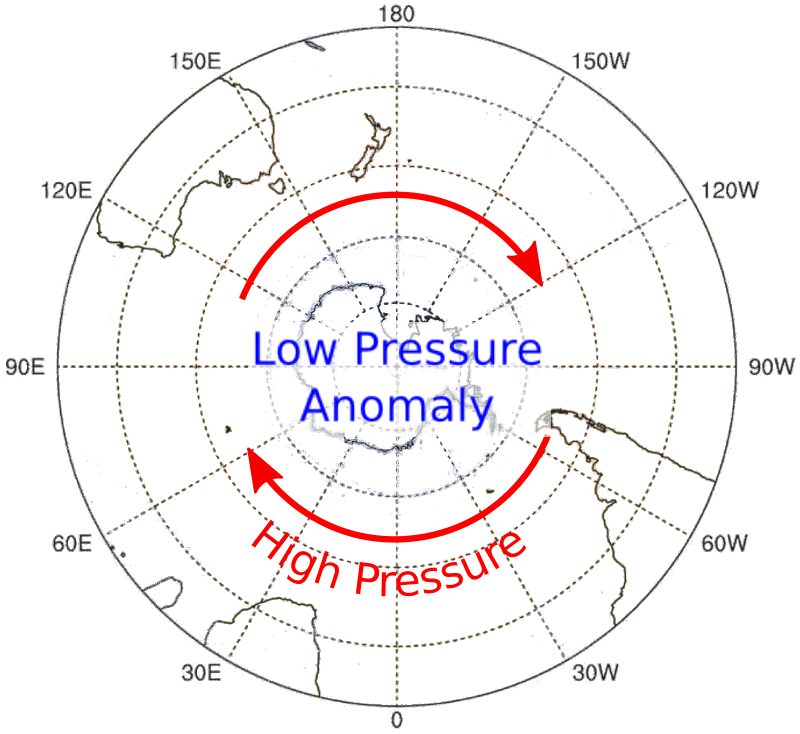

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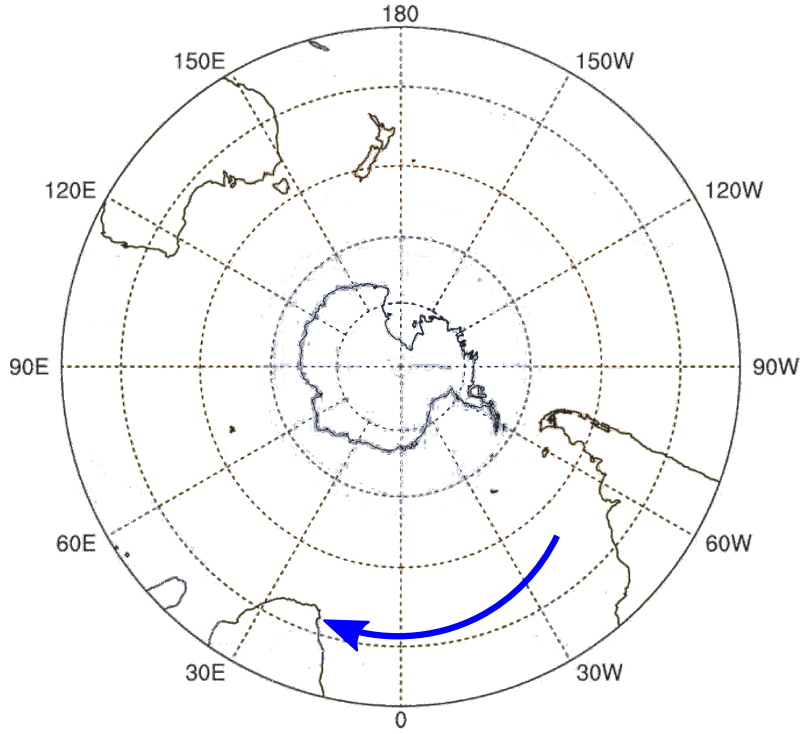

Negative AAO
Subtropical Jet moves North
More Moisture Flux
Less fire

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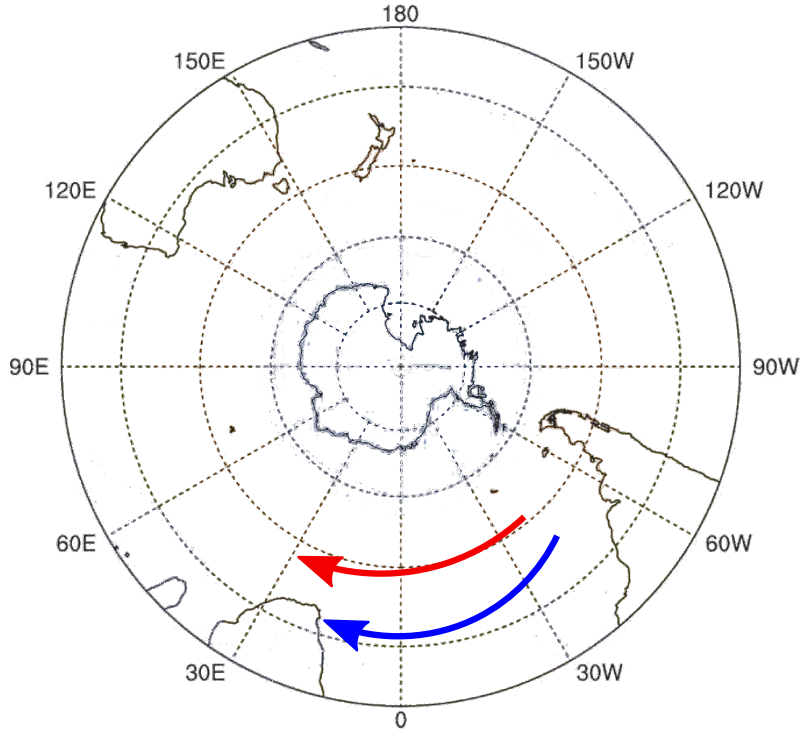

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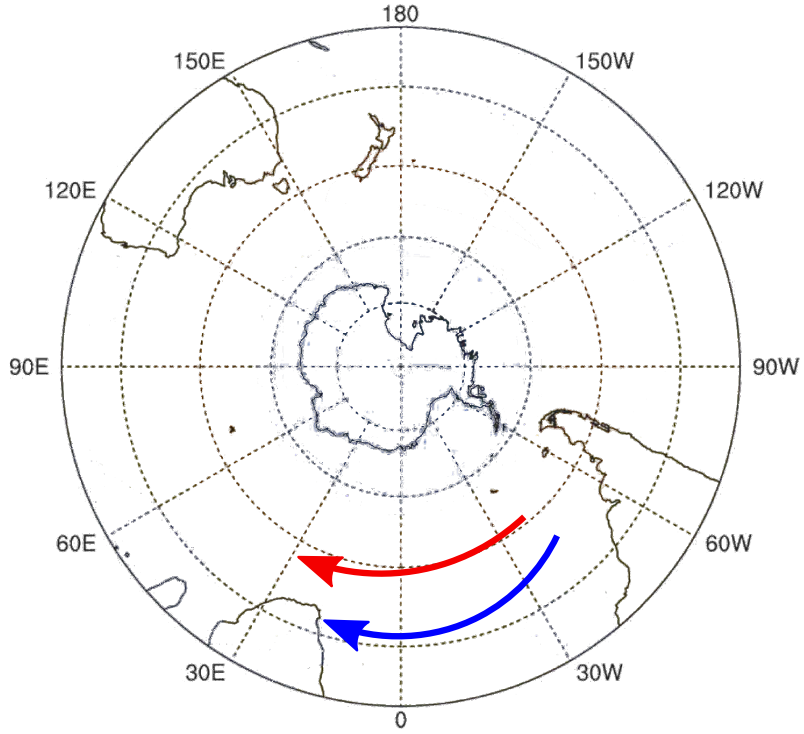
Fire, Weather, & the Antarctic Ocean Oscillation (AAO)

- Estimate fire return times have decreased **≈4 years (17%) since 1950**
- Increasing trend in AAO since mid-1970s due in part to ozone hole



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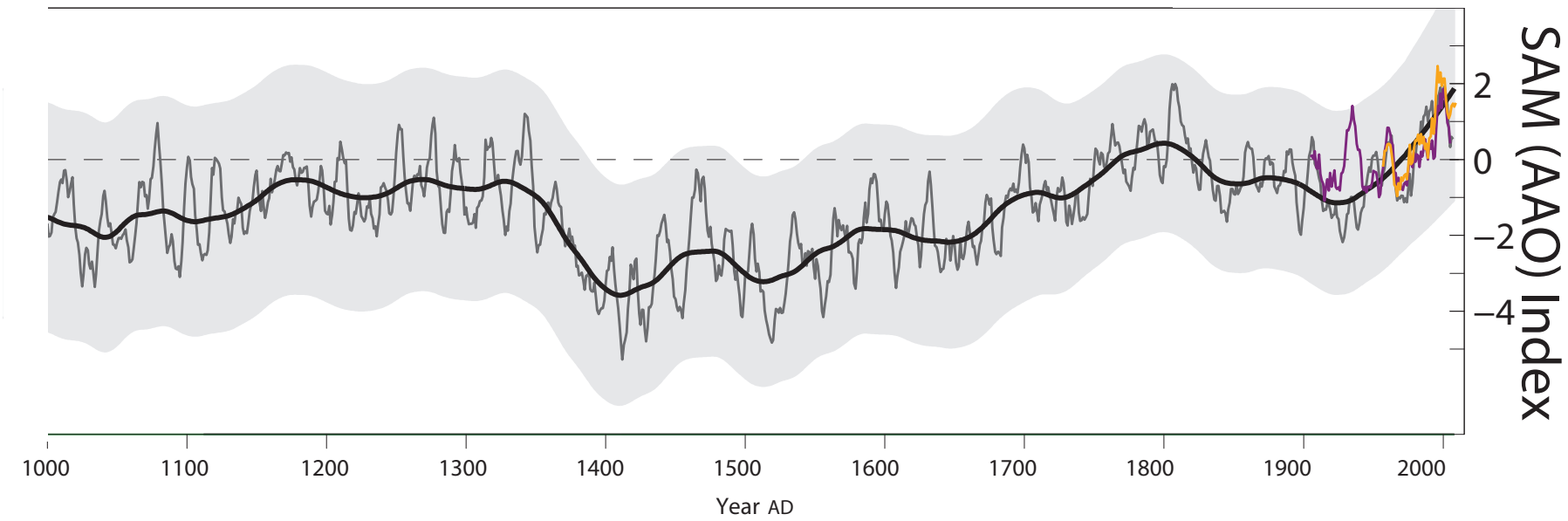
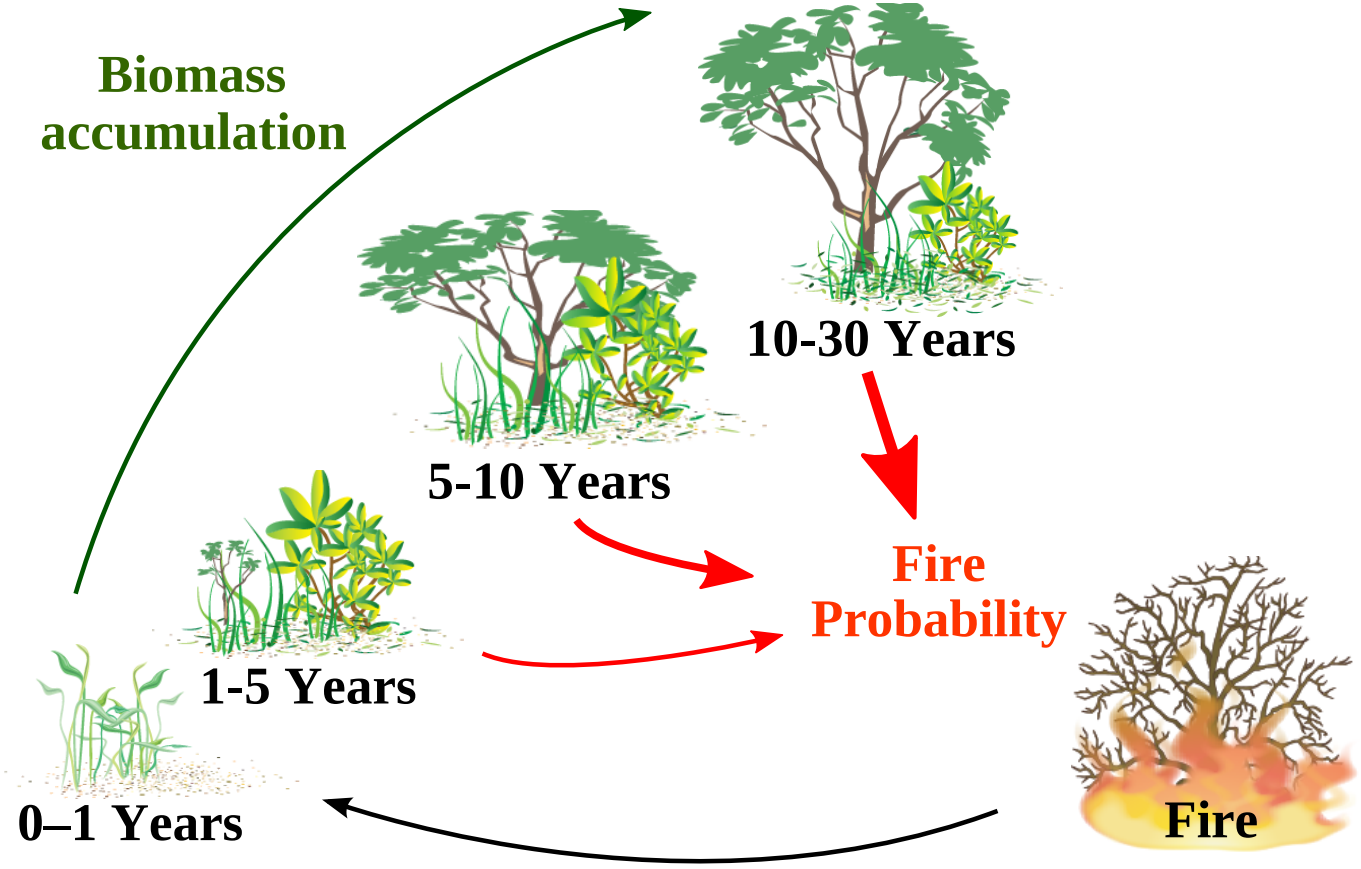
AAO over the past 1000 years (via proxies)



SAM reconstruction for the past millennium, as 7 yr moving average (thin grey line) and 70 yr loess filter (thick black line), with 95% confidence interval around the annual reconstruction (grey shading; with 70 yr loess smoothing), Marshall (orange lines; AD 1957–2007) and Fogt (purple lines; AD 1905–2005) SAM indices, relative to AD 1961–1990 mean (dashed black line).

Abram, et al. (2014) *Nature Climate Change* doi:10.1038/nclimate2235

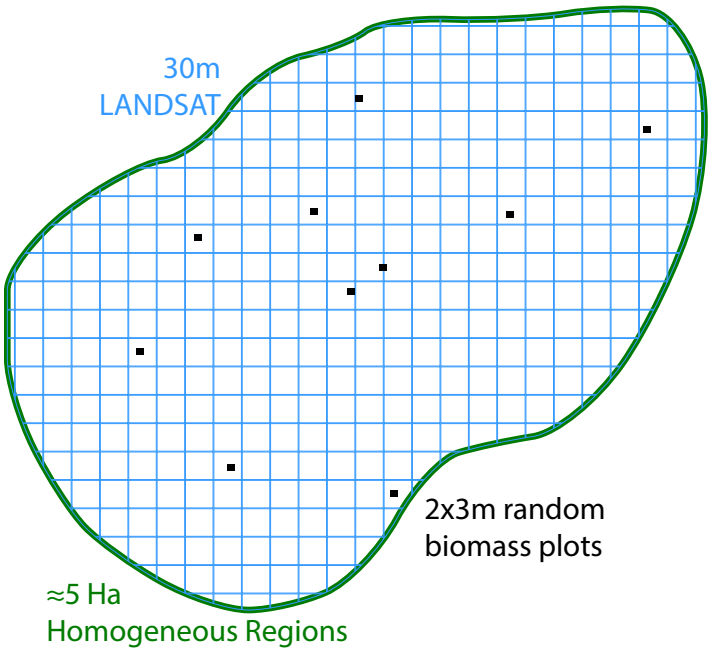
Fire risk is sensitive to climate variability, but what about recovery?



Can we learn about post-fire recovery from satellite?

Data: LANDSAT & Field Biomass

Model: Bayesian multi-scale regression



Wilson, Silander, Gelfand, & Glenn, *International Journal of GIS* (2011)

Can we learn about post-fire recovery from satellite? Yes!

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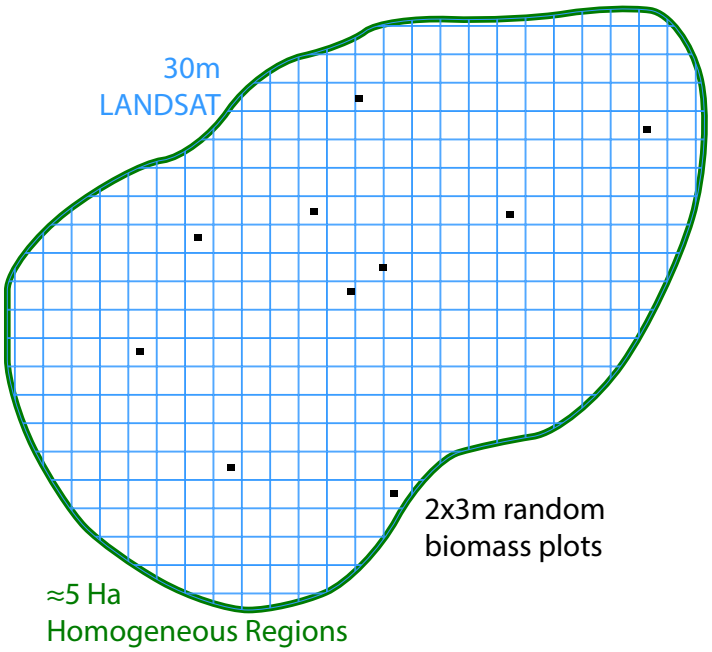
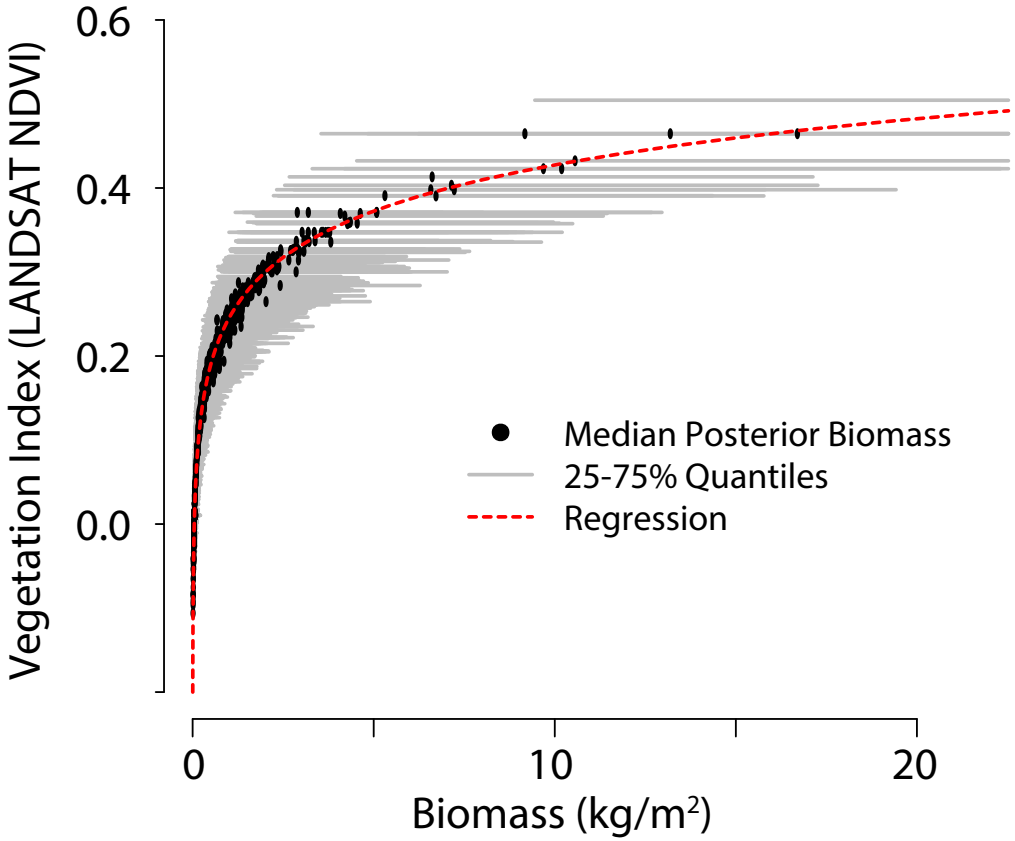
Model: Bayesian multi-scale regression **(with uncertainties!)**





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Satellite Vegetation Index (MODIS NDVI)

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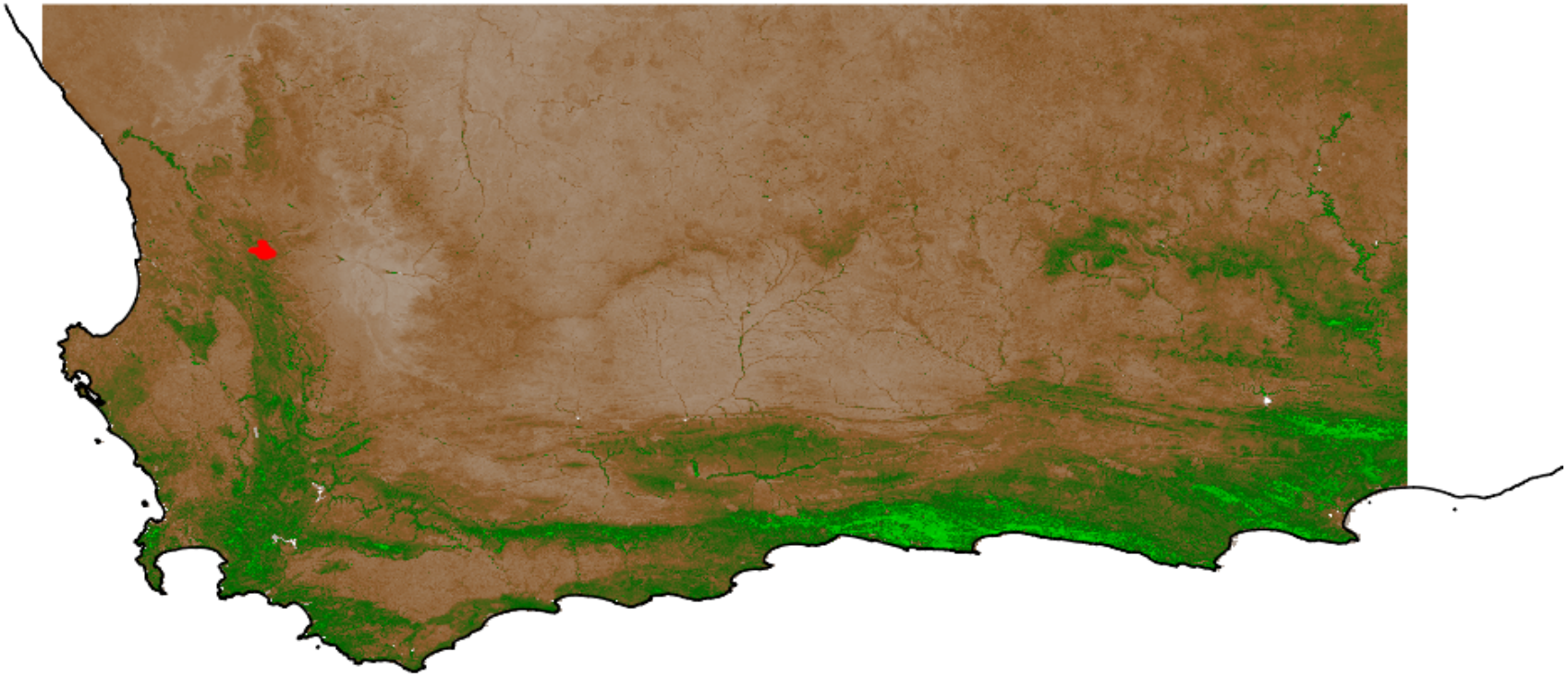
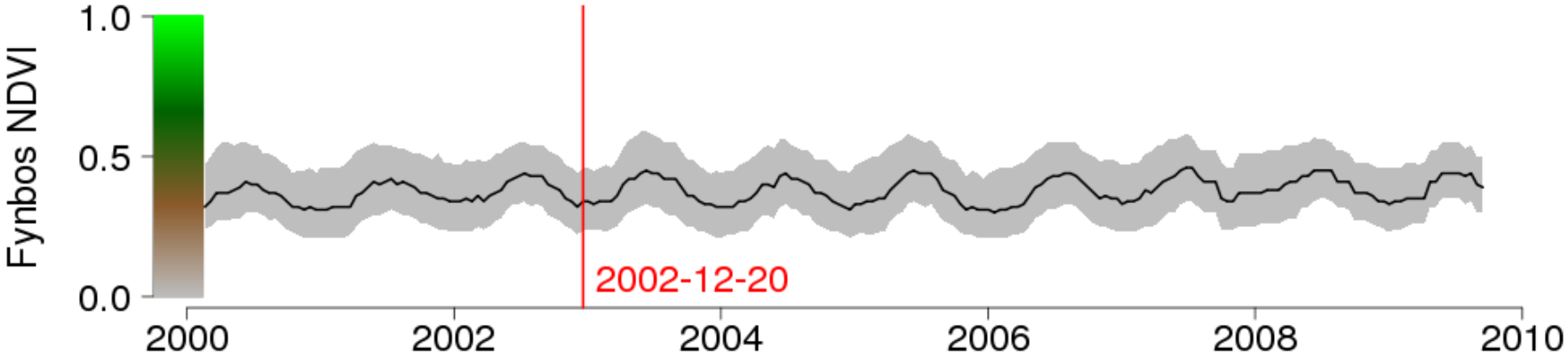
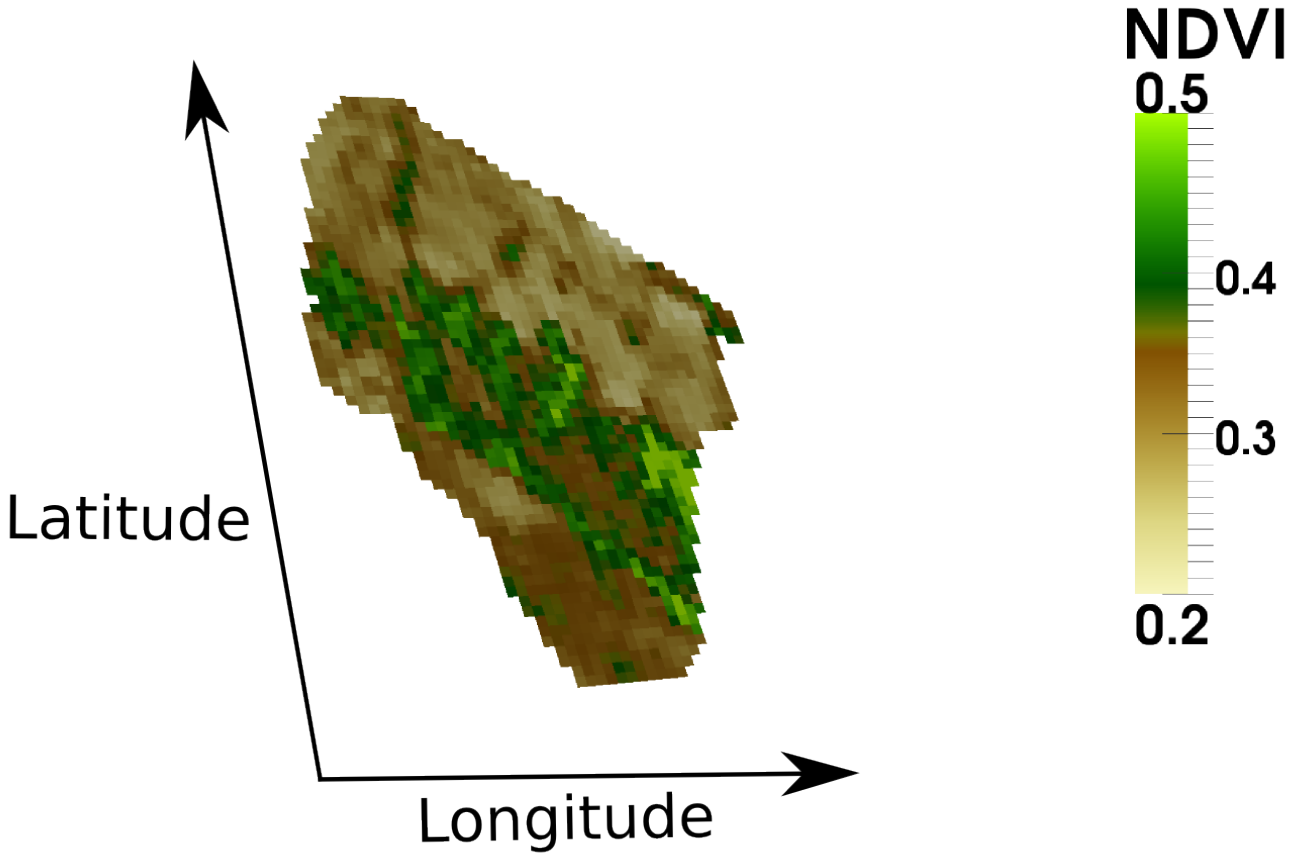




What drives the spatial variation in post-fire recovery?



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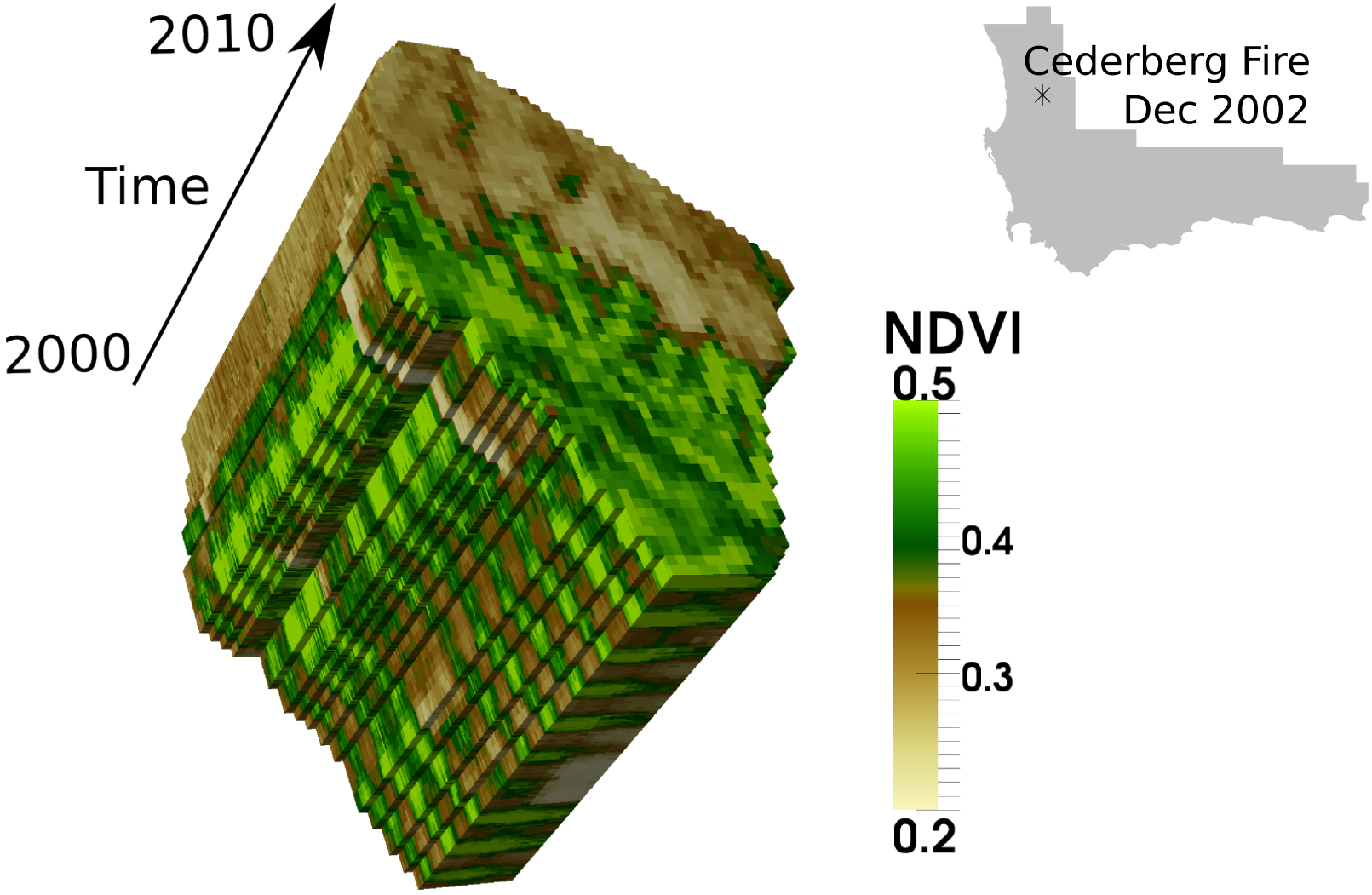

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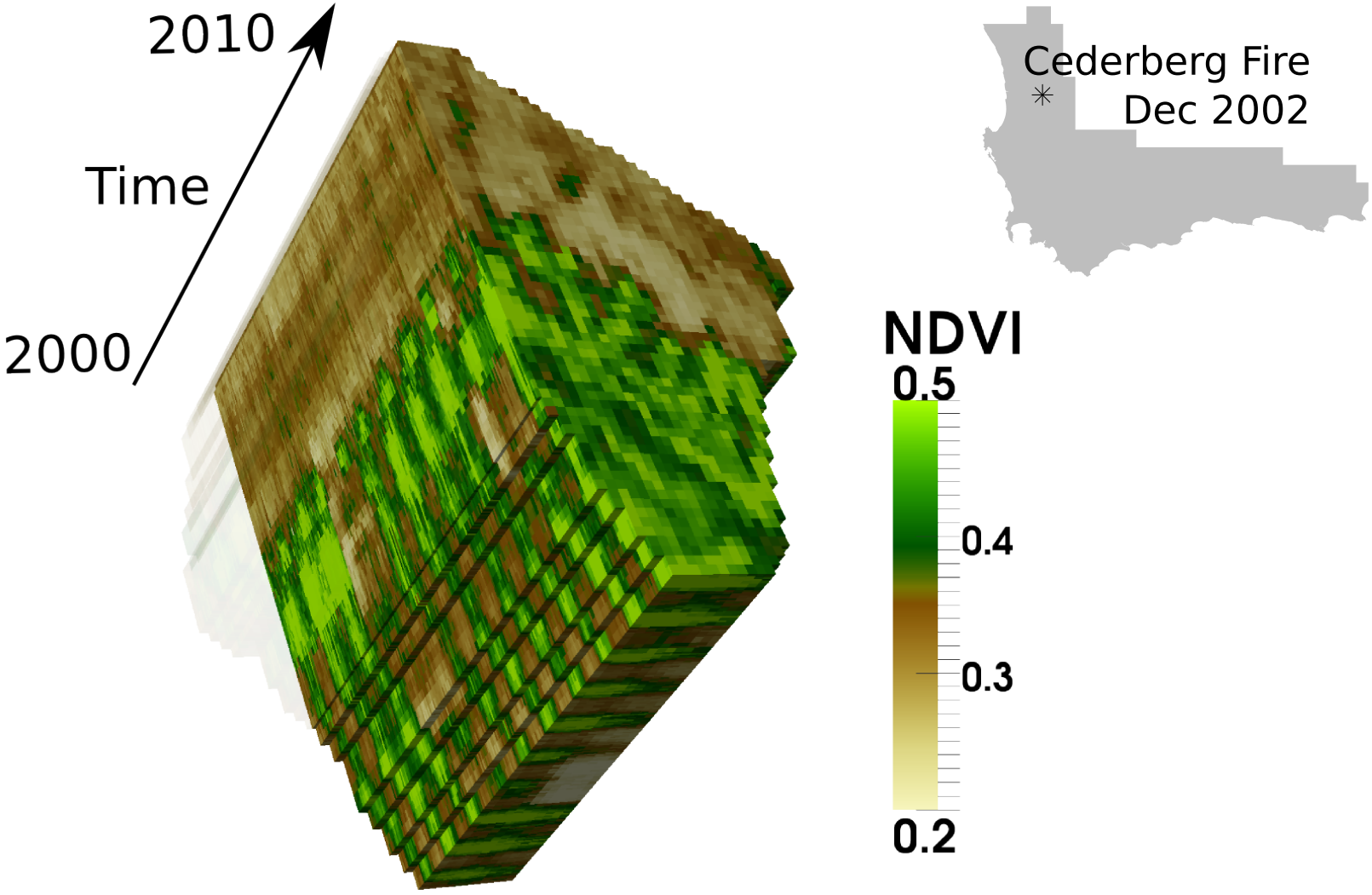

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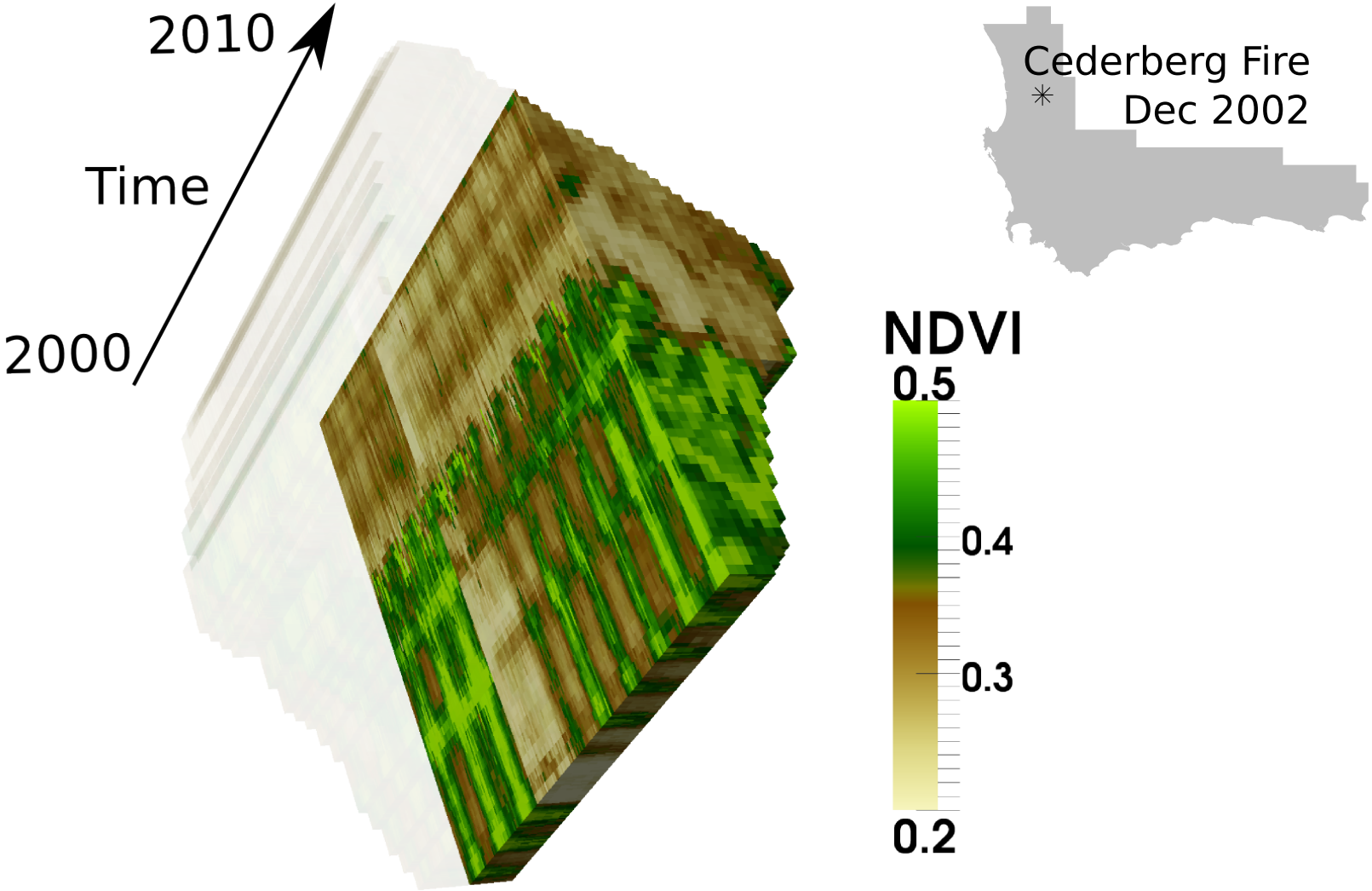

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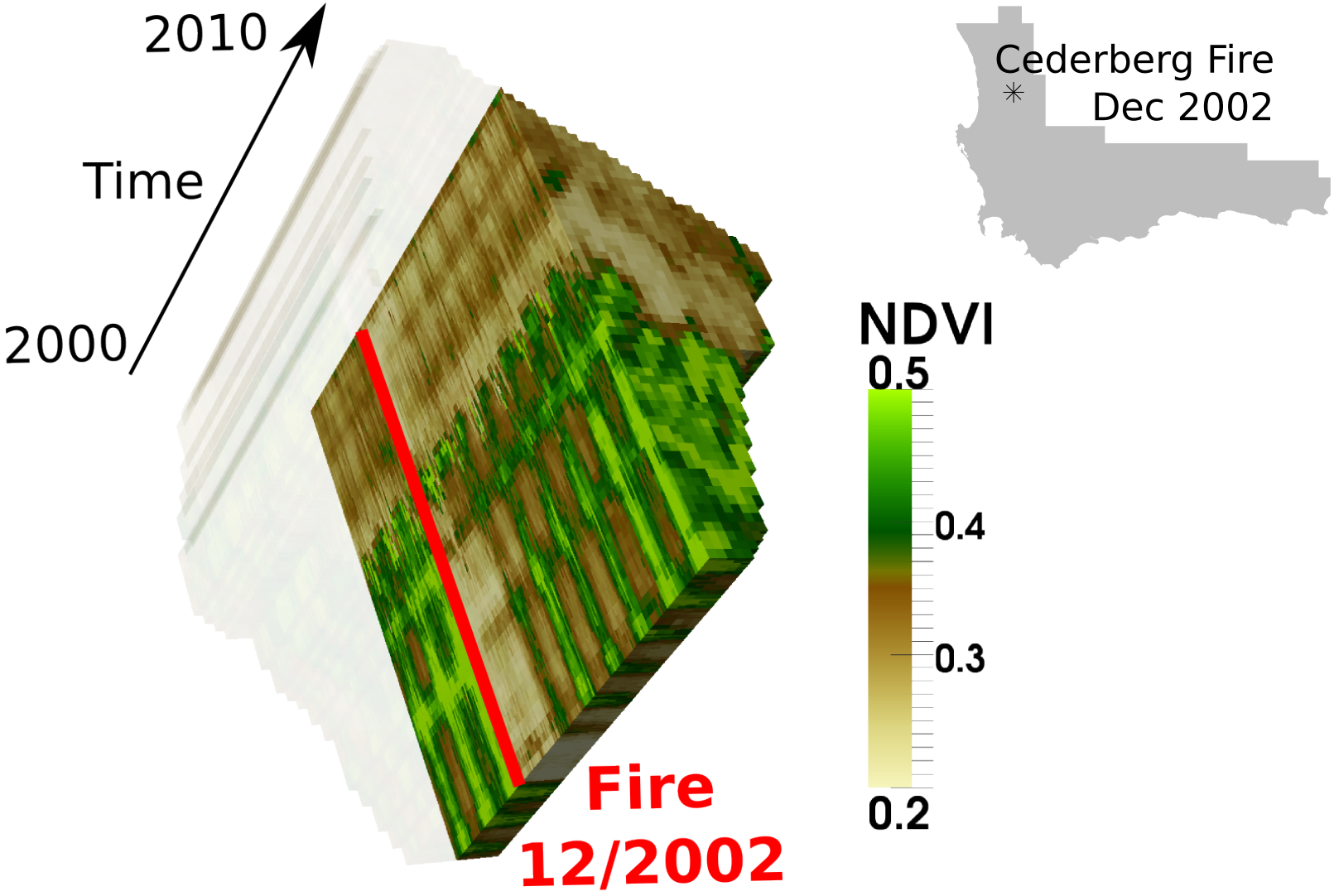
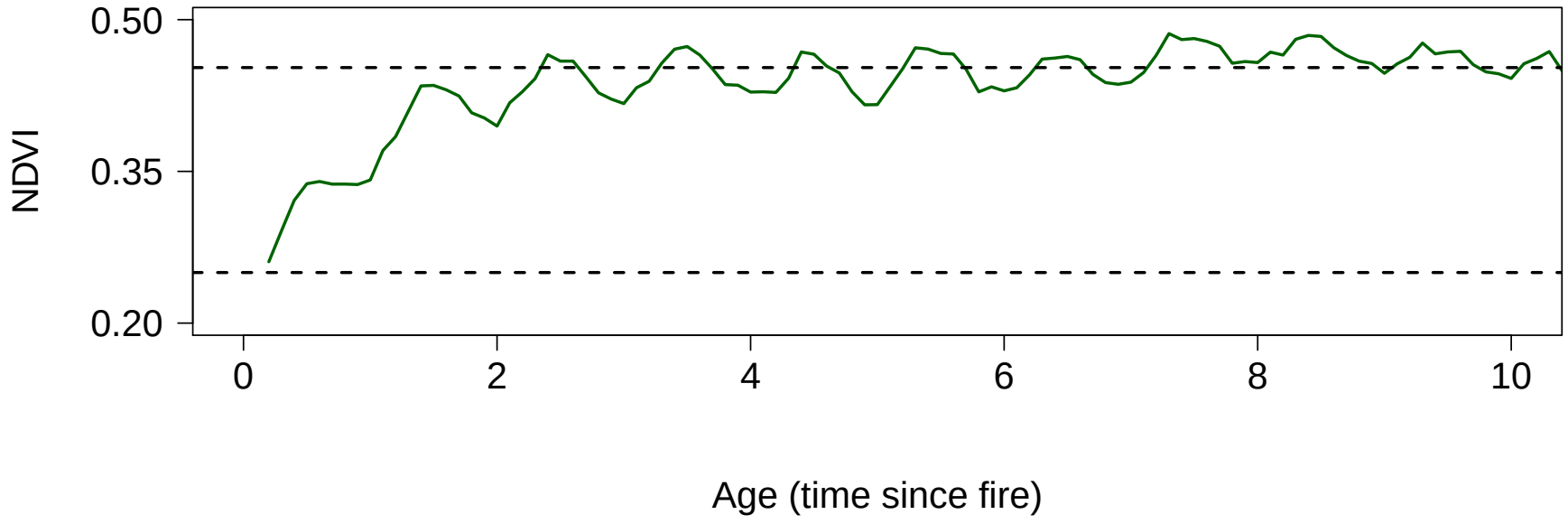


Post-fire vegetation dynamics via MODIS

$$NDVI(\text{age}) = \mathbf{?}$$

Post-fire vegetation dynamics via MODIS

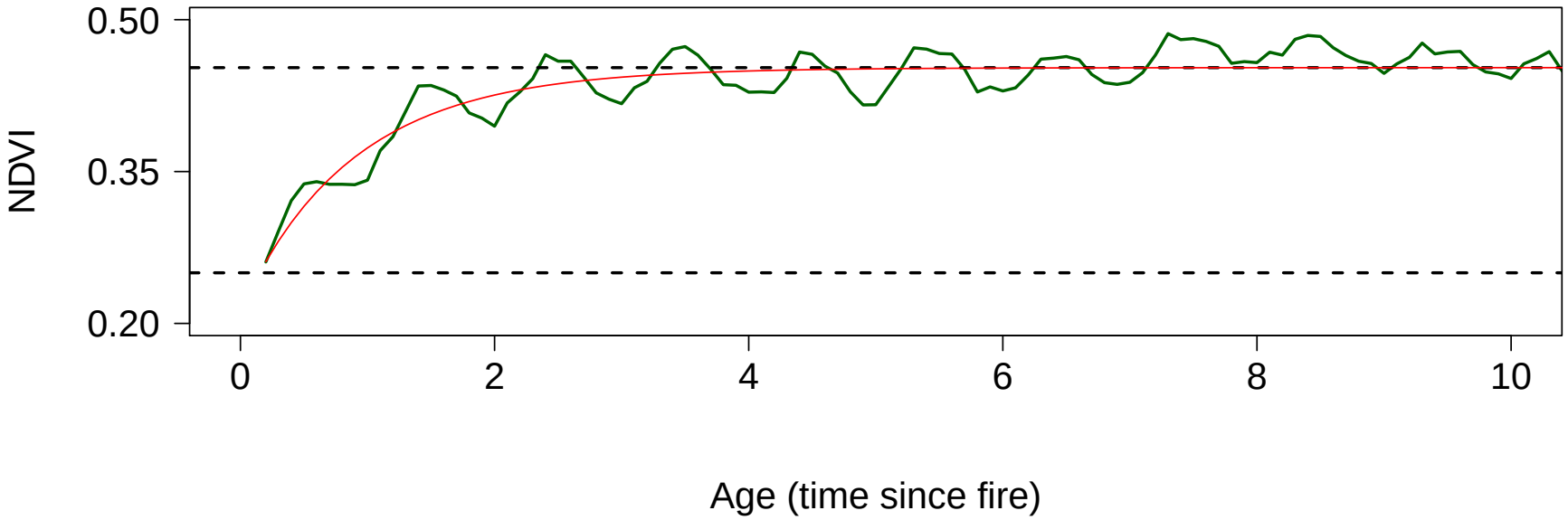


$$NDVI(\text{age}) = \alpha + \gamma$$

α: **Post-fire NDVI at time zero**

$\alpha + \gamma$: **Potential NDVI**

Post-fire vegetation dynamics via MODIS



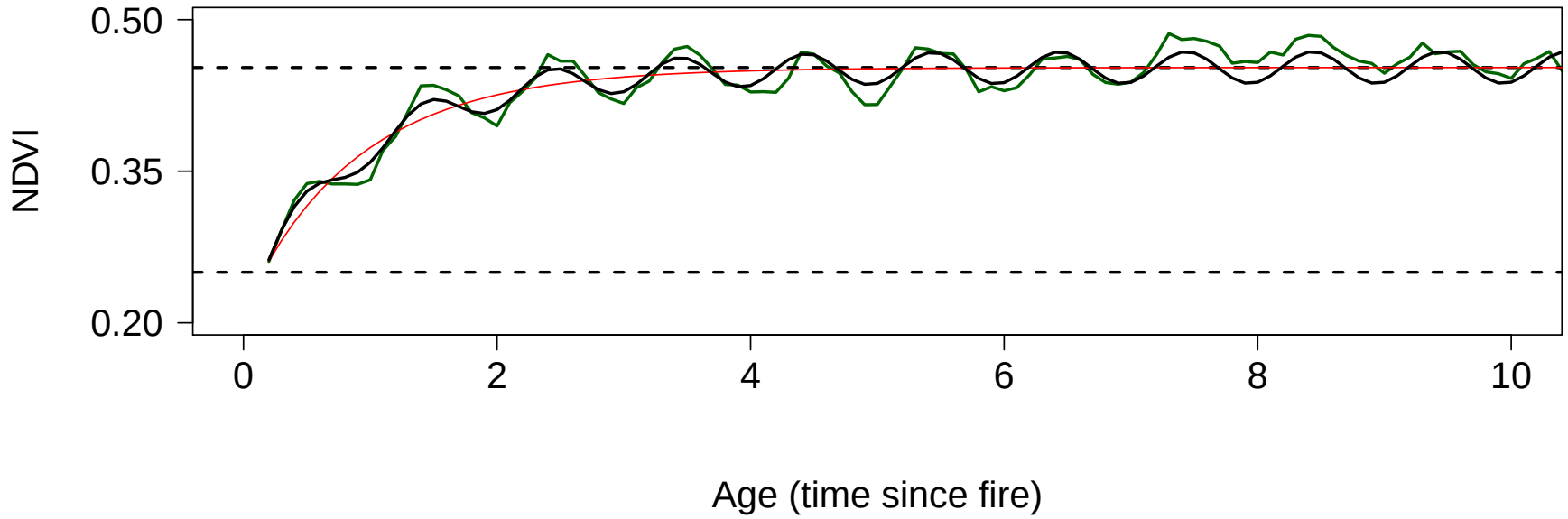
$$NDVI(\text{age}) = \alpha + \gamma * \left(1 - e^{-(\frac{\text{age}}{\lambda})}\right)$$

α: Post-fire NDVI at time zero

$\alpha + \gamma$: Potential NDVI

λ: **Recovery rate**

Post-fire vegetation dynamics via MODIS



$$NDVI(\text{age}) = \alpha + \gamma * \left(1 - e^{-(\frac{\text{age}}{\lambda})}\right) +$$
$$\mathbf{A}_i\mathbf{sin}\left(2\pi \times \mathbf{age} + \left[\phi + \frac{\pi}{6}(m-1)\right]\right) + \epsilon$$

α: Post-fire NDVI at time zero

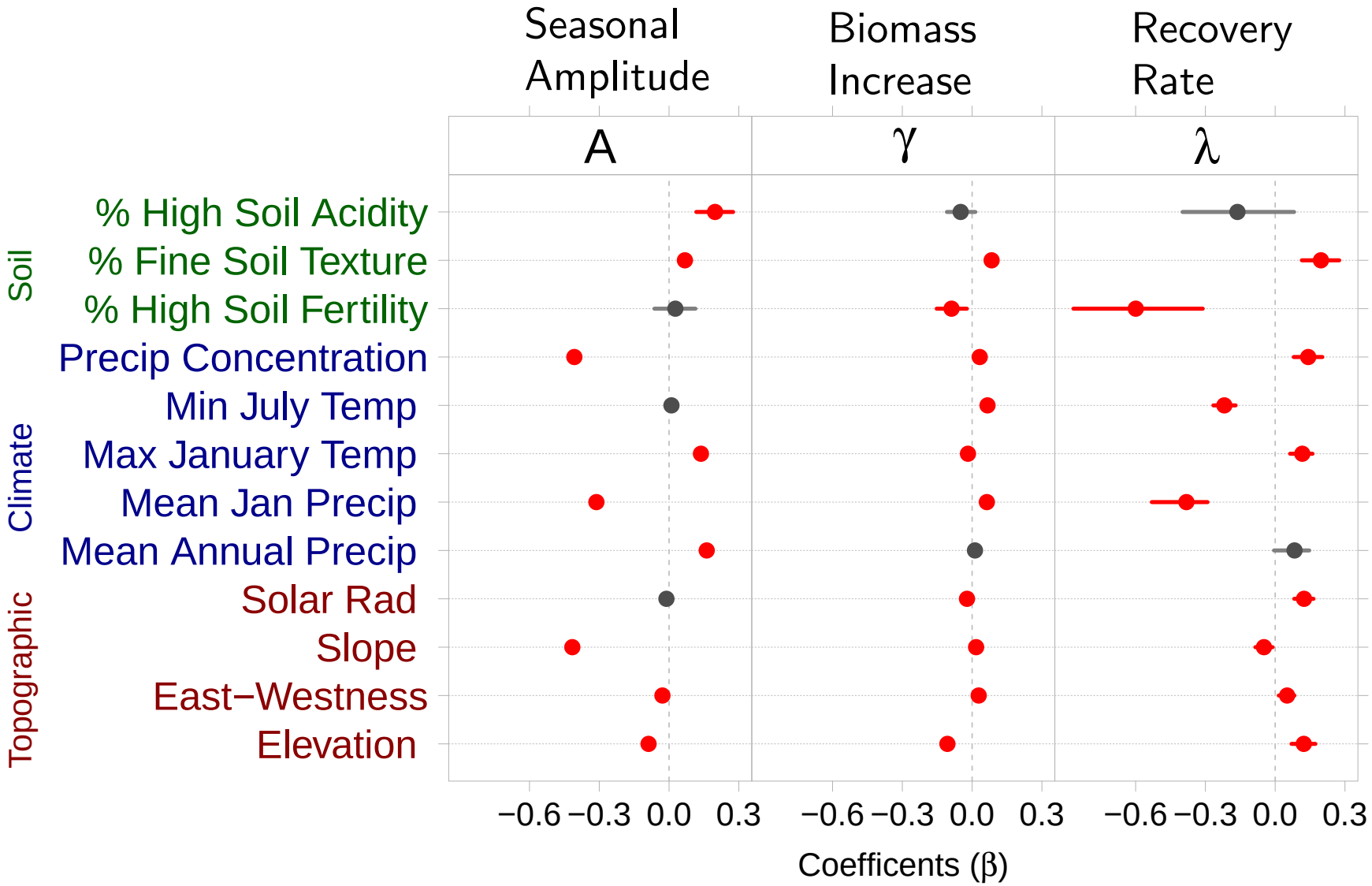
$\alpha + \gamma$: Potential NDVI

λ: Recovery rate

ϕ: **Accounts for month of fire**

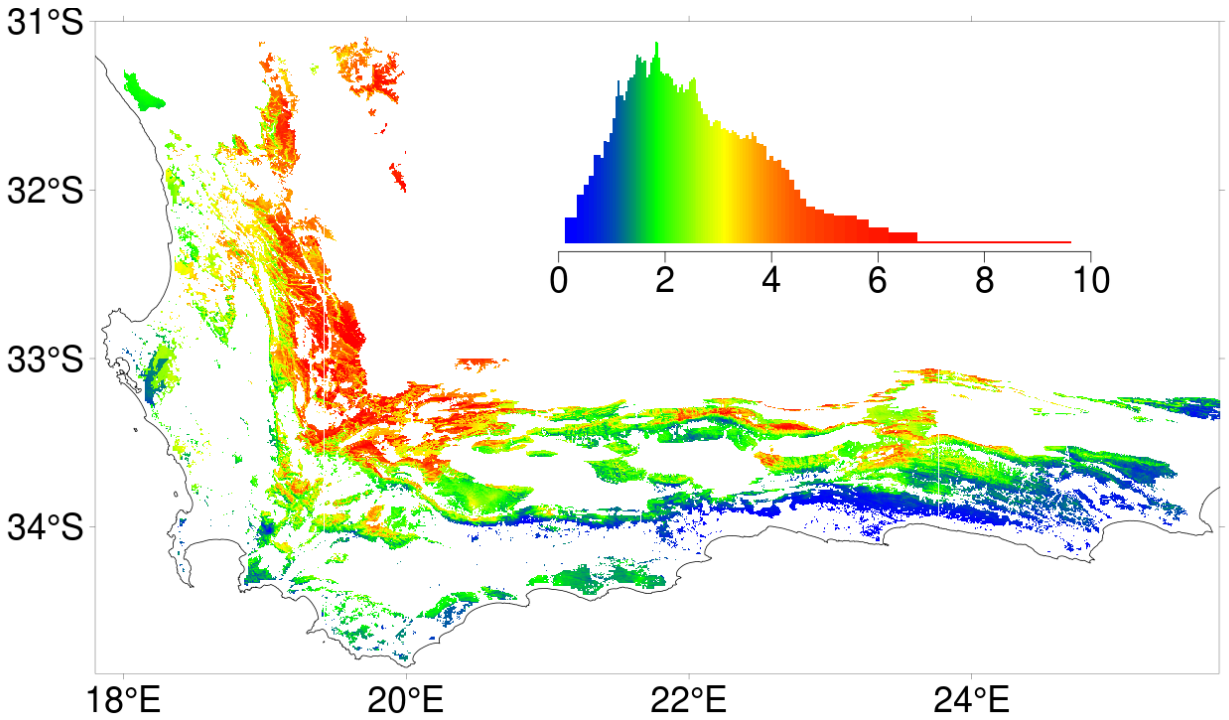
A: **Seasonal amplitude**

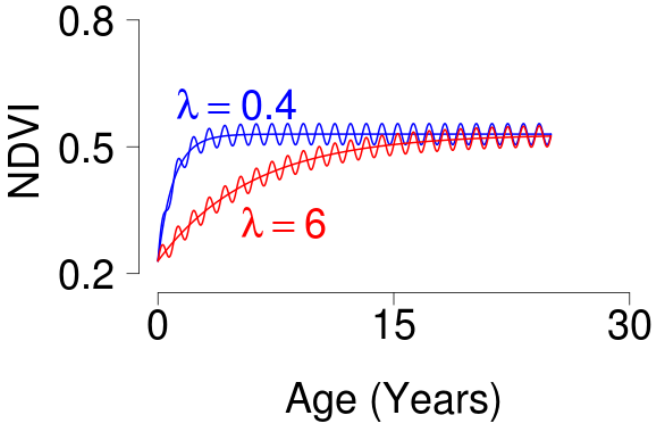
Coefficients between environment/climate and recovery



Red indicates significance (95% HPD credible intervals)

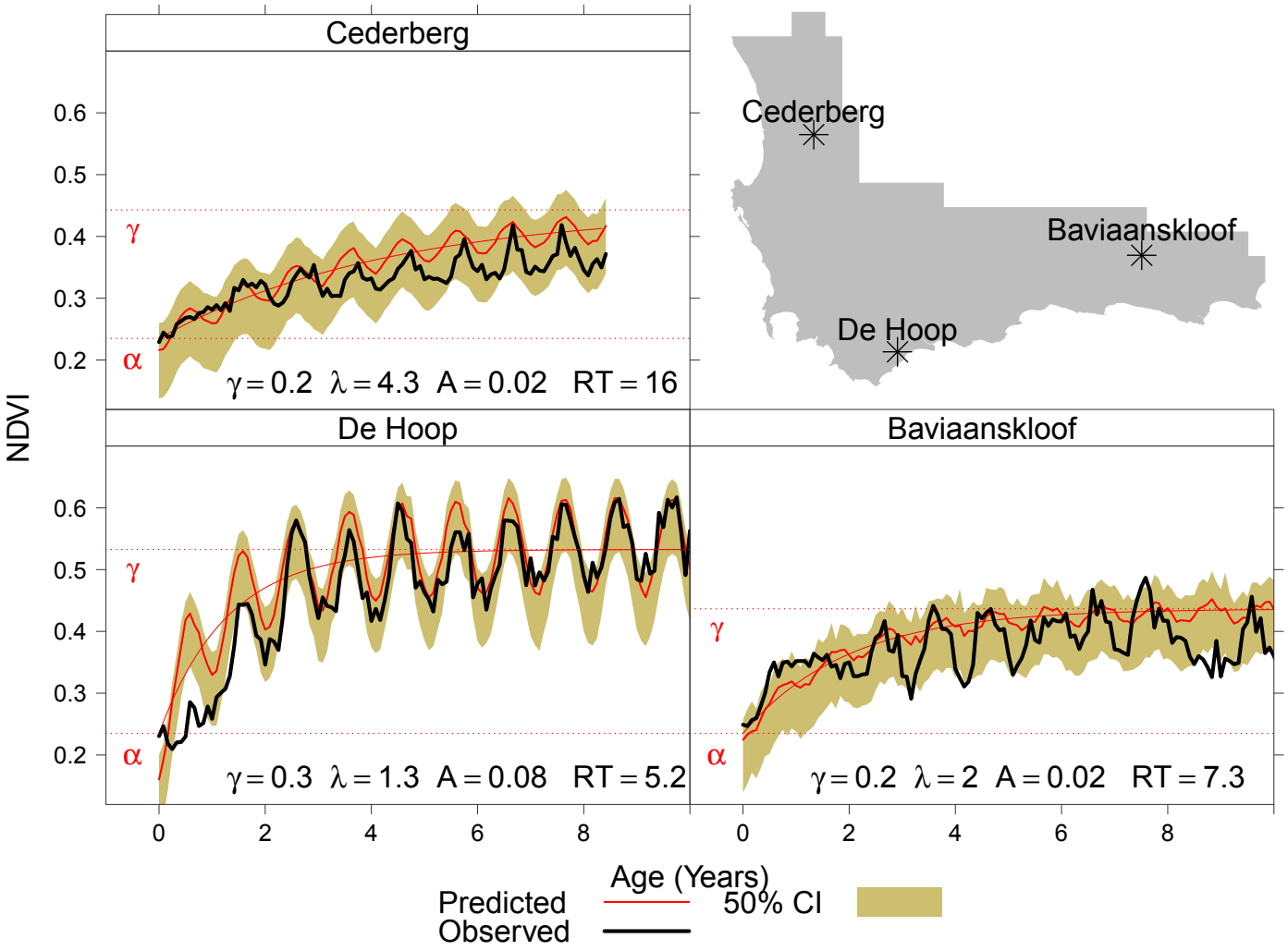
λ: "Recovery Rate"





- Soil Fertility
- Summer Precipitation
- Warm Winter Temps

Can it predict recovery in new areas?



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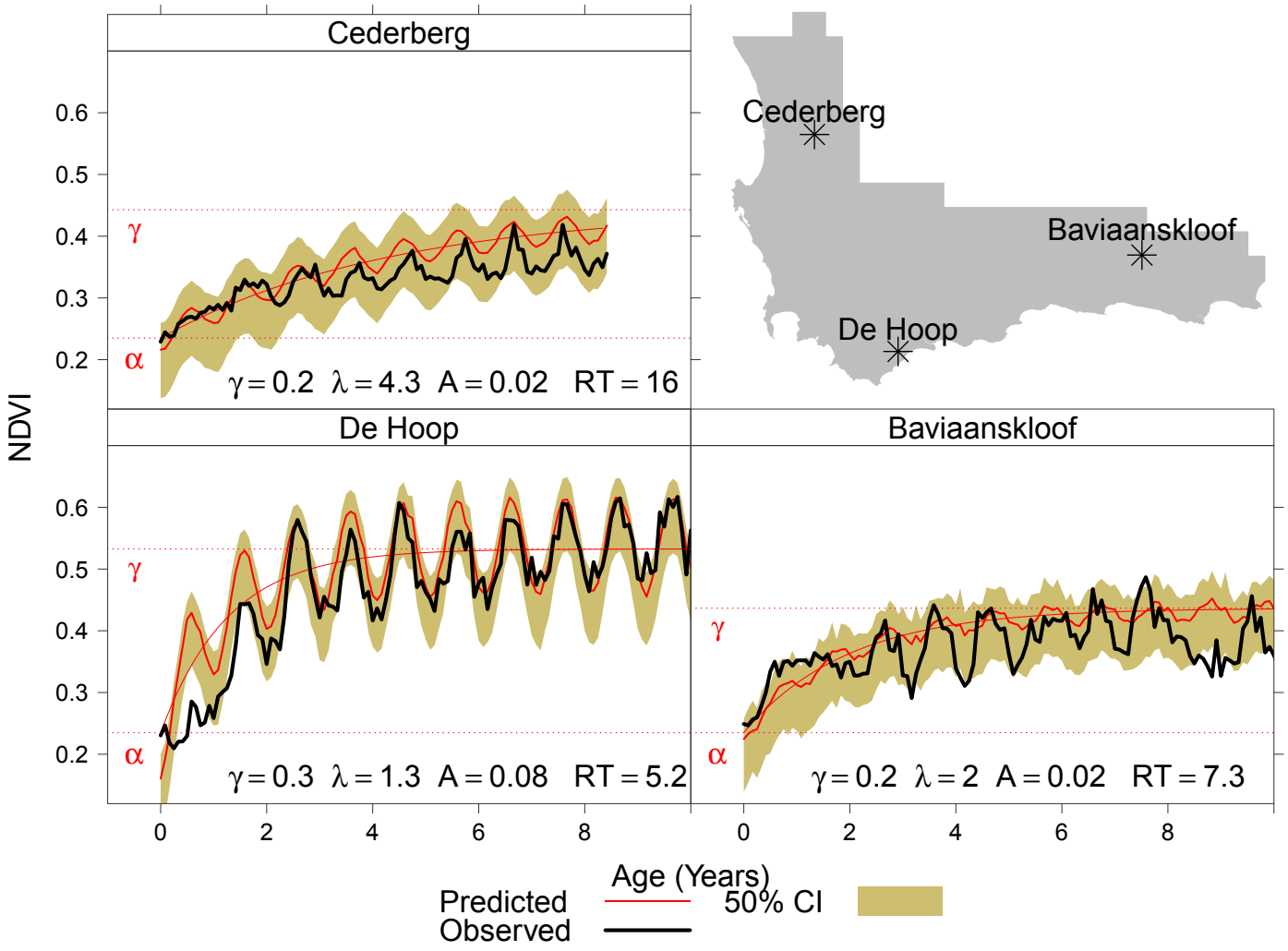
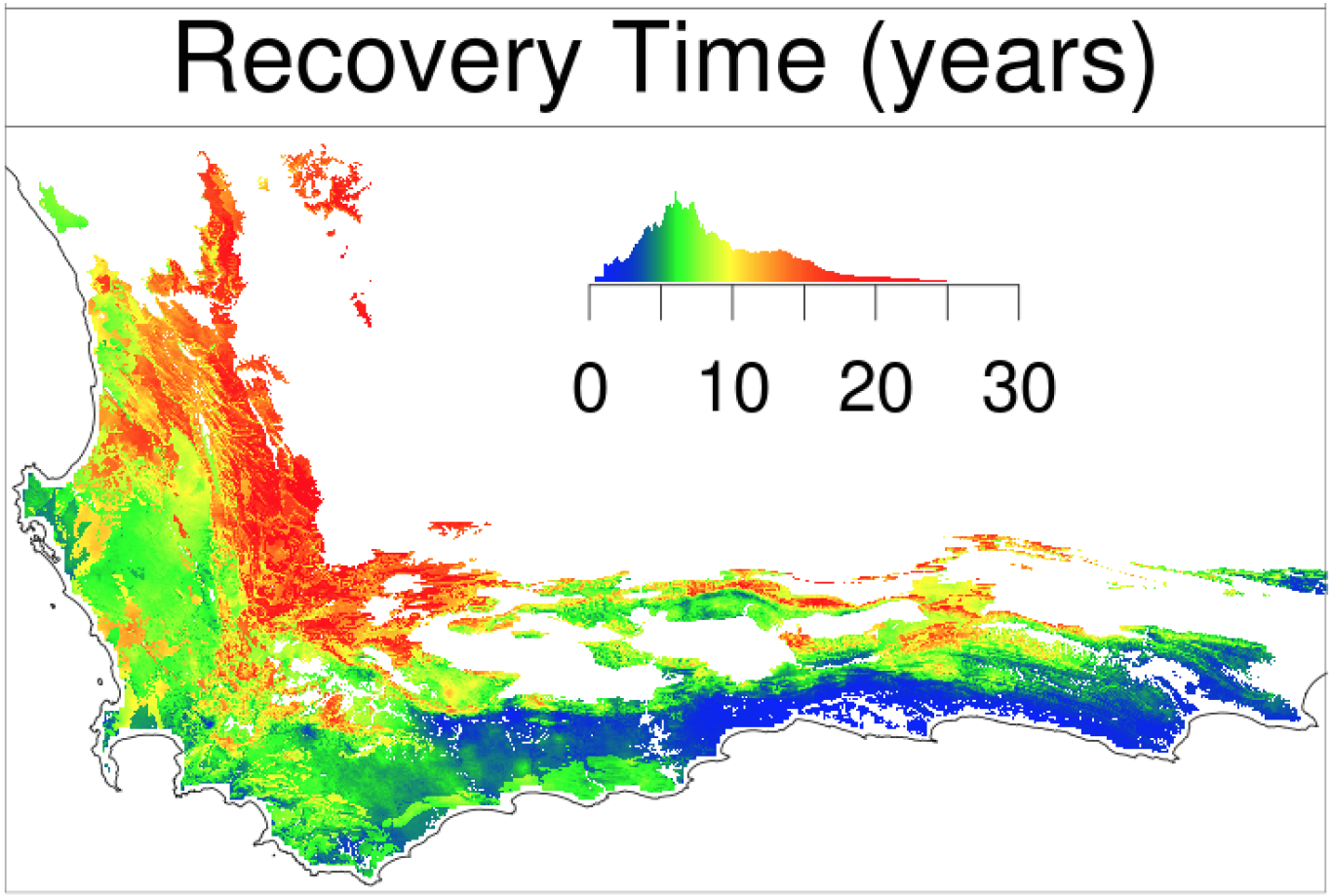
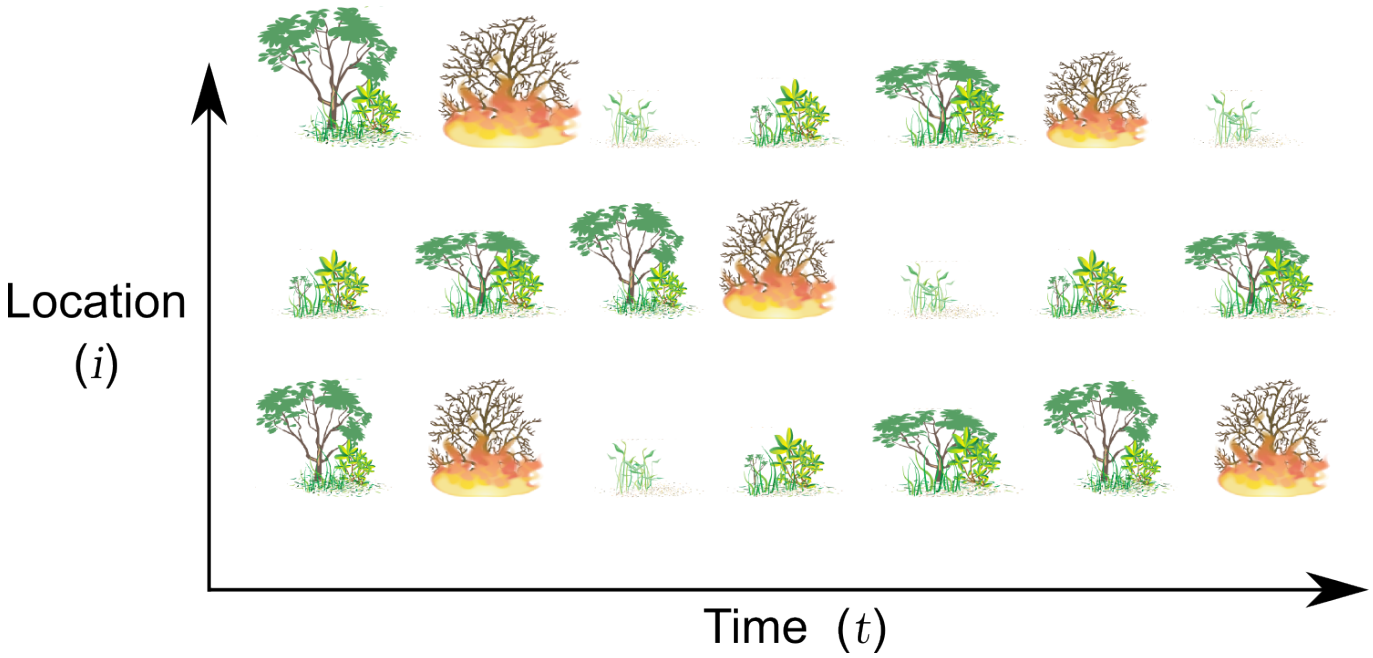


Estimate *Recovery Time* using asymptote

Spatial distribution of predicted recovery time (years)

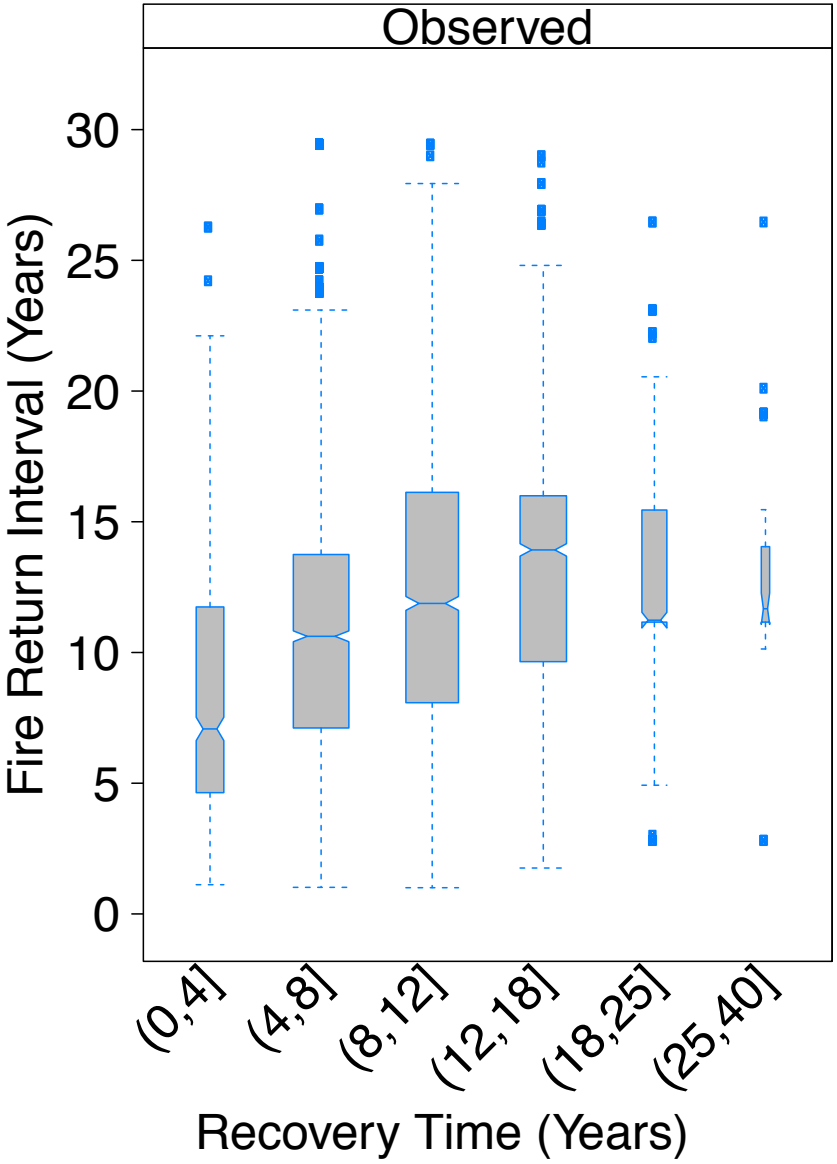


Is "Recovery Time" meaningful? A comparison with CapeNature fire records



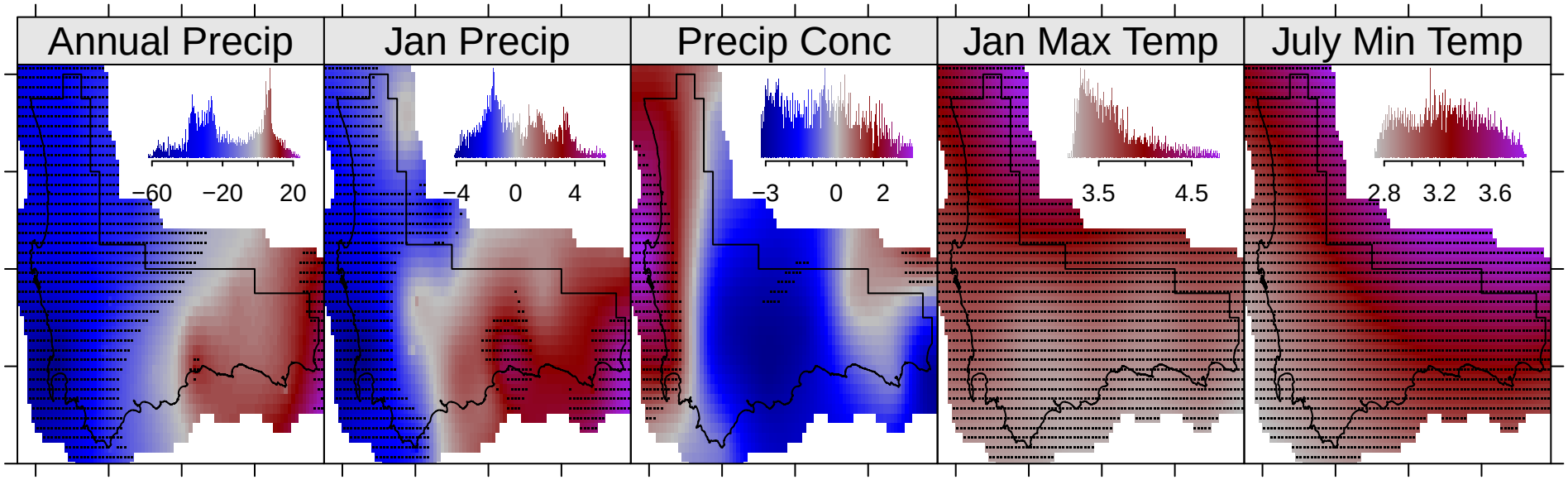
- Bias towards shorter observed intervals
- Must account for *censored* observations...

Is "Recovery Time" meaningful? A comparison with CapeNature fire records



- Fire frequency associated with 'recovery time'
- Use 'recovery time' to estimate fire return frequencies?

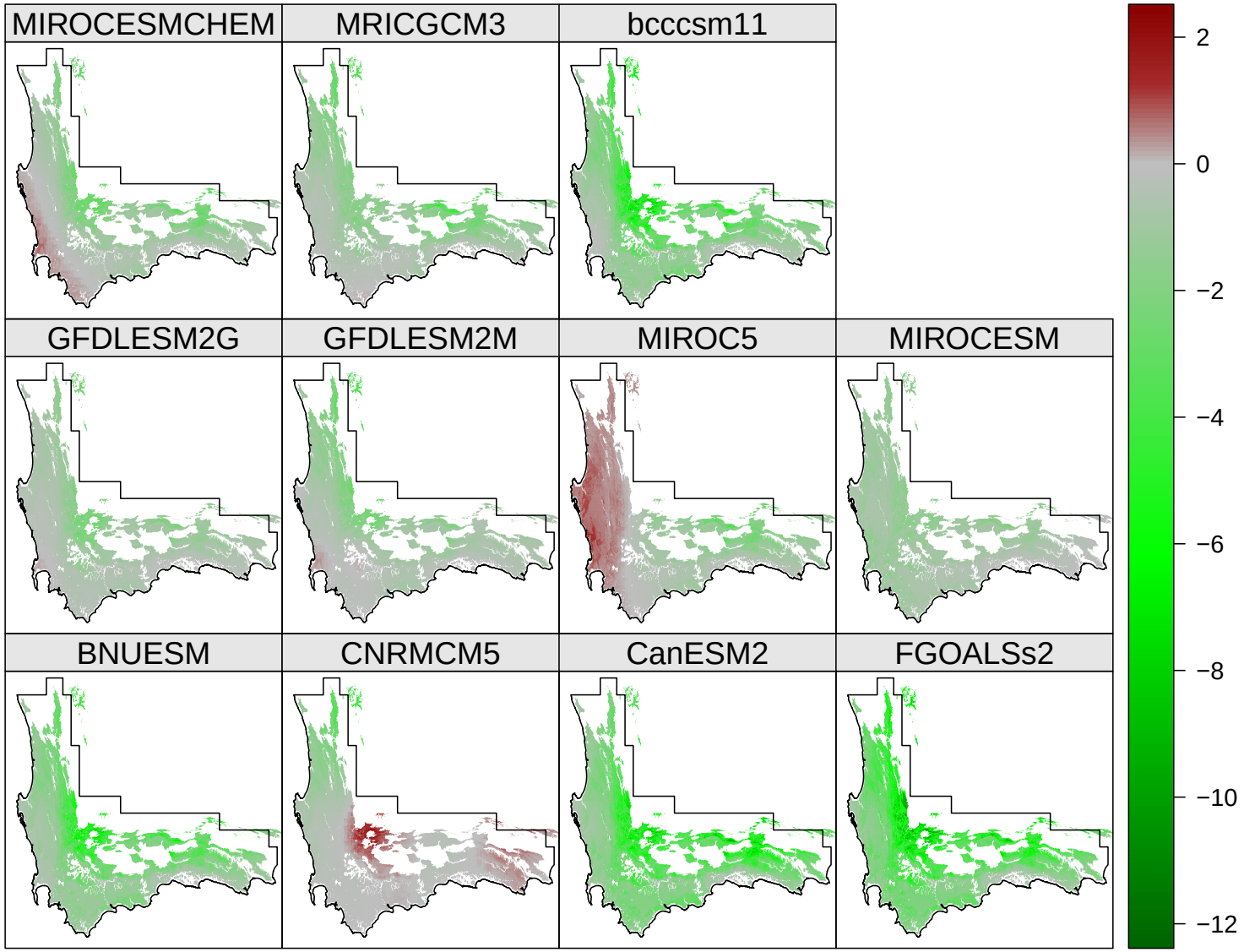
Projected climate change: multimodel mean change



- Warmer everywhere
- Drier in the west, wetter in the east

CMIP5 GCM RCP8.5 2081–2100 multi-model mean (n=11) downscaled to stations by CSAG and interpolated
Stippling indicates ≥8 out of 11 models agree

Projected change in recovery time (years)



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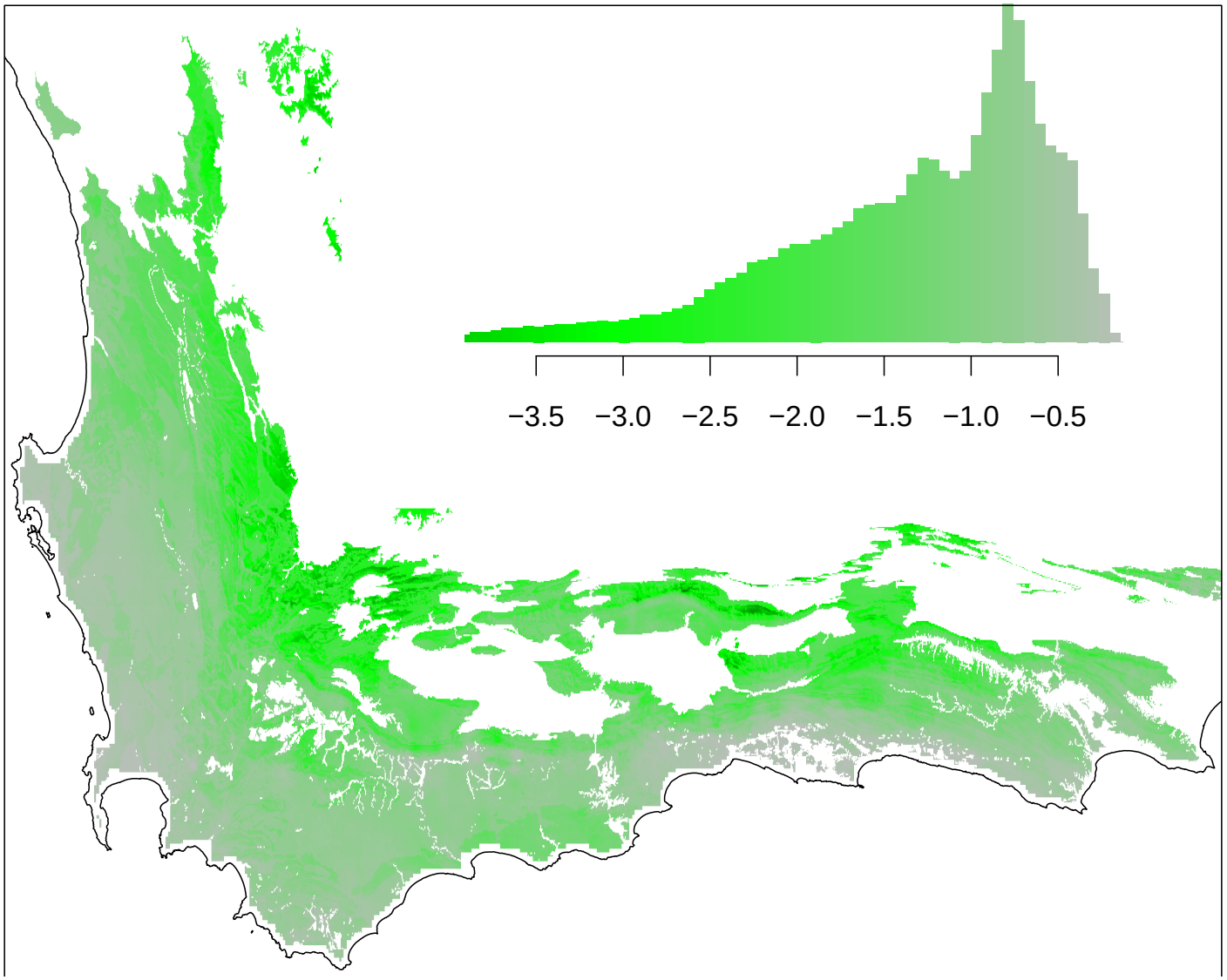

CMIP5 GCM RCP8.5 2081–2100 multi-model mean (n=11)

Summary

- Satellite data ⇒ archive of ecosystem properties
- Strong 'recovery gradients' associated with climate

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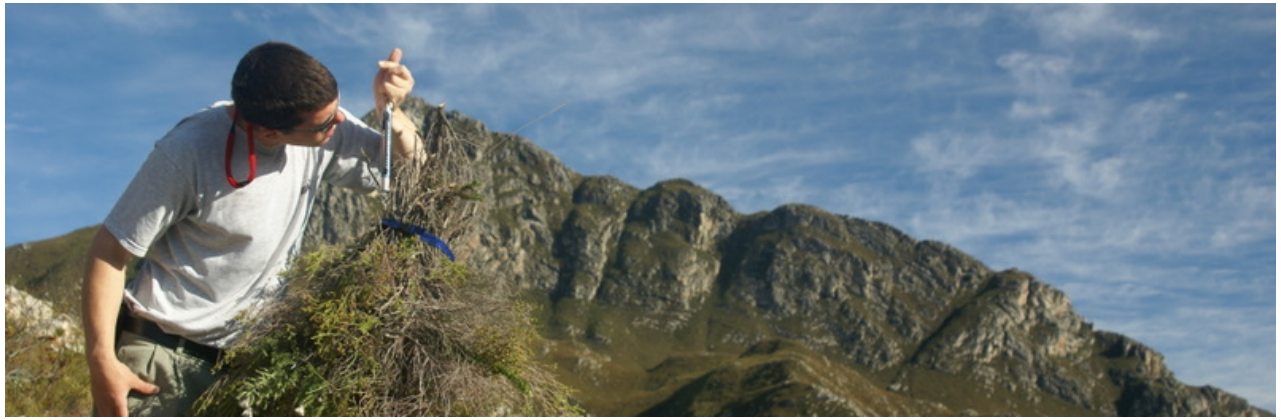
Summary

- Satellite data ⇒ archive of ecosystem properties
- Strong 'recovery gradients' associated with climate
- Future climate ⇒ *faster* recovery, but dependent on ⇕ precip
- Potential for near real-time monitoring of recovery trajectories
- High spatio-temporal resolution, but **low ecological resolution**.



Measuring biomass in the Kogelberg Mountains

Kick-starting a unified research programme...

Integrating vegetation composition, structure and function.

Thank you!

adam.wilson@yale.edu

Cape mountain zebra (*Equus zebra zebra*), Cape Point, South Africa

Spatio-temporal Survival Analysis

$$i \in 1 : I \qquad \text{(location)}$$
$$t \in 1 : T \qquad \text{(time)}$$
$$Z_i = \text{time since last fire in location } i$$

$$p_{i,t} = P(Z_i > t | Z_i > t-1) \qquad \textit{Survival (no-fire) Probability}$$
$$p_{i,t} = \Phi(\boldsymbol{X}_{i,t}\boldsymbol{\beta}) \qquad \text{probit regression}$$
$$P(Z_i \in \{t-1 < Z_i \leq t\}) = (1 - p_{i,t})p_{i,t-1} \ldots p_{i,1} \qquad \text{and missing data...}$$

Wilson, Latimer, Silander, Gelfand, & deKlerk *Ecological Modelling* (2010)

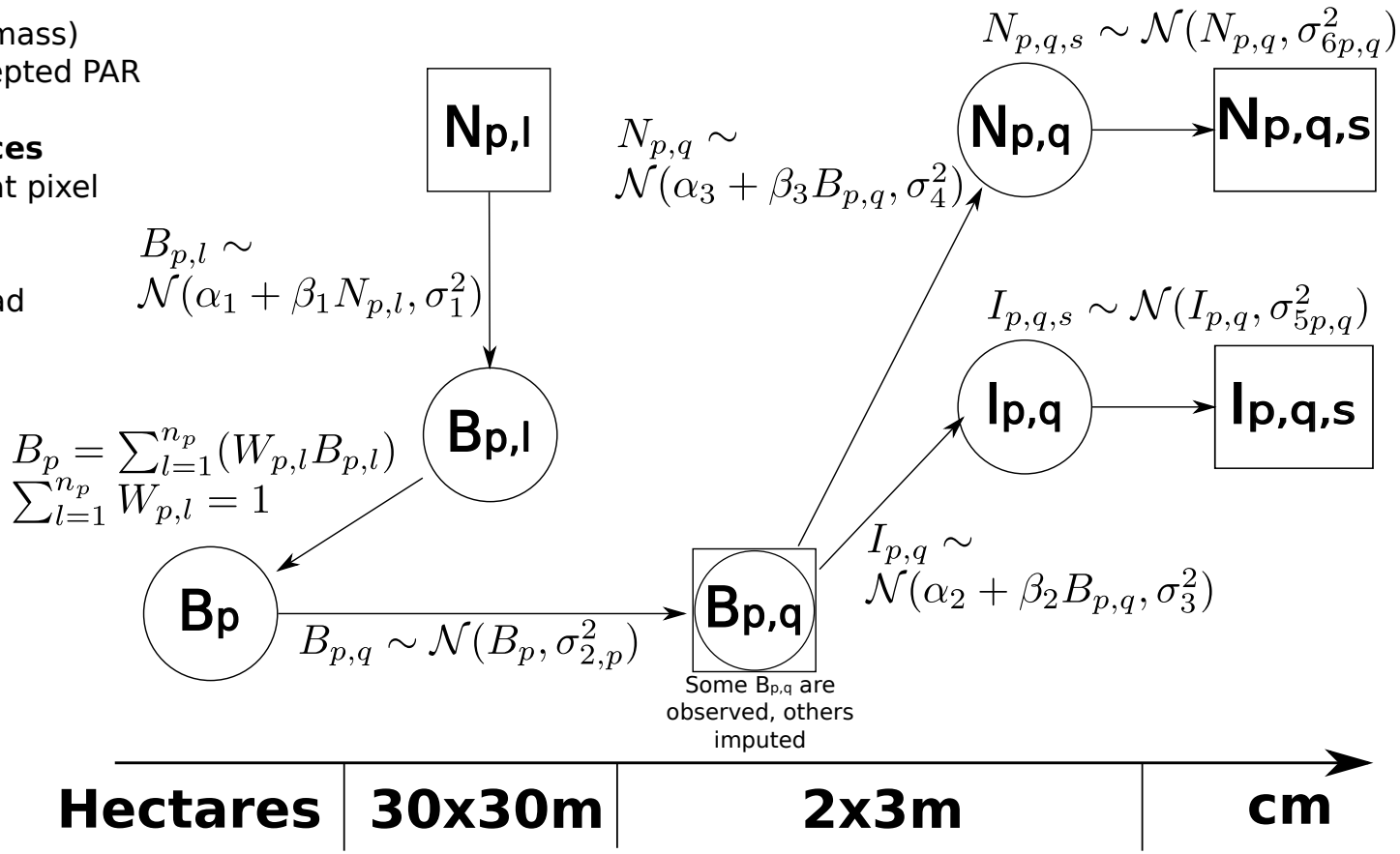
Hierarchical Scaling Model Framework

Variables

N NDVI
B ln(Biomass)
I Intercepted PAR

Indices

l Landsat pixel
p plot
q quad
s subquad



Increasing Spatial Resolution - Decreasing Area Sampled

Wilson, Silander, Gelfand, & Glenn, *International Journal of GIS* (2011)

Post-fire Recovery Model Framework

Recovery Trajectory

$i \in 1:I$ (space) $t \in 1:T$ (time)

$$\text{NDVI}_{i,t} \sim \mathcal{N}\left(\mu_{i,t}, \frac{1}{\sqrt{\tau}}\right)$$

$$\mu_{i,t} = \alpha_i + \gamma_i\left(1 - e^{-\left(\frac{age_{i,t}}{\lambda_i}\right)}\right) + \text{A}_i \sin\left(2\pi \times \text{age}_{i,t} + \left[\phi + \frac{\pi}{6}(m_{i,t} - 1)\right]\right)$$

Regressions

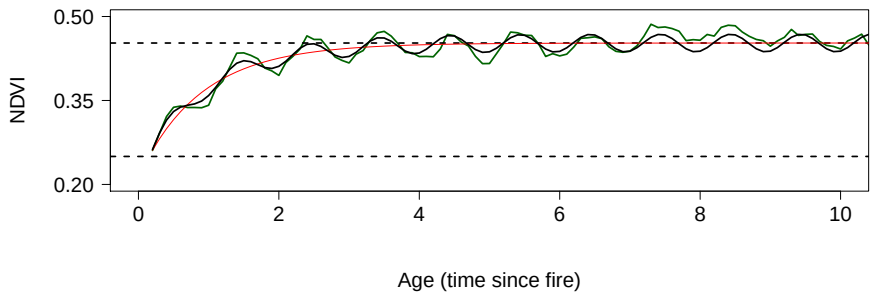
$\xi \in \{\gamma, \lambda, A\}$ (Recovery Parameters)

$$\xi_i \sim ln\mathcal{N}\left(\mathbf{X}\boldsymbol{\beta}_\xi, \frac{1}{\sqrt{\tau_\xi}}\right)$$

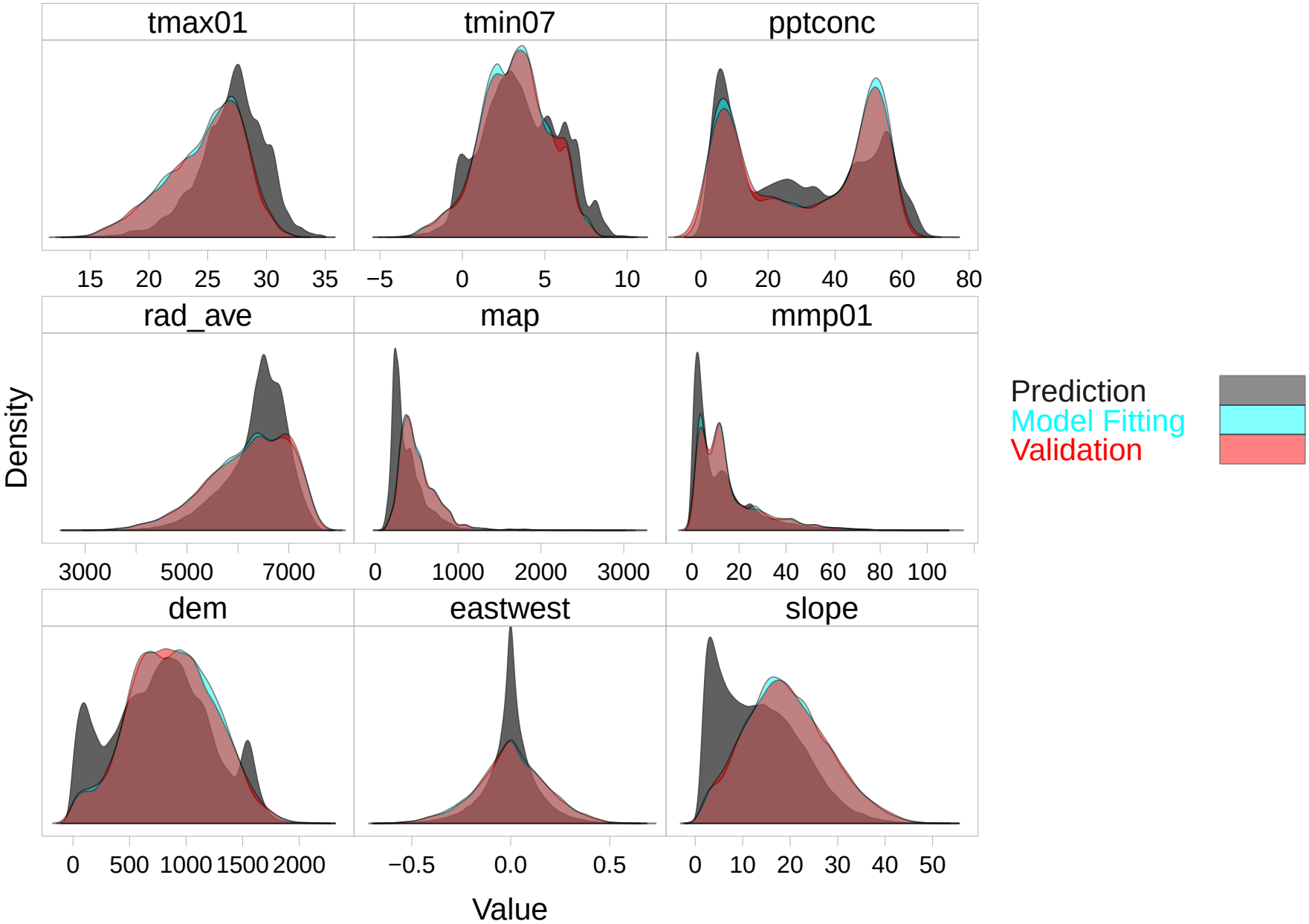
Priors

p$\in 1:P$ (# Covariates)

$$\beta_{\xi,p} \sim \mathcal{N}(0, 10)$$
$$\tau_\xi \sim \Gamma(0.1, 0.1)$$
$$\phi \sim \text{Uniform}(-\pi, \pi)$$
$$\alpha_i \sim \mathcal{N}(\mu_\alpha, \frac{1}{\sqrt{\tau_\alpha}})$$
$$\mu_\alpha \sim \mathcal{N}(0.15, 0.1); \tau_\alpha \sim \Gamma(0.1, 0.1)$$



Fitting and Prediction Environmental Space



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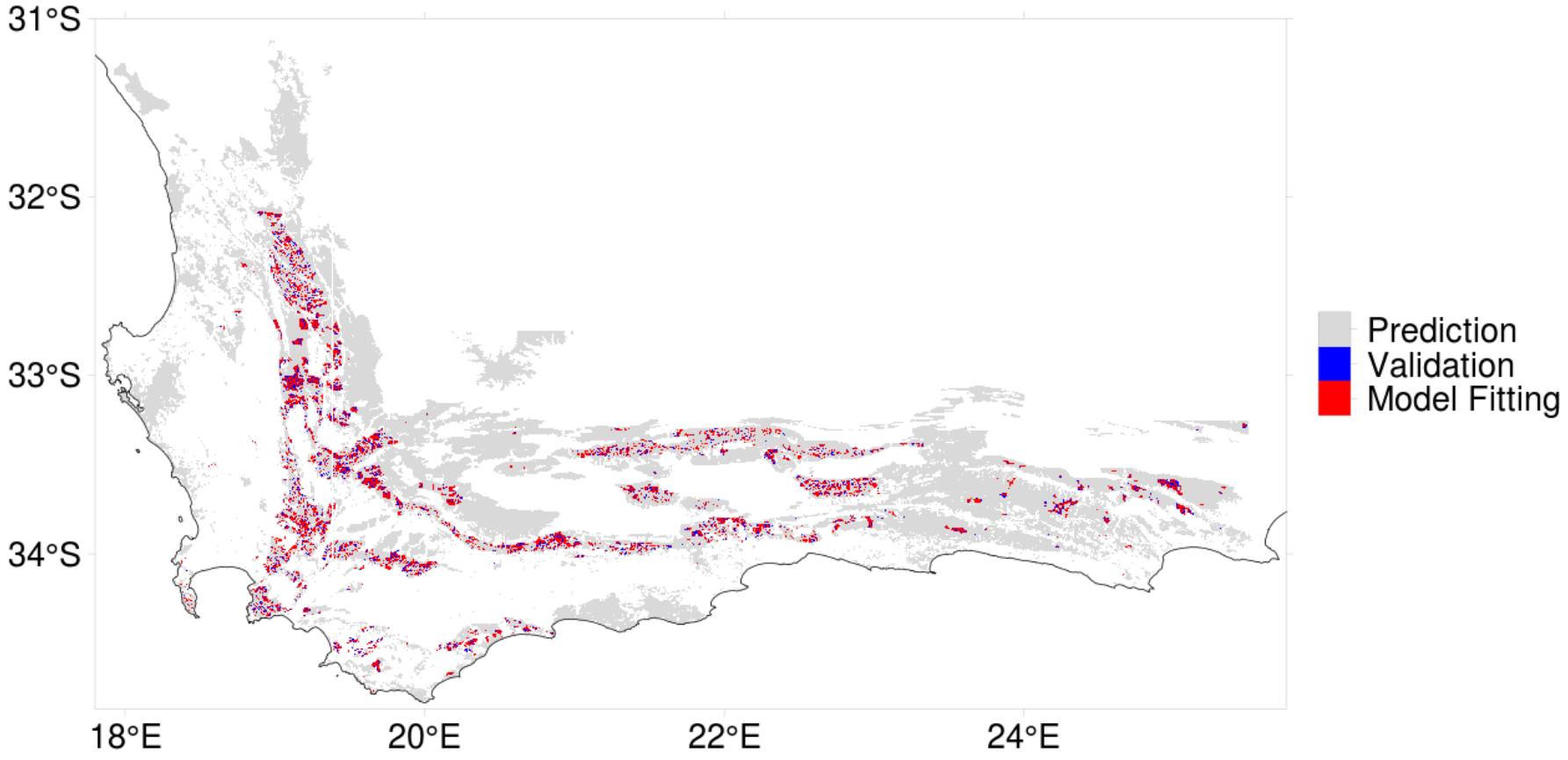
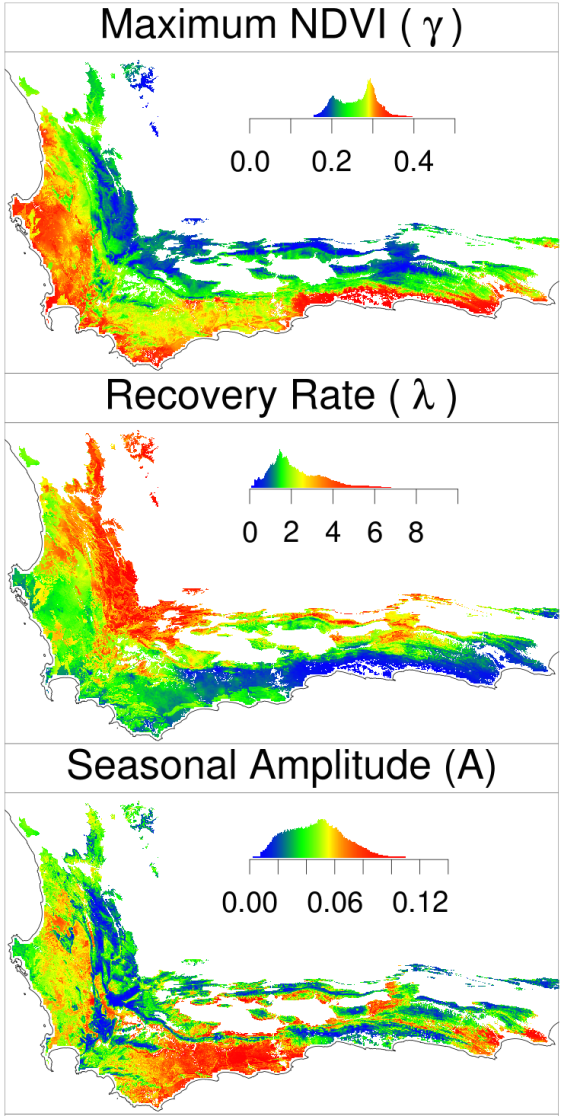


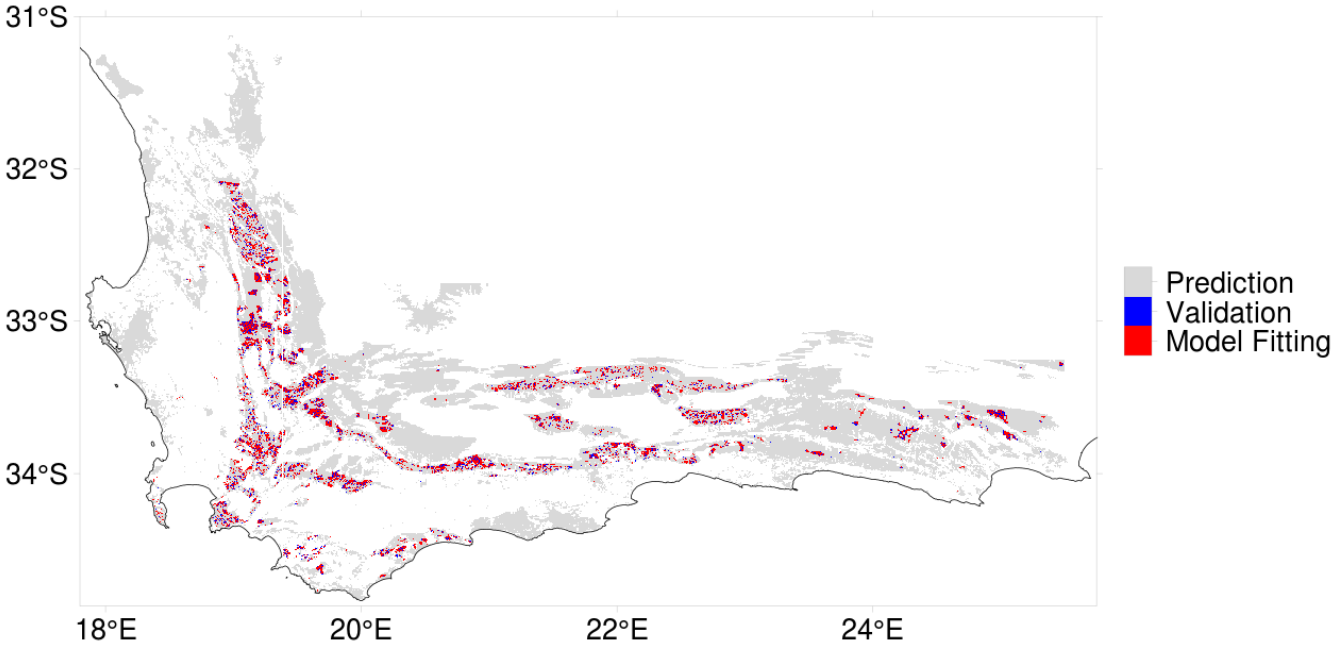
Spatial distribution of estimated recovery parameters



Parameters predicted for full *fynbos* biome including transformed areas.

Spatial Effects?

Patchy observations (and large n) suggest predictive process



possible in JAGS:

$W^* \sim \text{MVN}(0, \Sigma^*)$

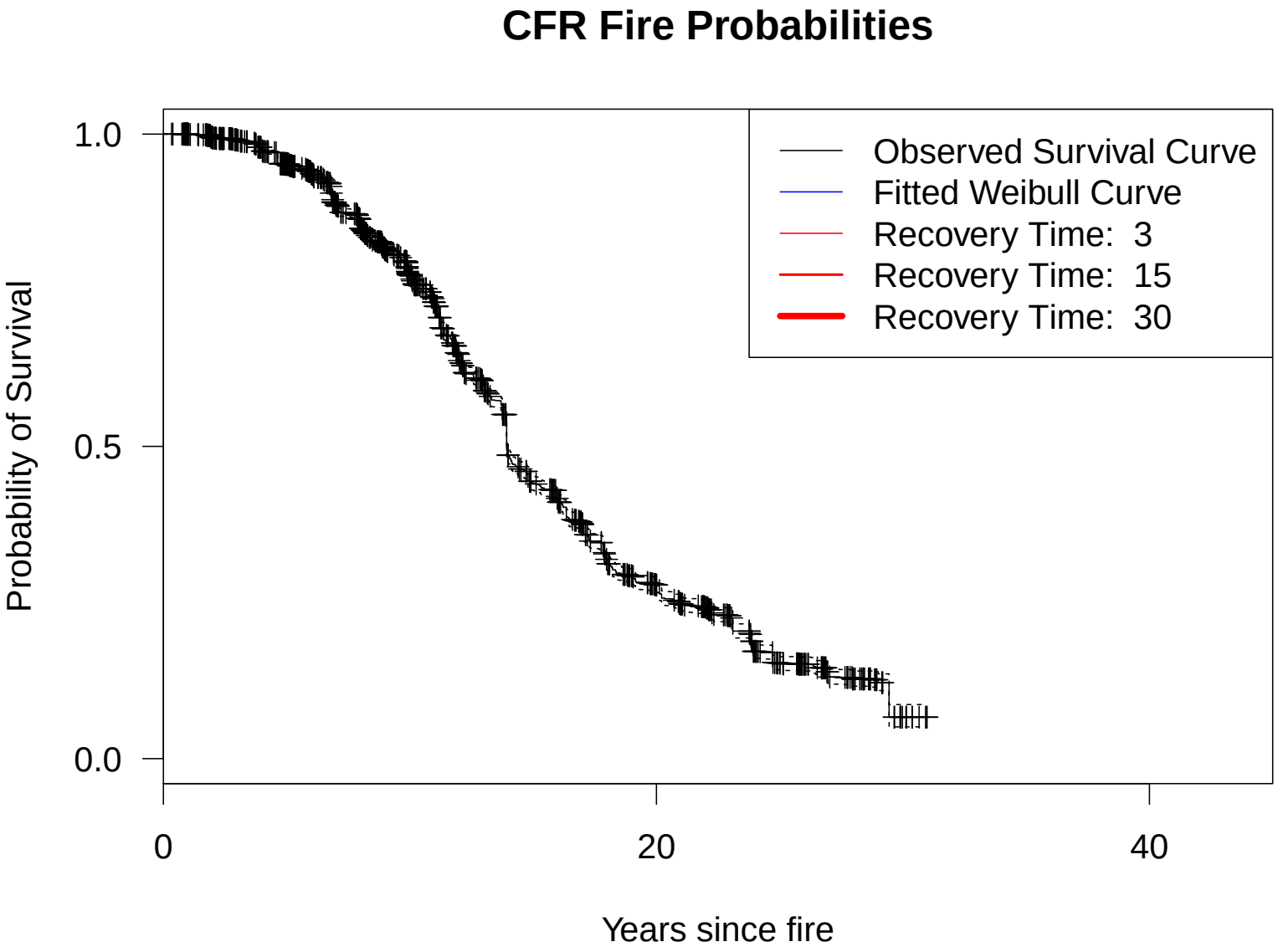
$\Sigma^*_{i,j} = \sigma H(\delta_{i,j}) = \sigma e^{-\phi \delta_{i,j}} \qquad i, j \in 1, ..., n$

$\text{W} = \Sigma'_{W,W^*} \Sigma^{*-1} W^*$

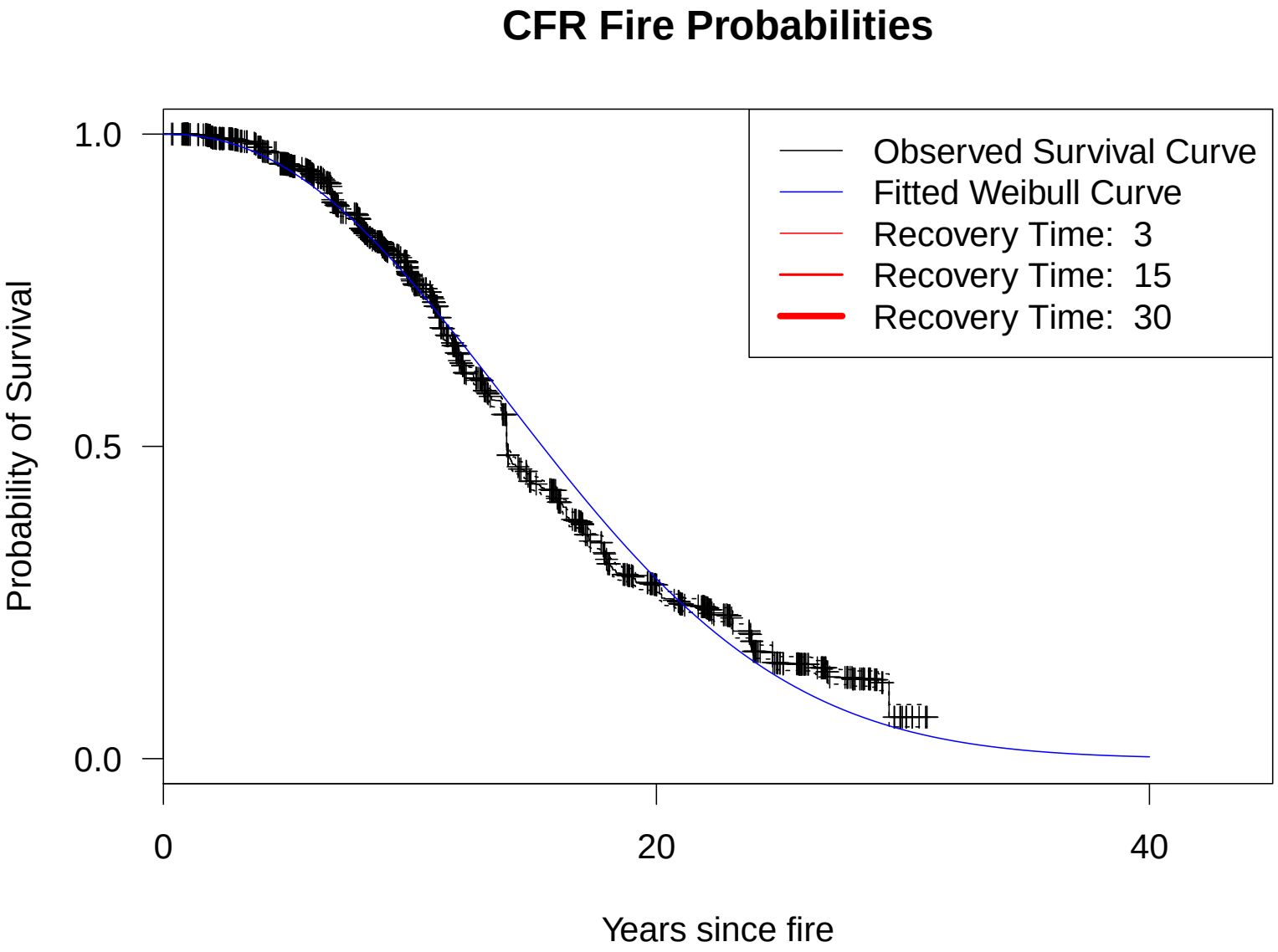
$\text{NDVI}_{i,t} = \text{curve} + \text{seasonality} + W$

(from Latimer,*et.al* 2009)

Estimating fire intervals using "recovery time"



Estimating fire intervals using "recovery time"



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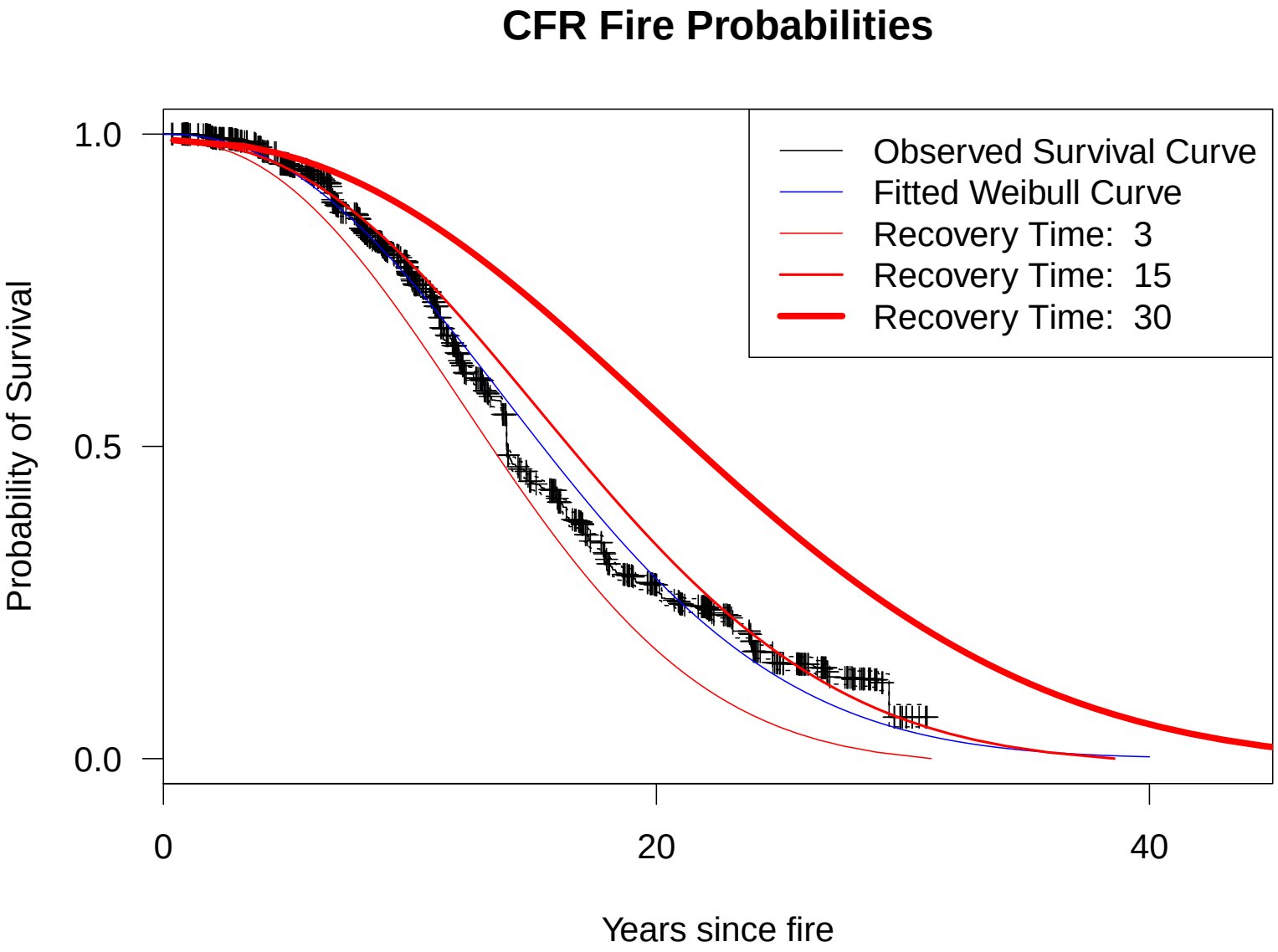

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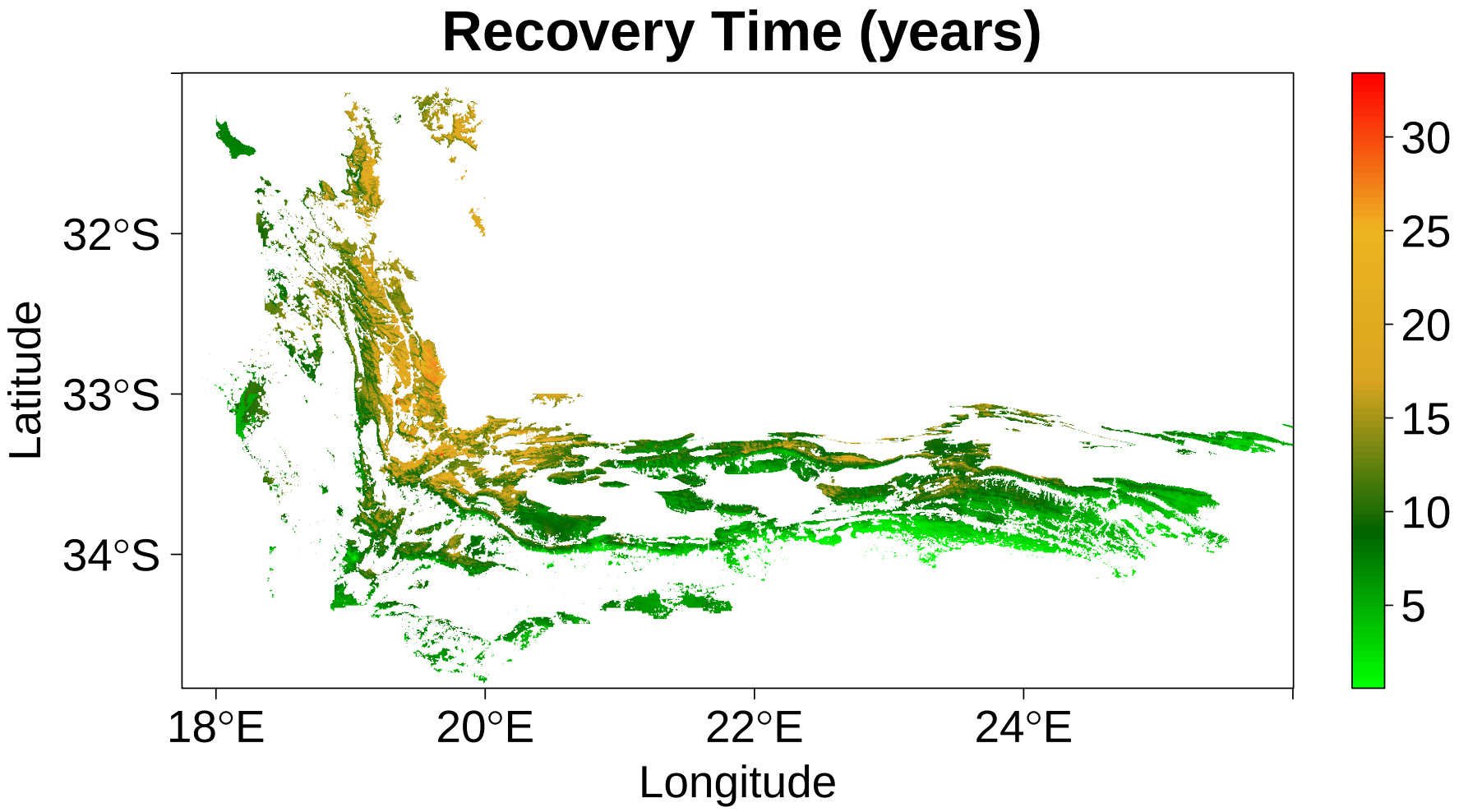

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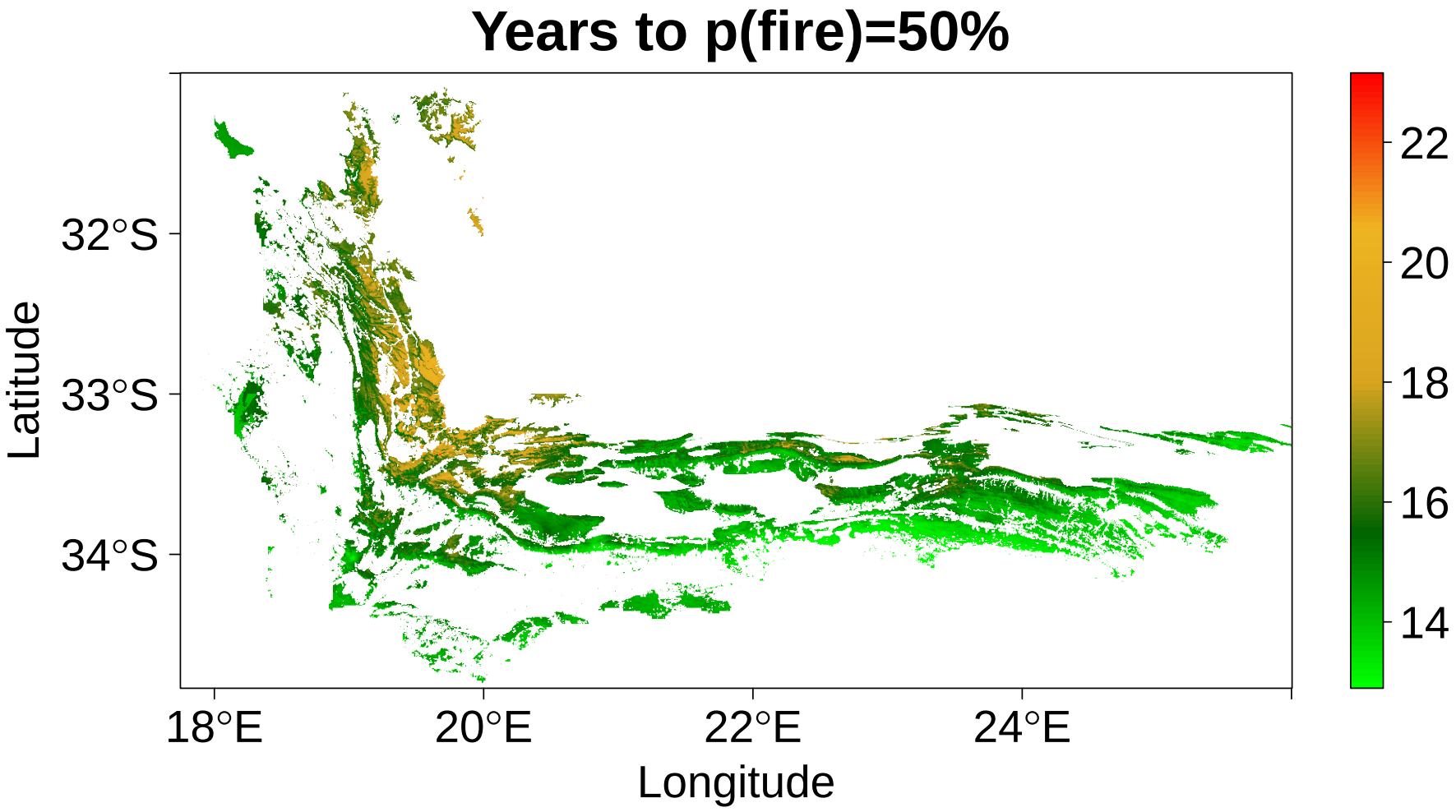

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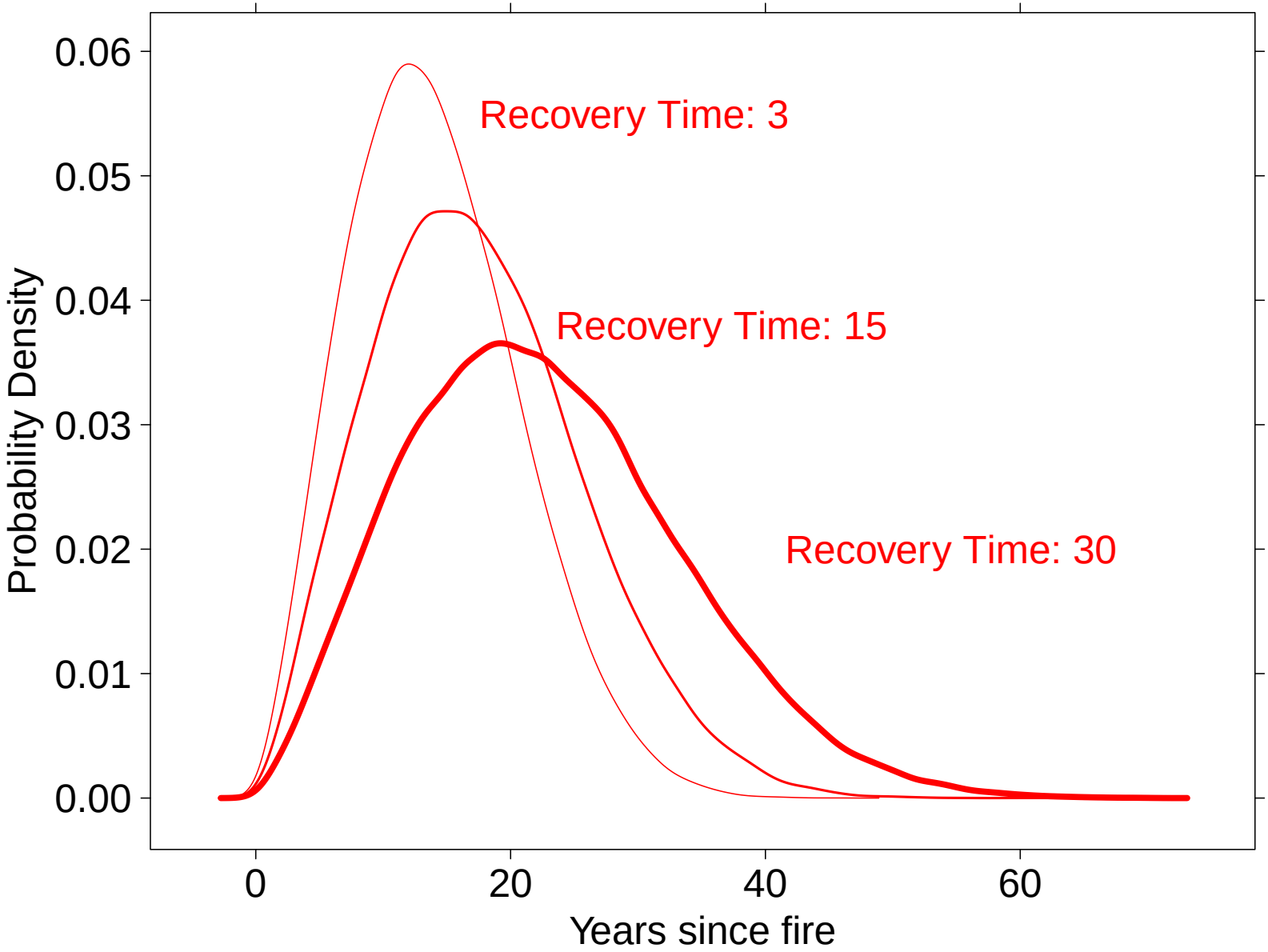

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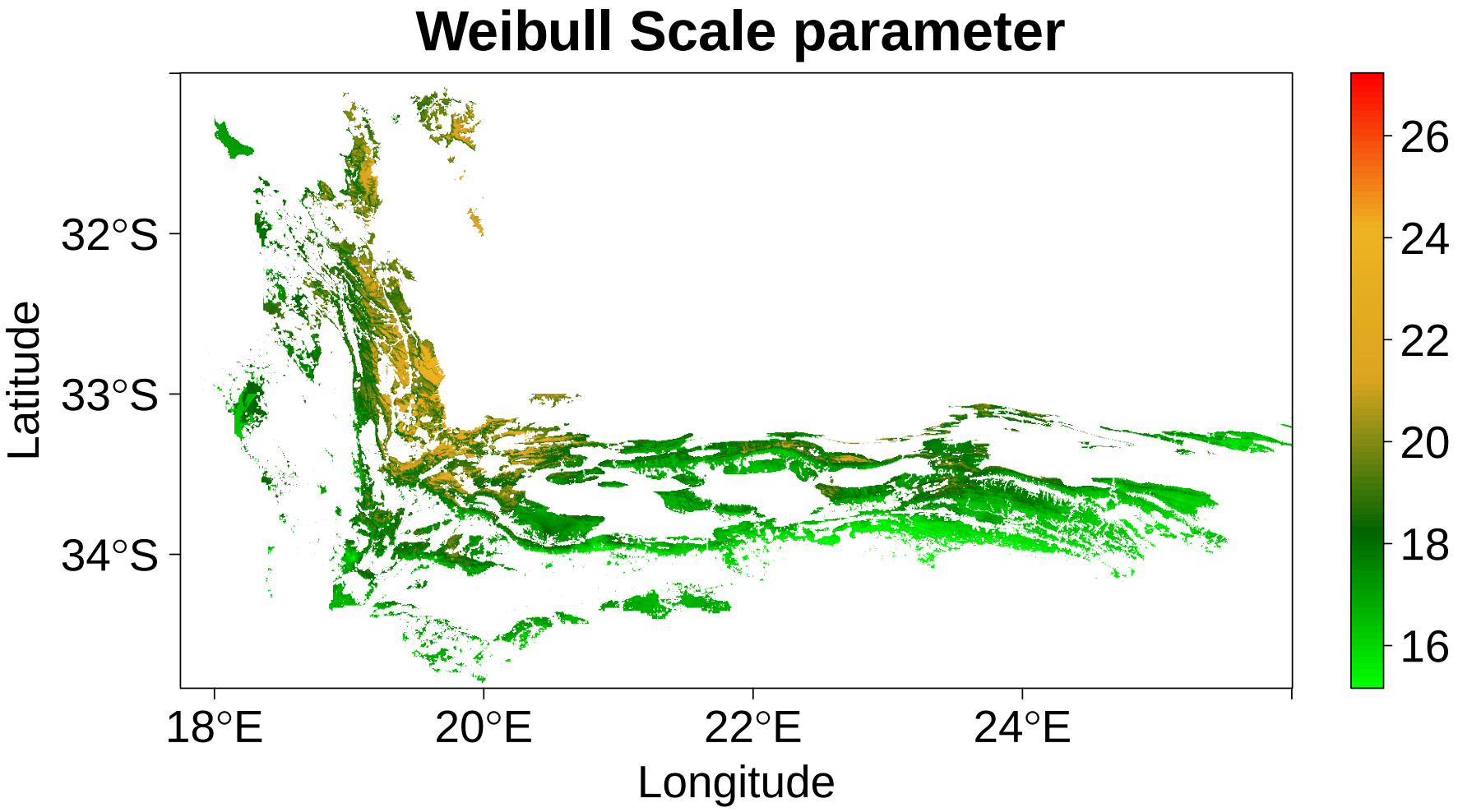
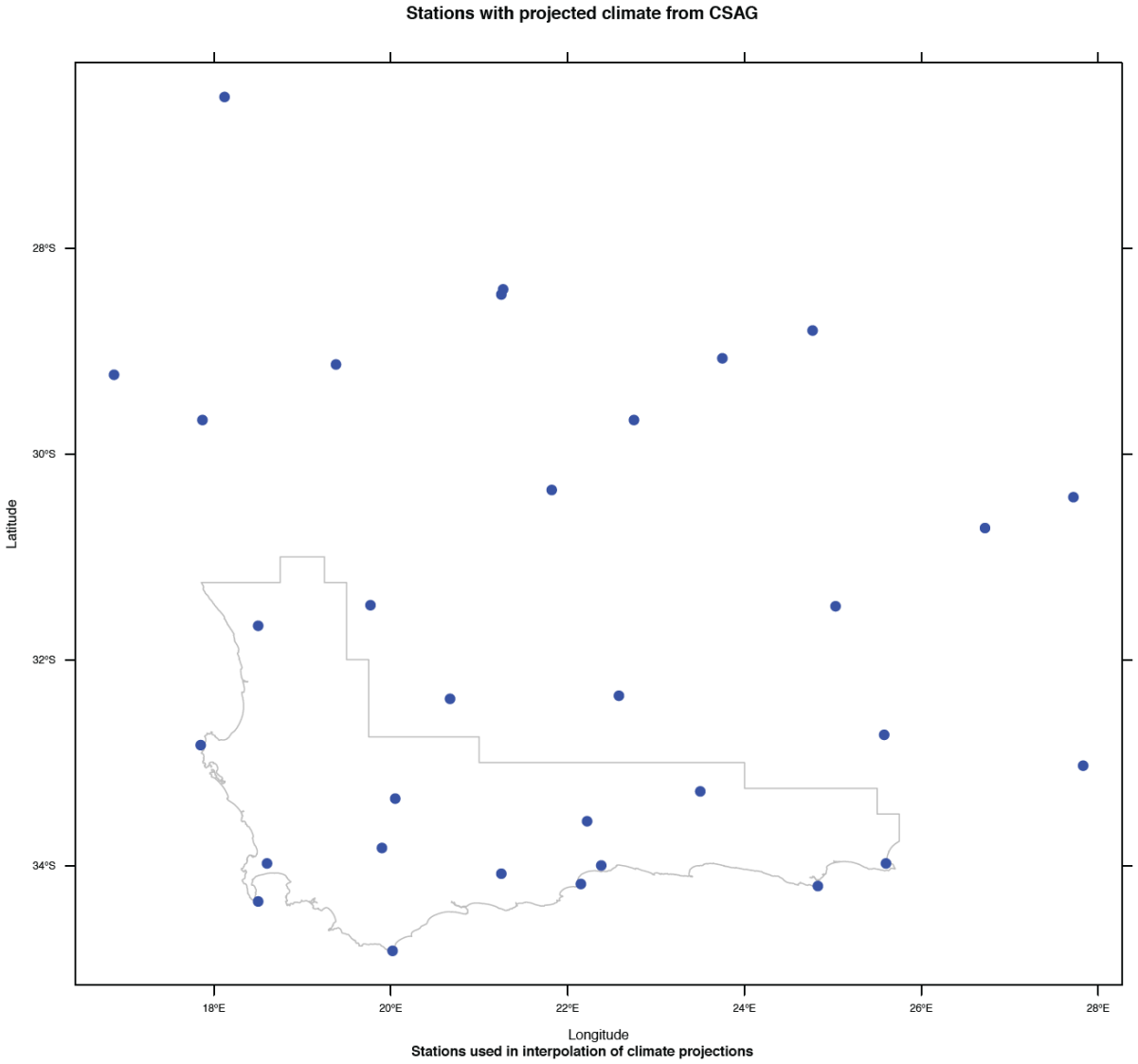


Climate Projections



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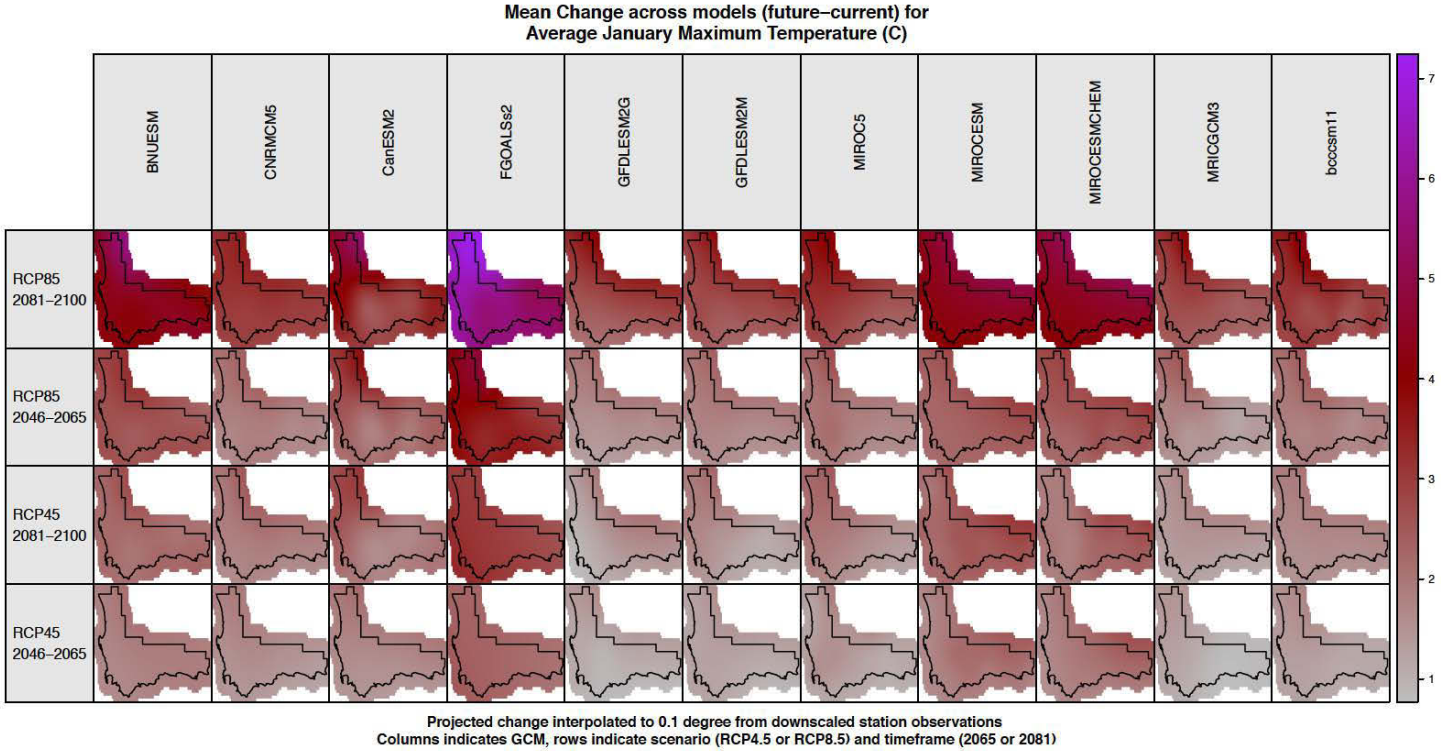

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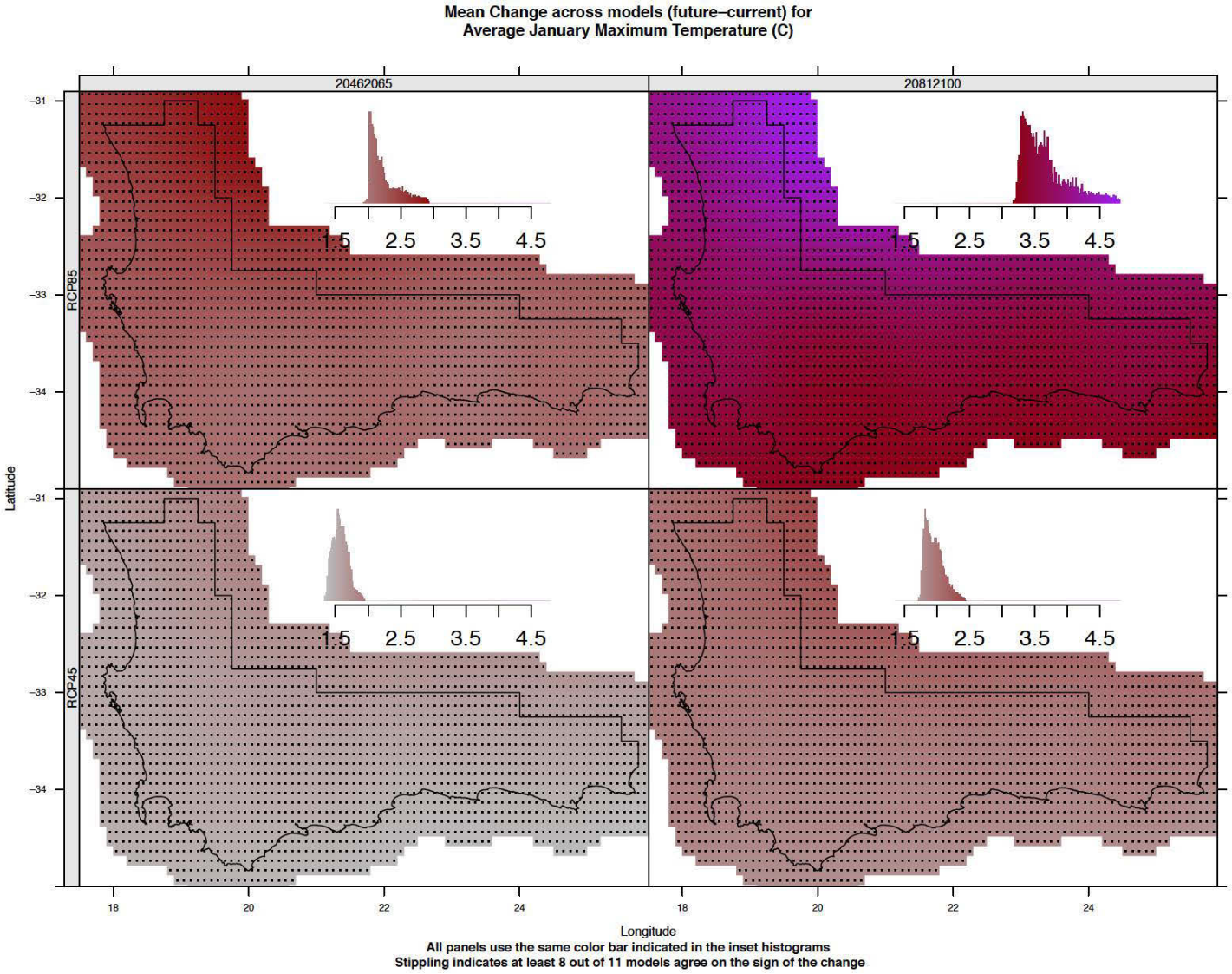

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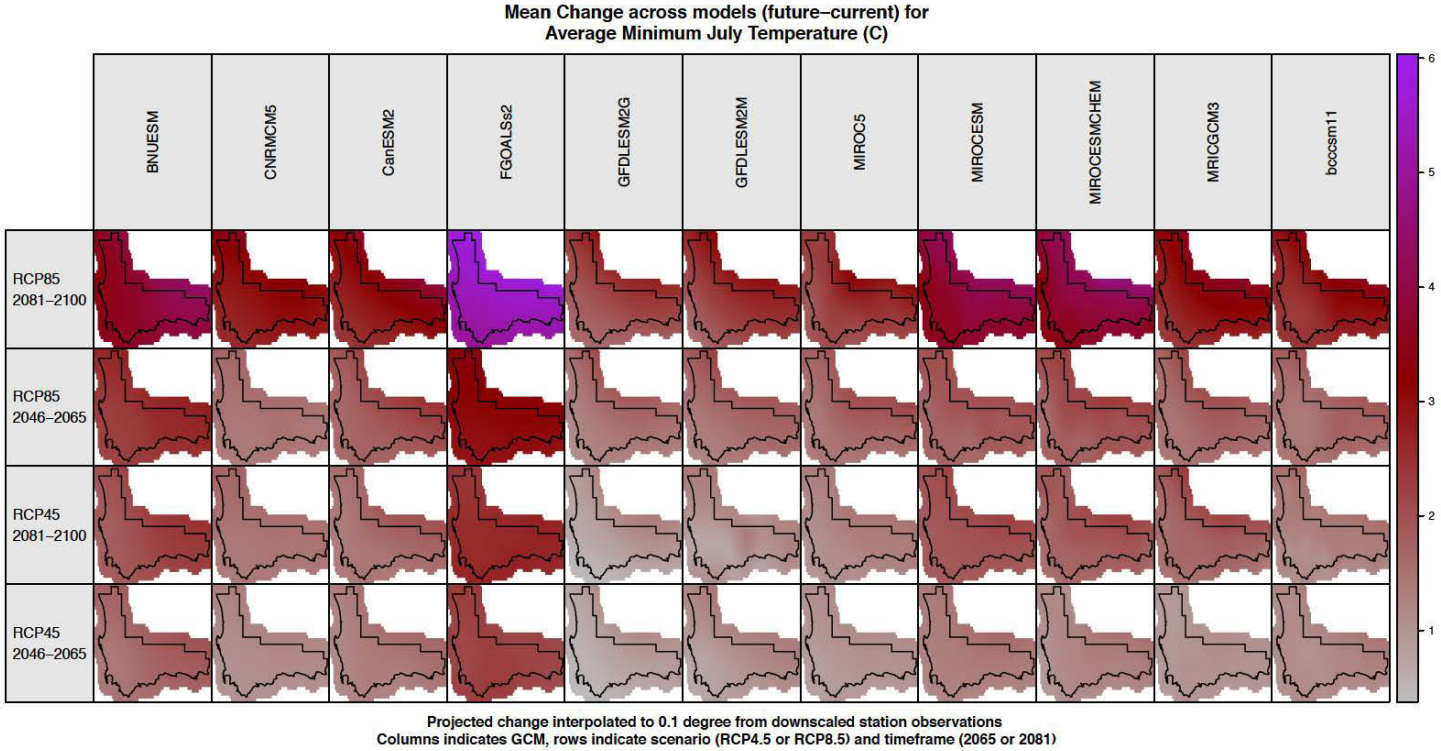

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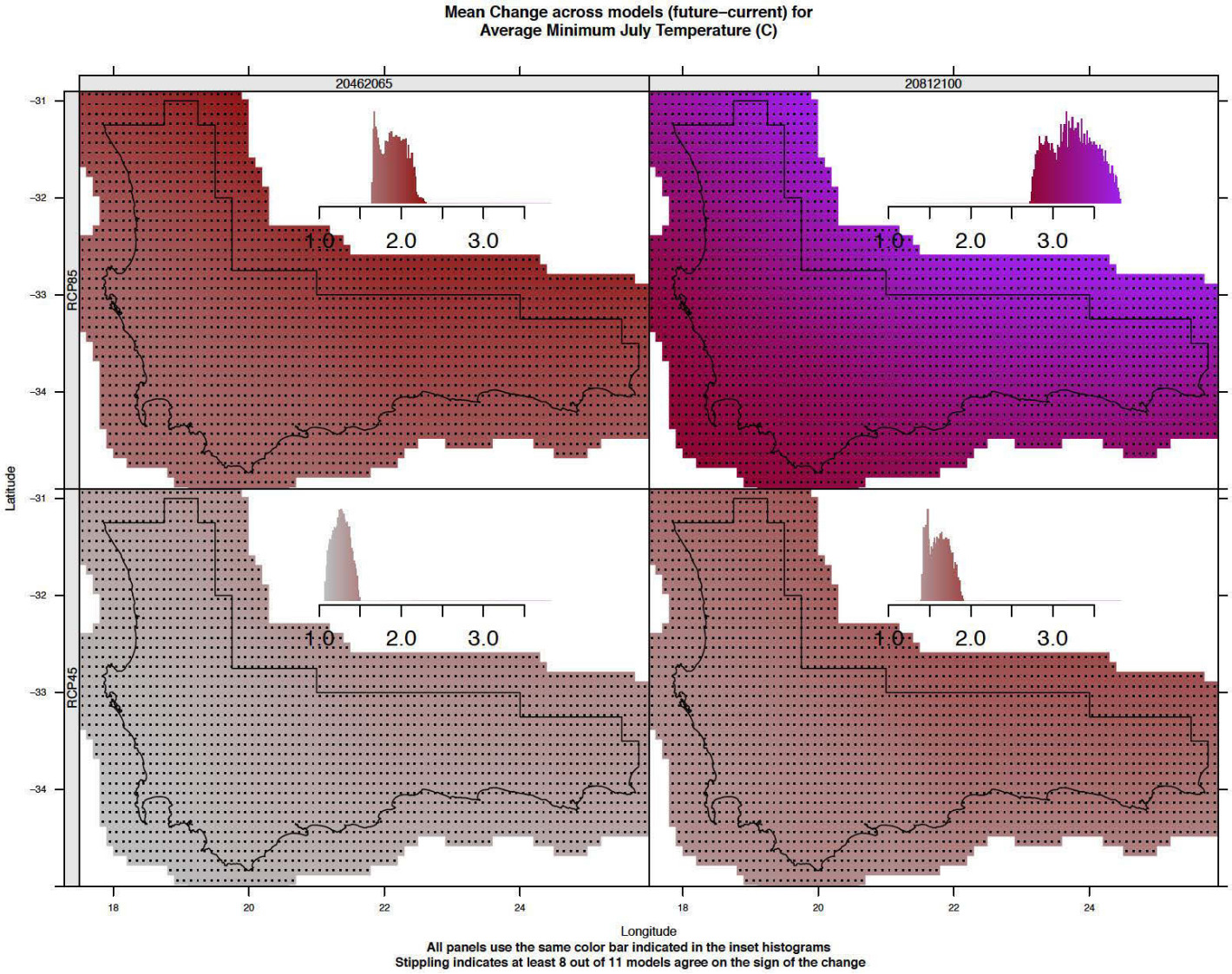

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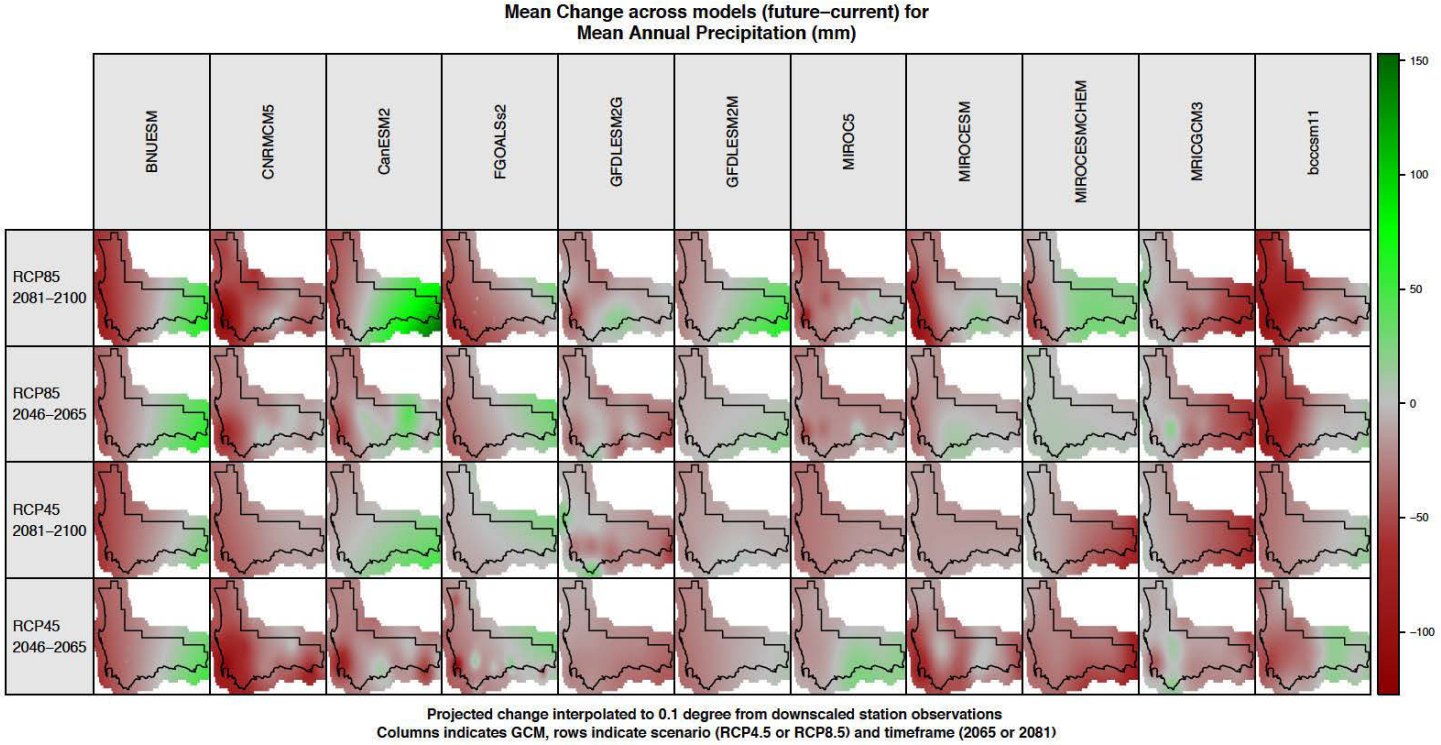

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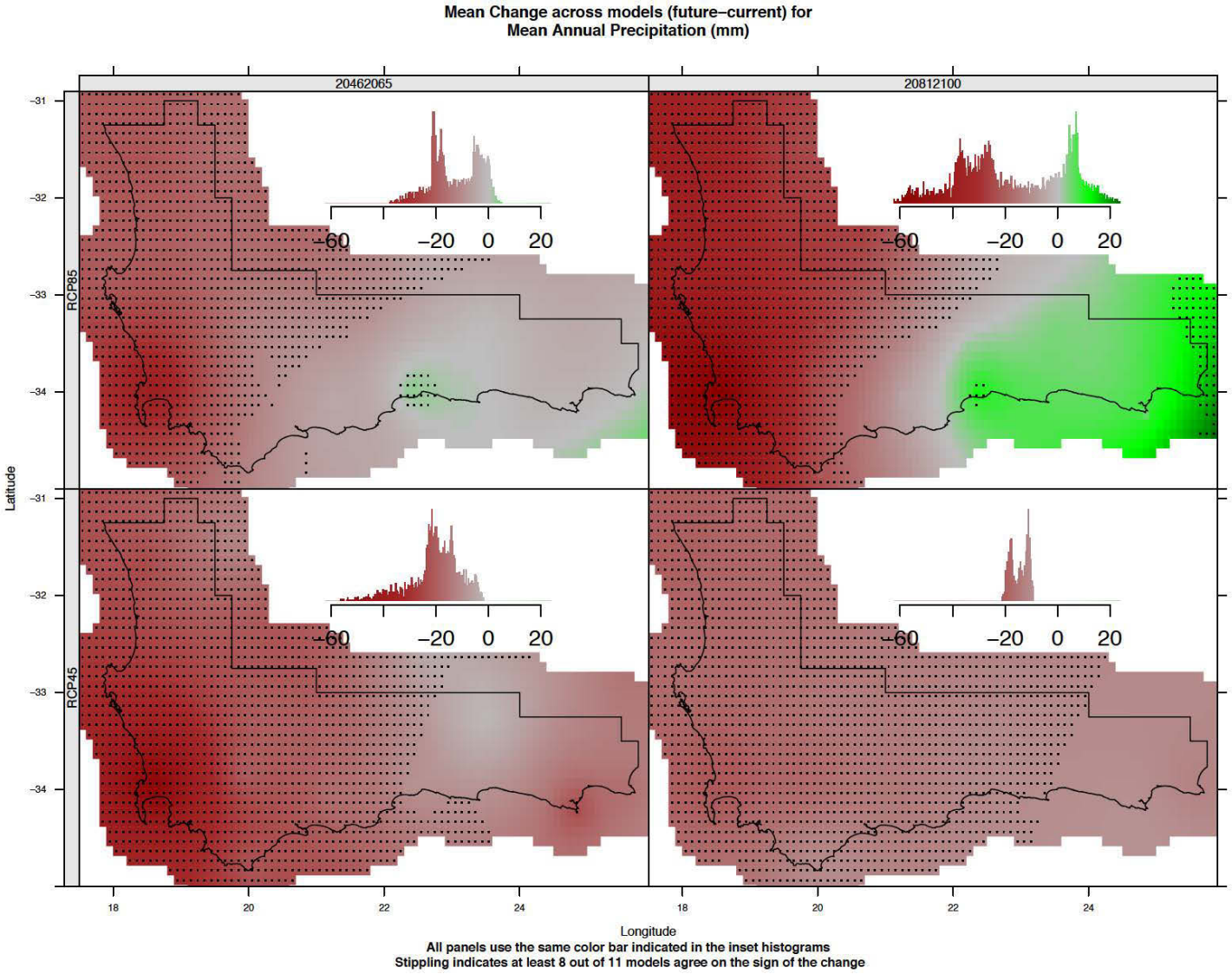

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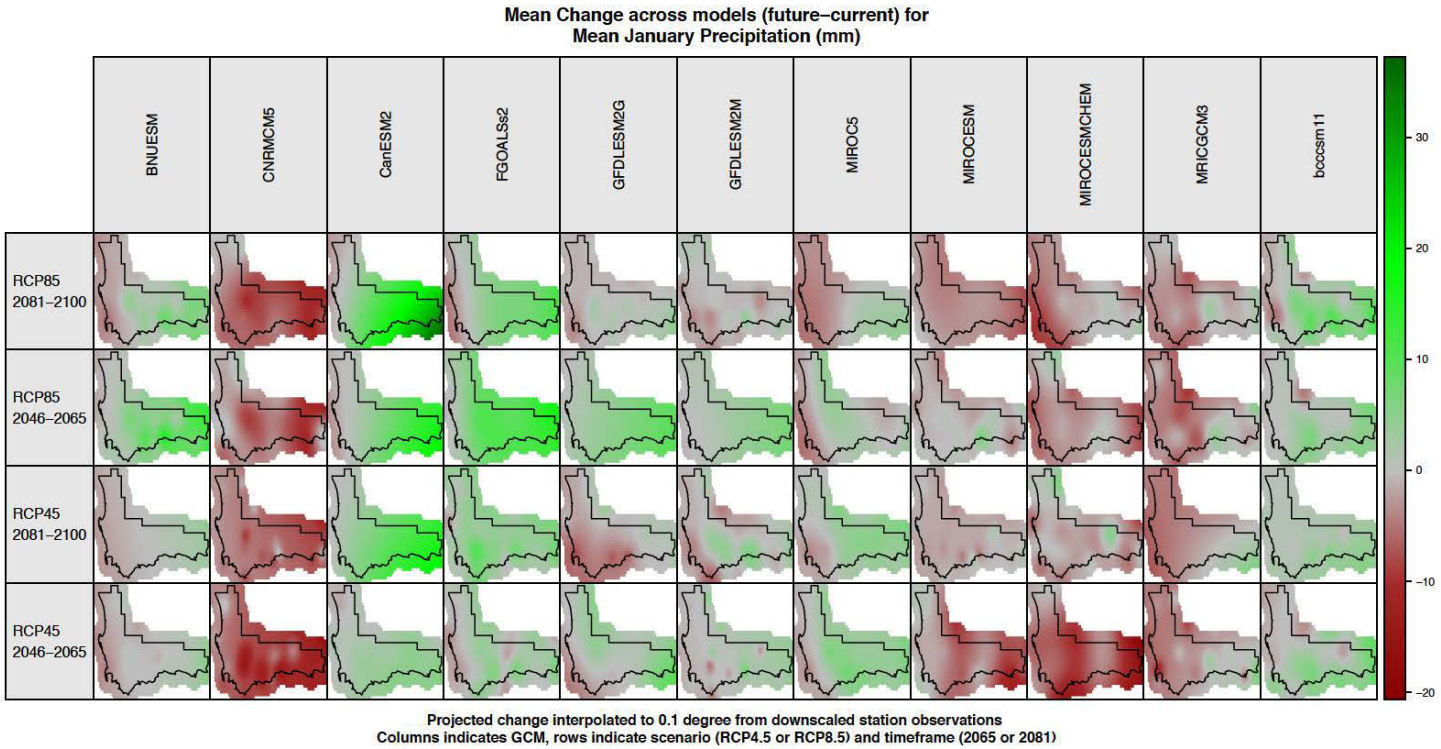

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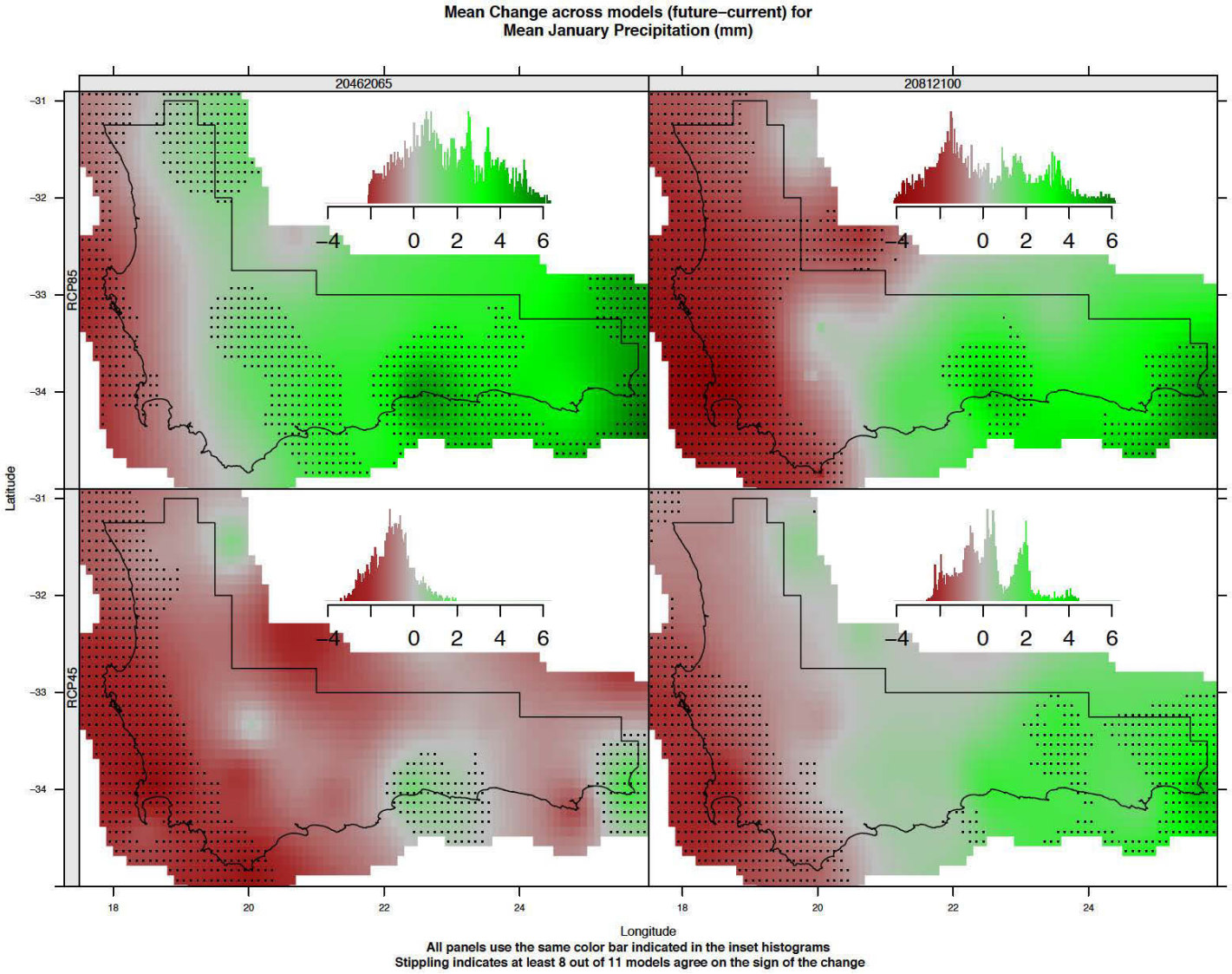

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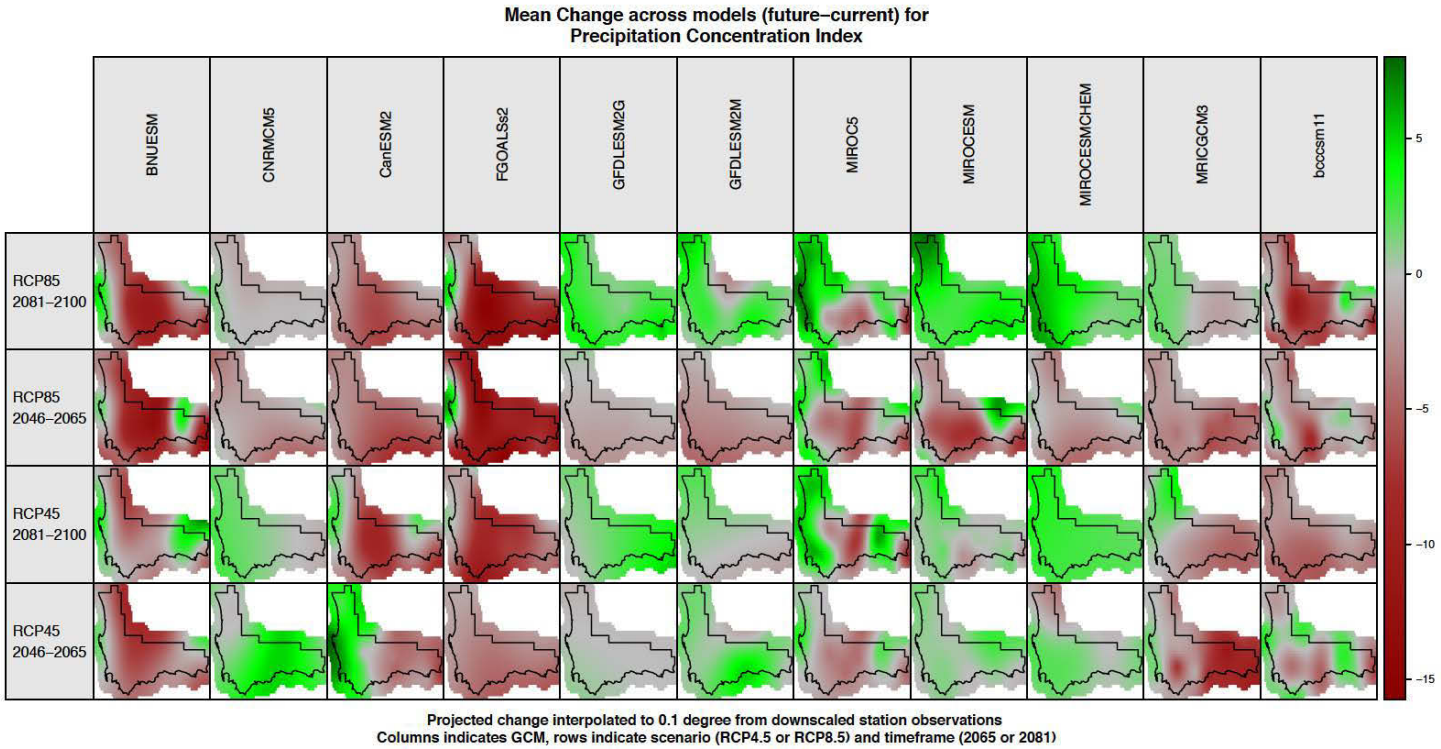
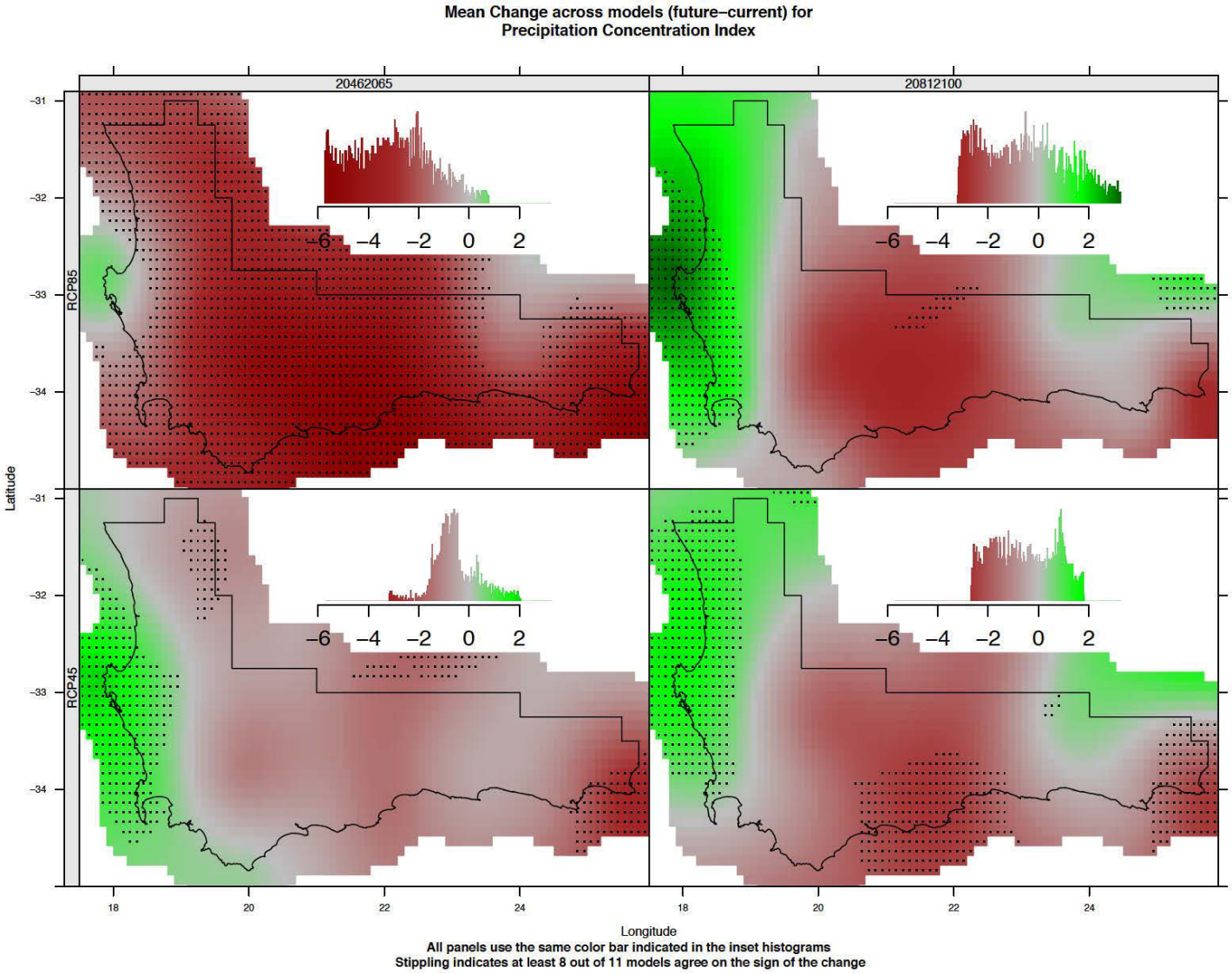
Climate Projections