Feedbacks between soil engineers and vegetation can increase ecosystem robustness

(Emergence of multi-scale regular vegetation patterns)

PRINCETON UNIVERSITY

Corina E. Tarnita

Self-organization and the emergence of complexity

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(3) how does self-organization influence the robustness of systems in the face of perturbation, stress, and catastrophe?

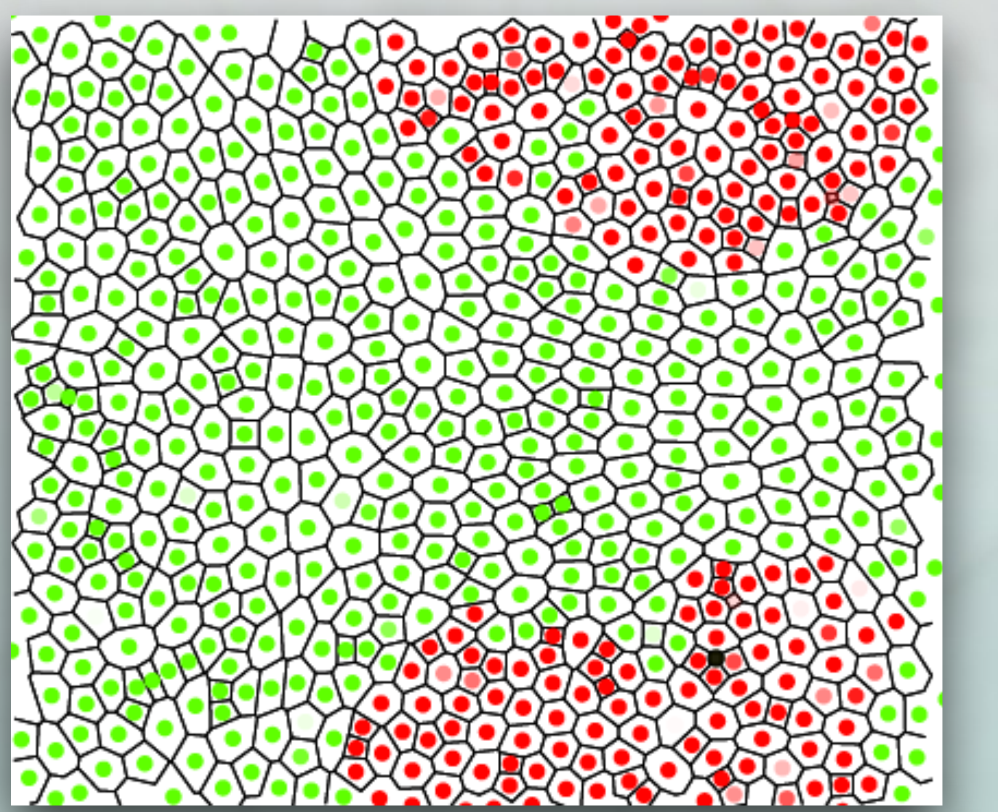
Attraction & Repulsion

Group formation

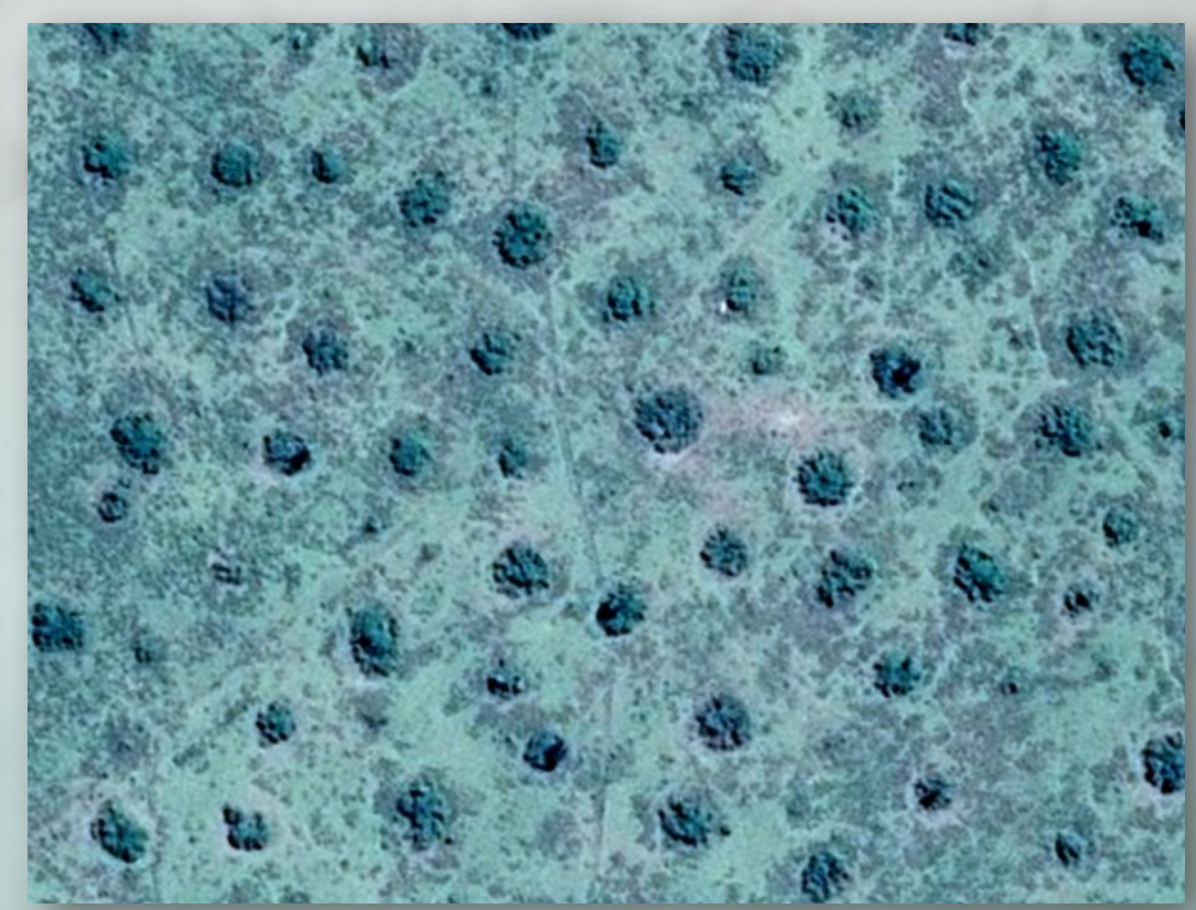
Multicellularity

Human cooperation

Social behavior



Tissue architecture



Landscape architecture


Medium-scale patterning, Bunker Reef

Mussel Beds in the Wadden Sea

Map data: Google, © 2015 Aerodata International Surveys


Gap pattern, Mali
N


Labyrinth pattern, Niger
N


Islands of fertility, Niger
N

Two Guiding Questions:

How do patterns form?

Why do patterns *matter*? What are their effects on the ecosystem?

Local Behavior Leads To Large-Scale Patterns

10 hour time-lapse of mussels on concrete substrate

Video credit: J. van de Koppel

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How Can Vegetation Patterns Be Explained?

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Sandy soil

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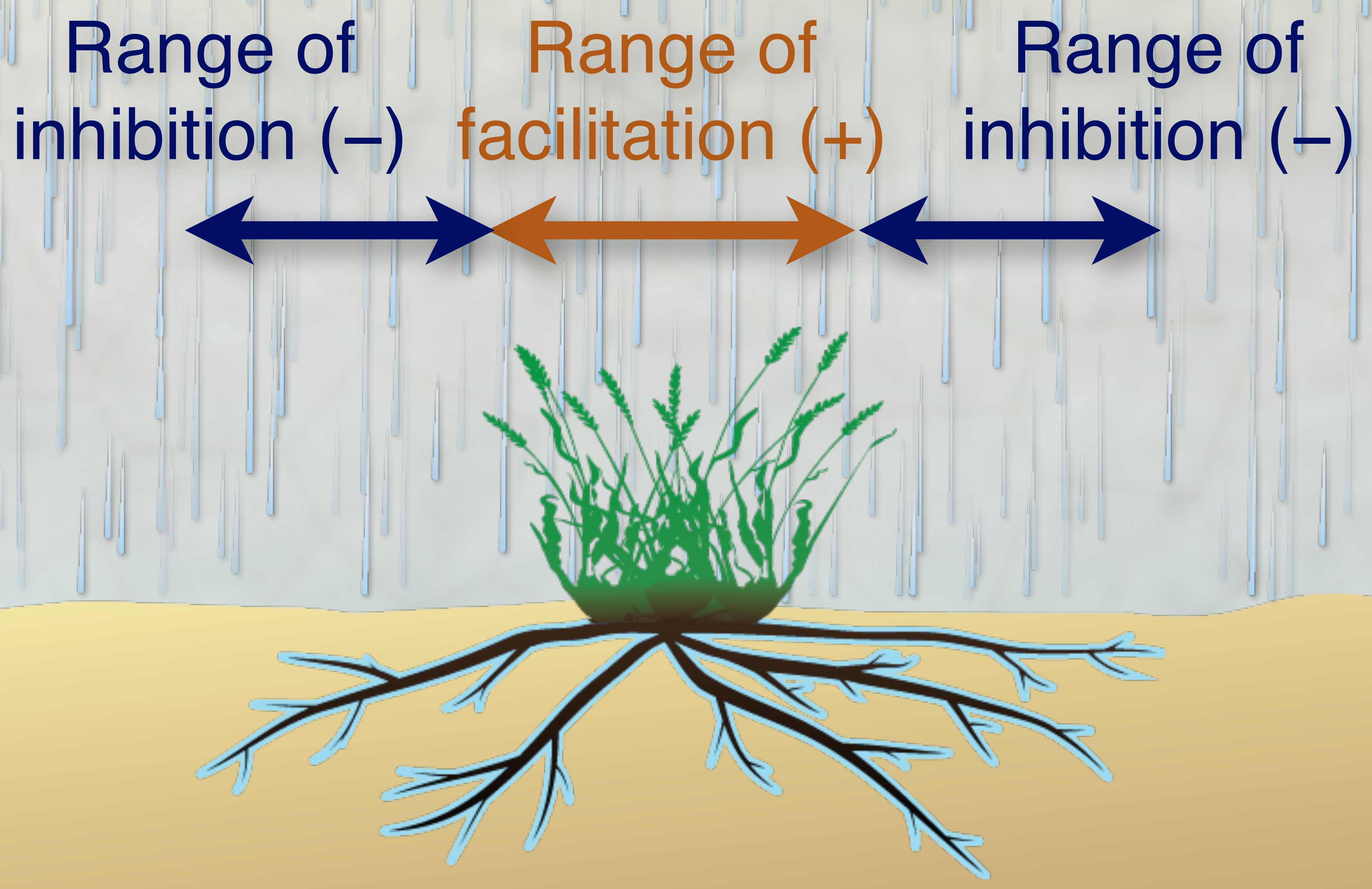

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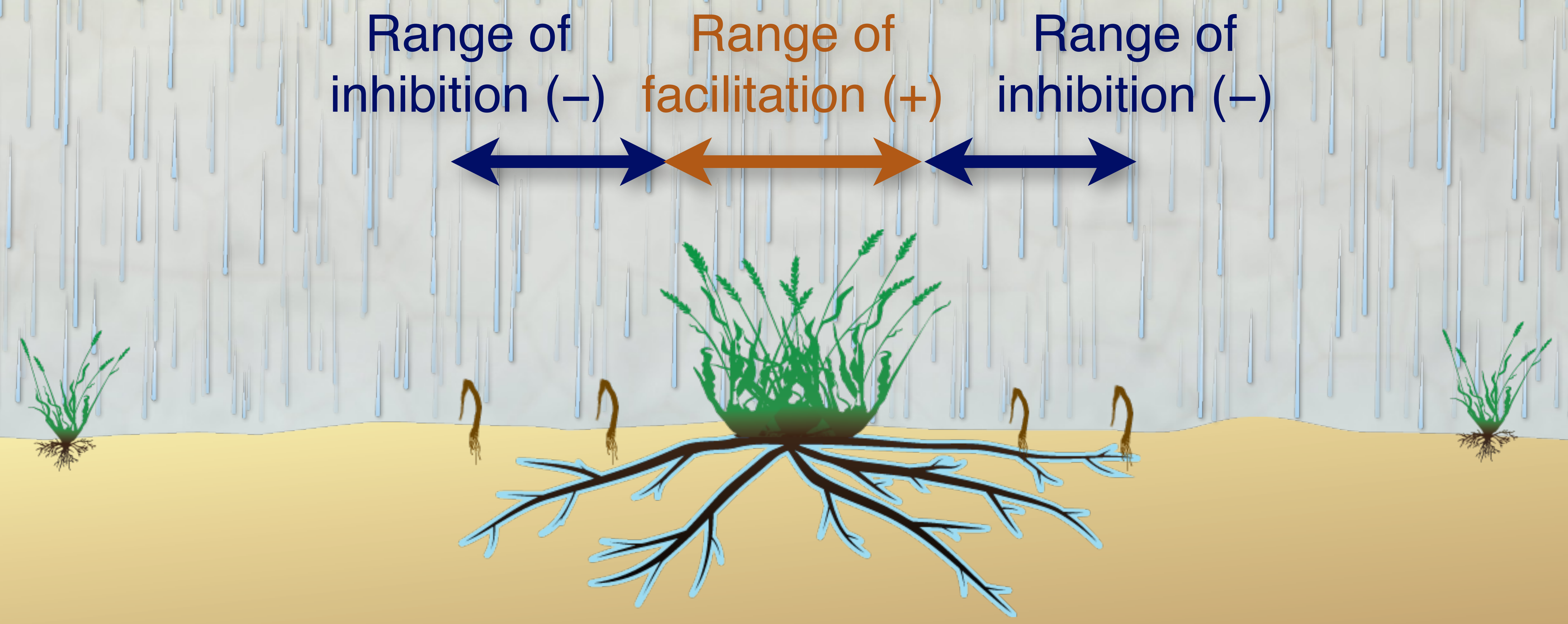
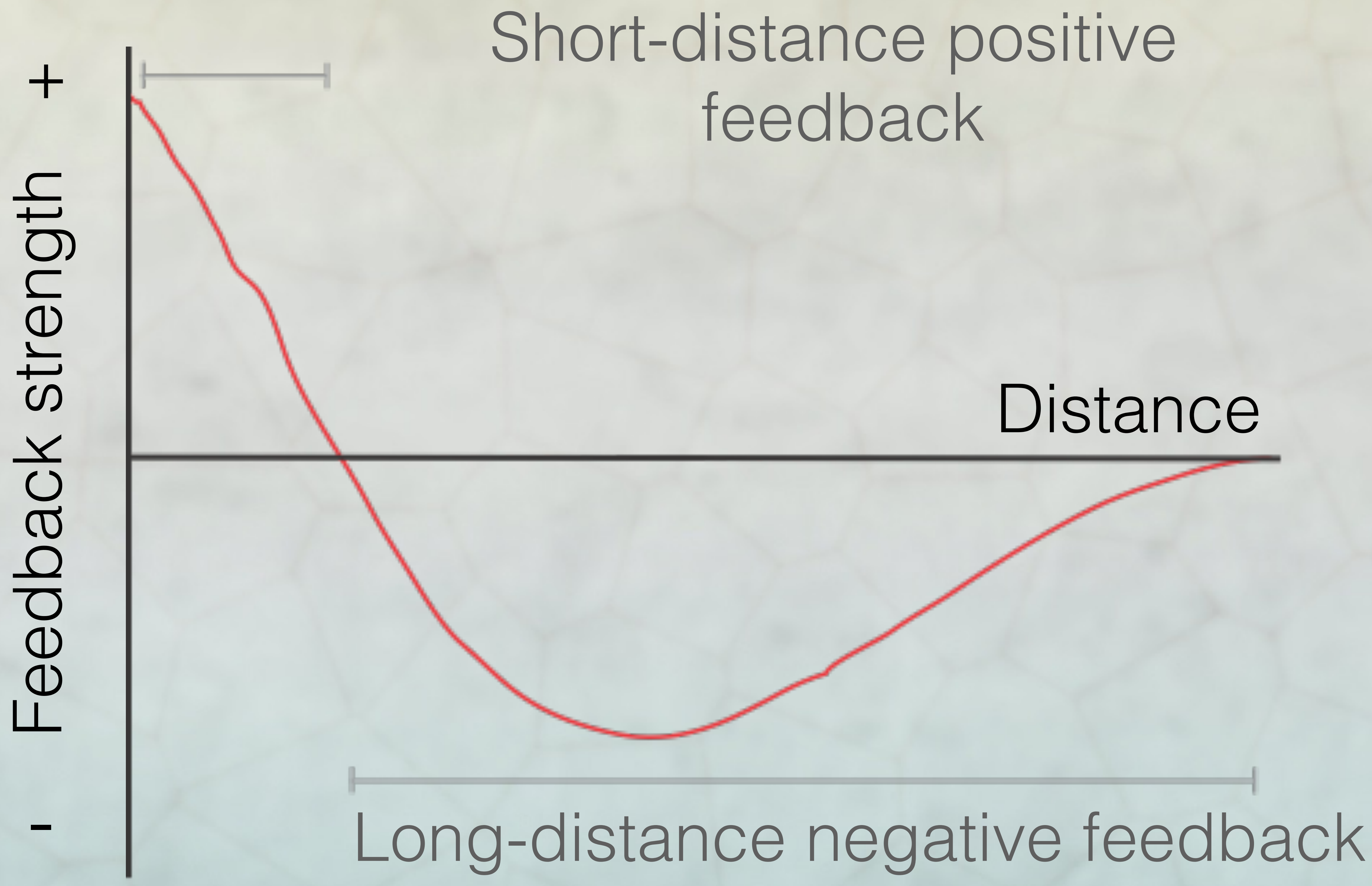


How Can Vegetation Patterns Be Explained?

Scale-dependent Feedbacks



Turing, *Phil Trans B* 1952
Levin and Segel, *SIAM* 1985
Klausmeier, *Science* 1999
Rietkerk and van de Koppel, *TREE* 2008

Turing, *Phil Trans B* 1952

$$\frac{\partial P}{\partial t} = c \times g_{\max} \times \frac{W}{W + k_1} \times P - d \times P + D_p \Delta P,$$

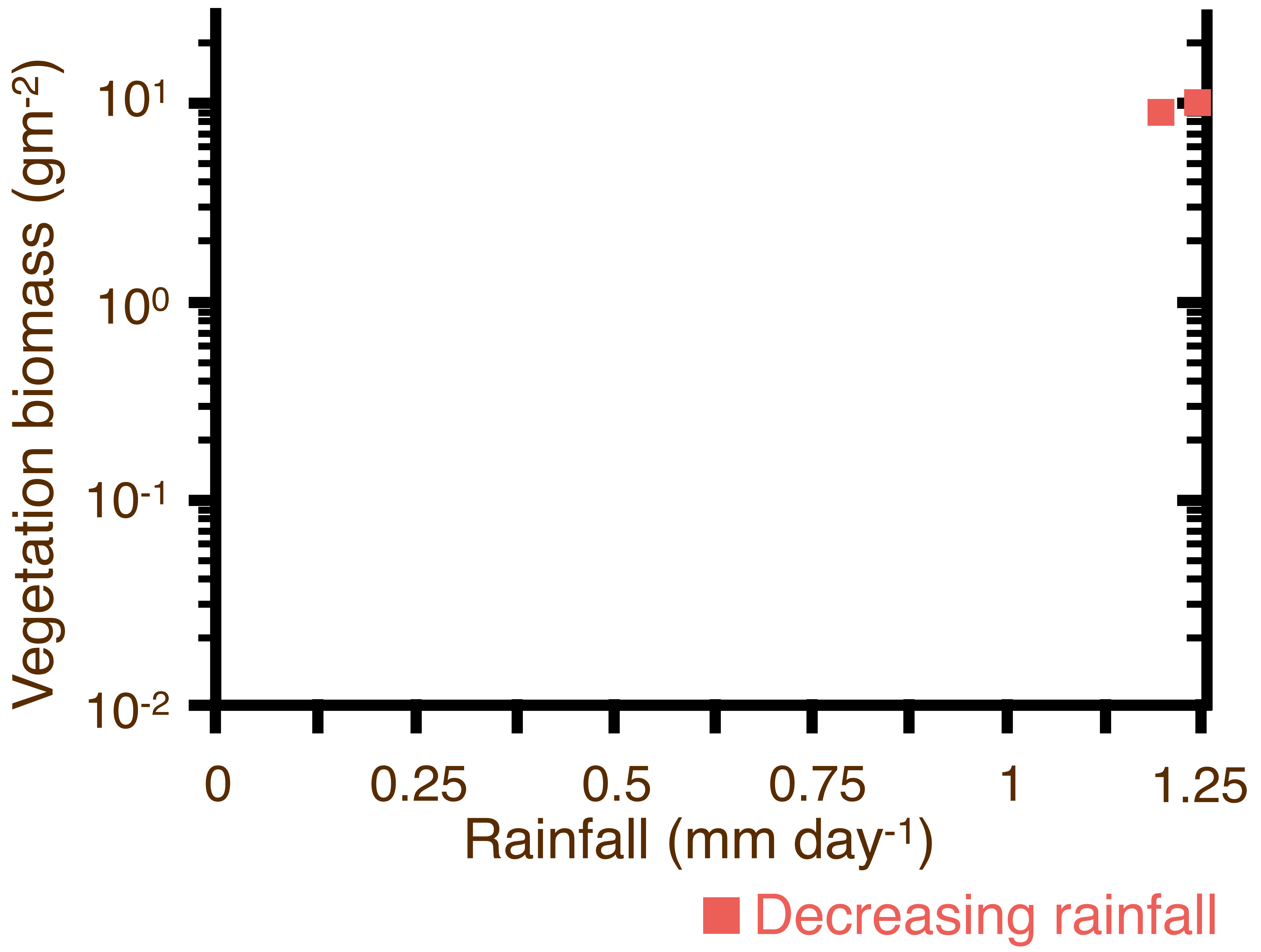
$$\frac{\partial W}{\partial t} = \alpha \times O \frac{P + k_2 \times W_0}{P + k_2} - g_{\max} \times \frac{W}{W + k_1} \times P - r_w \times W + D_w \Delta W,$$

$$\frac{\partial O}{\partial t} = R - \alpha \times O \frac{P + k_2 \times W_0}{P + k_2} + D_o \Delta O,$$

Rietkerk et al 2002, *Am. Nat.*

- c = Yield coefficient for plants (water use efficiency)
- g_{max} = Maximum plant growth rate.
- k_1 = Growth efficiency for plants growing on water as limiting nutrient.
- d = Plant mortality rate.
- r_w = Evaporation/loss rate for underground water.
- alpha = Maximum infiltration rate for the soil.
- k_2 = Infiltration efficiency of the soil.
- W_0 = With alpha and O, minimum water infiltration in the absence of vegetation
- D_p = Plant dispersion rate.
- D_w = Diffusivity of soil water
- D_o = Diffusivity of surface water

Water Stress Induces Vegetation Patterns



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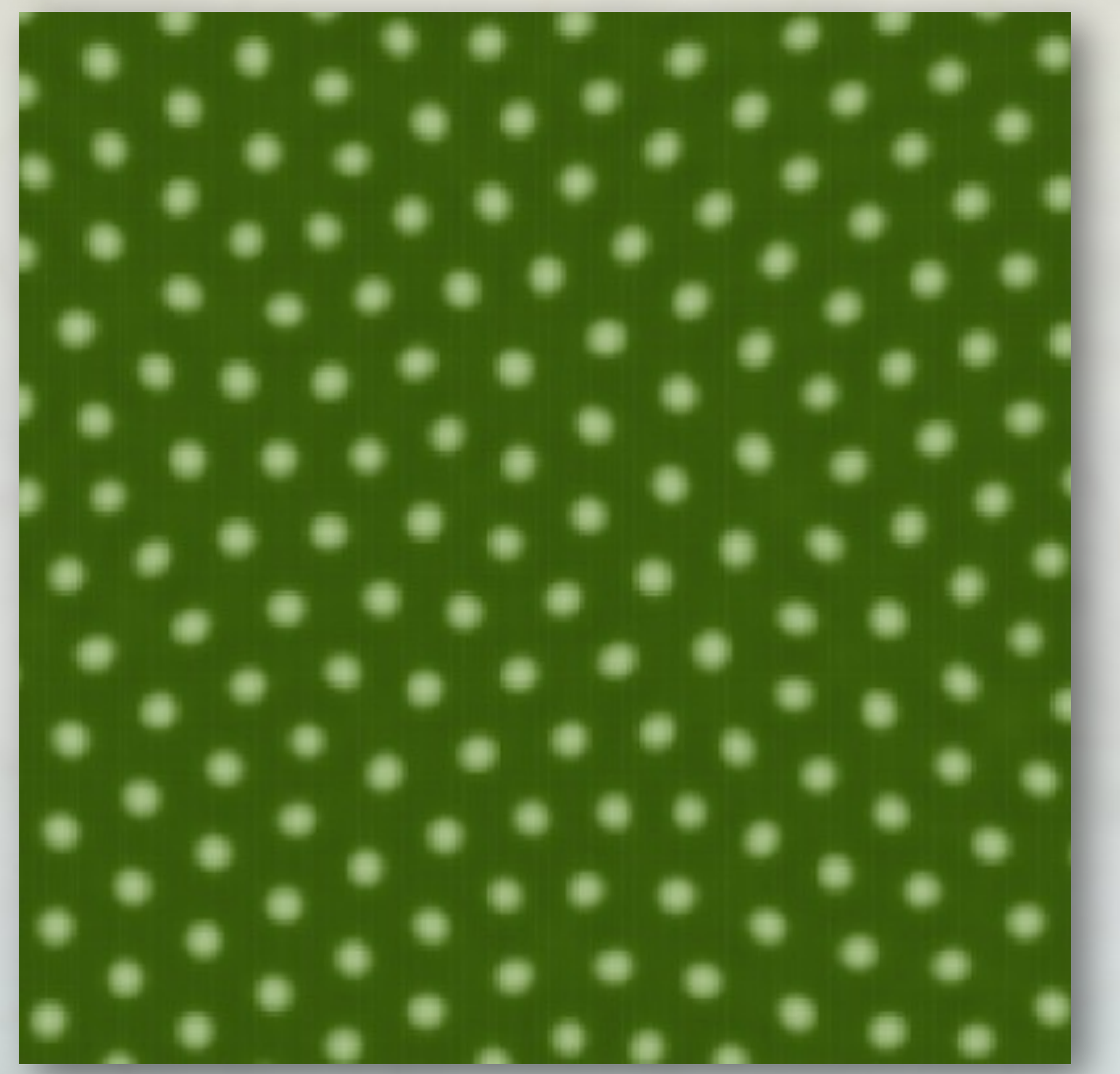

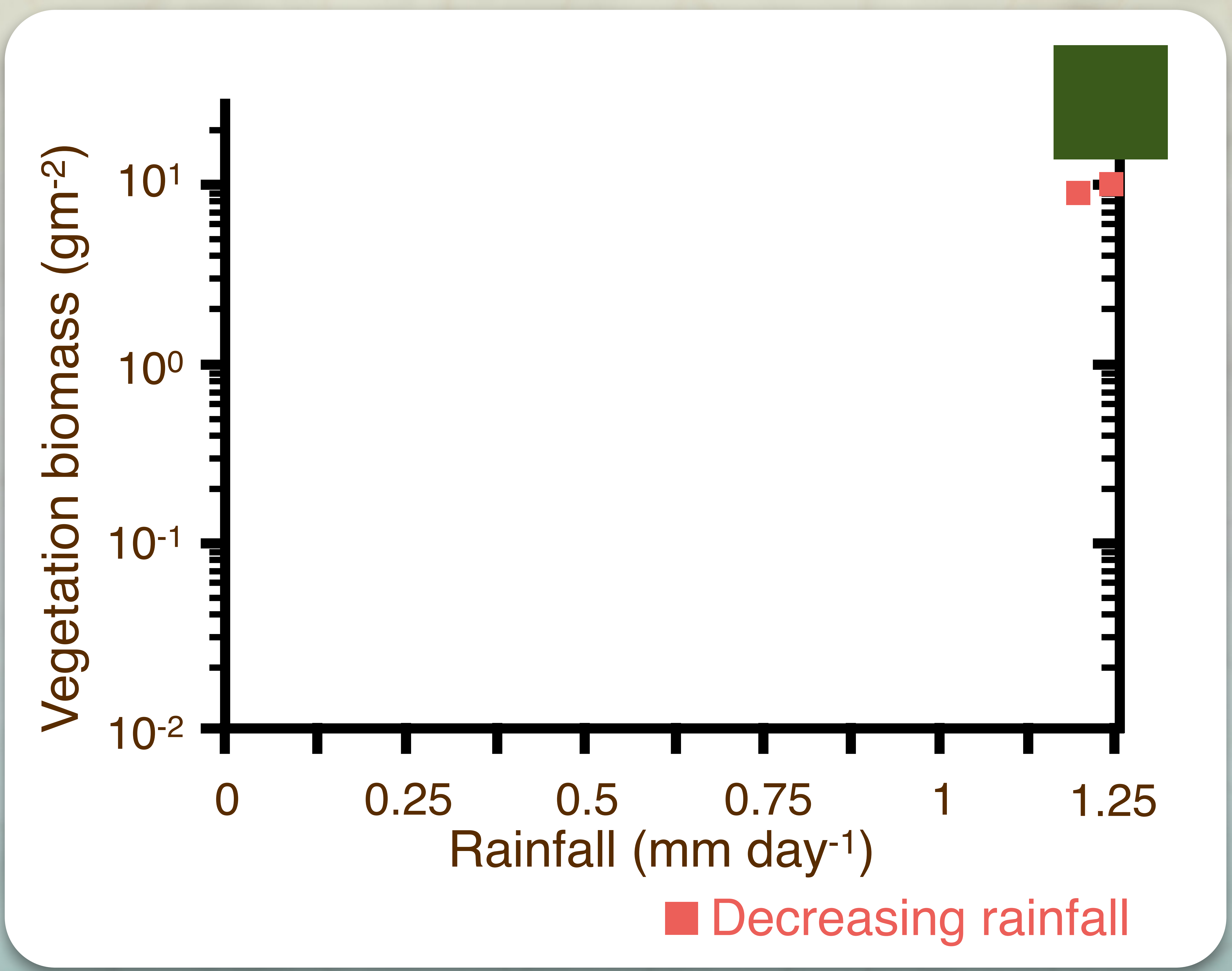

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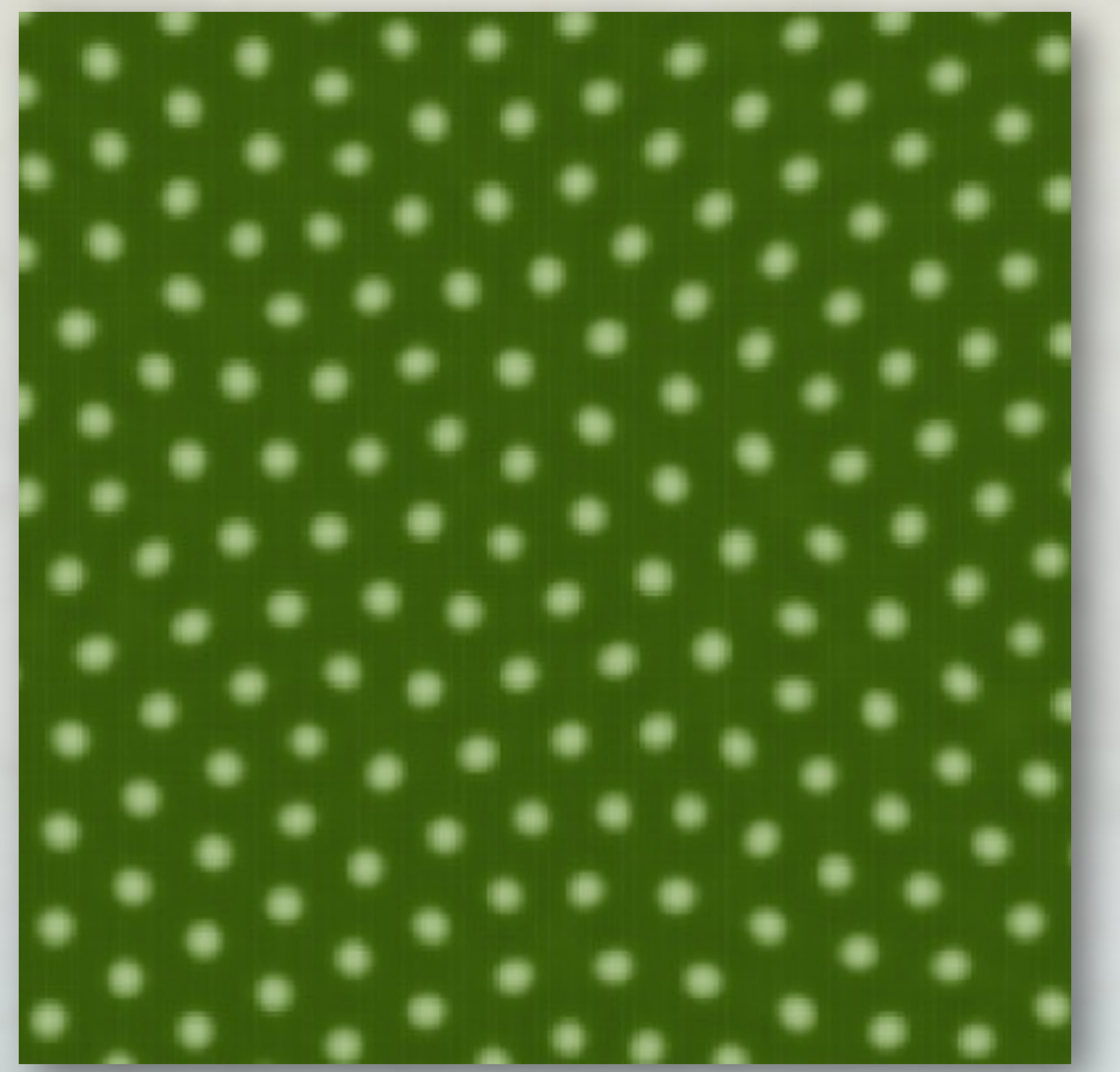

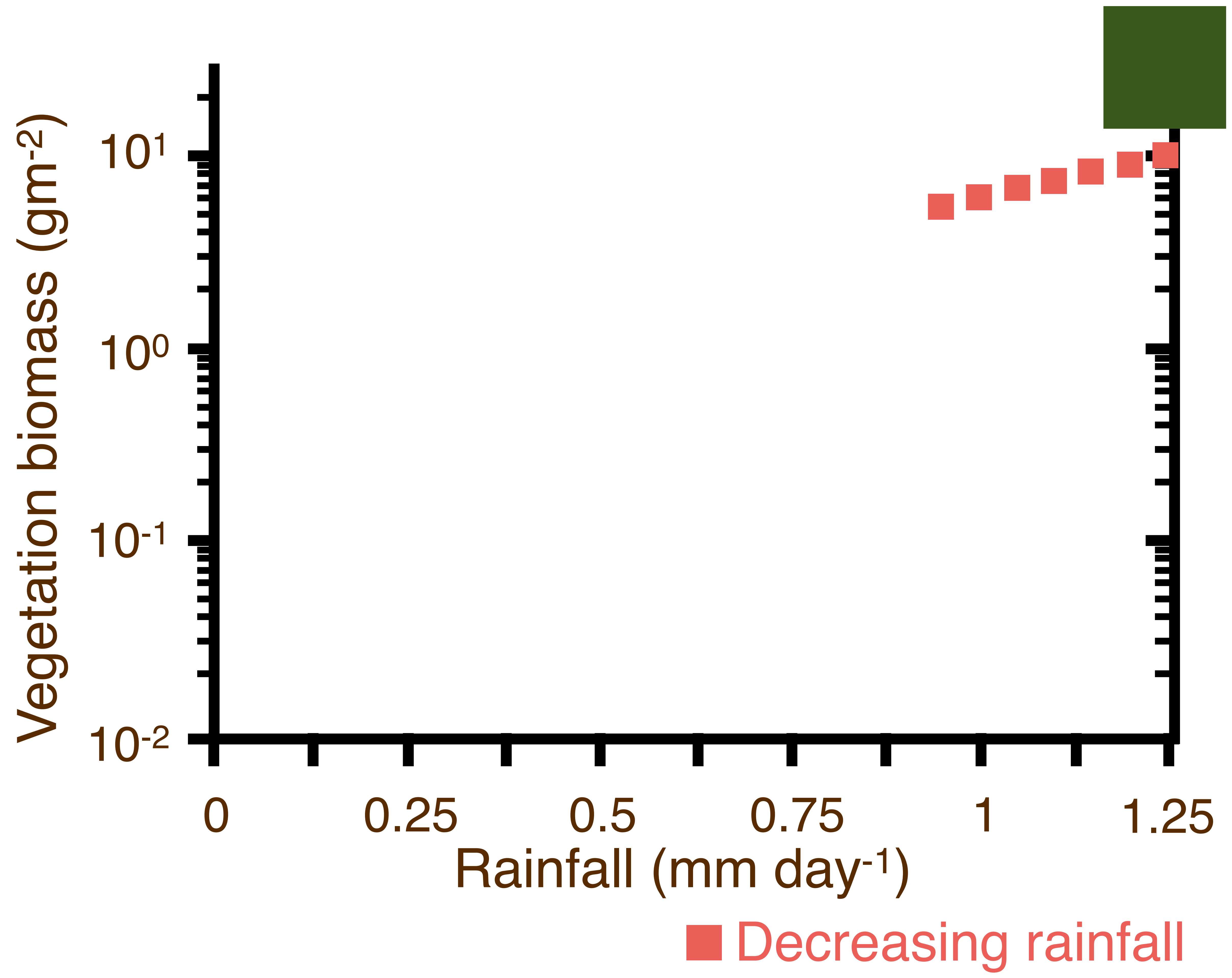

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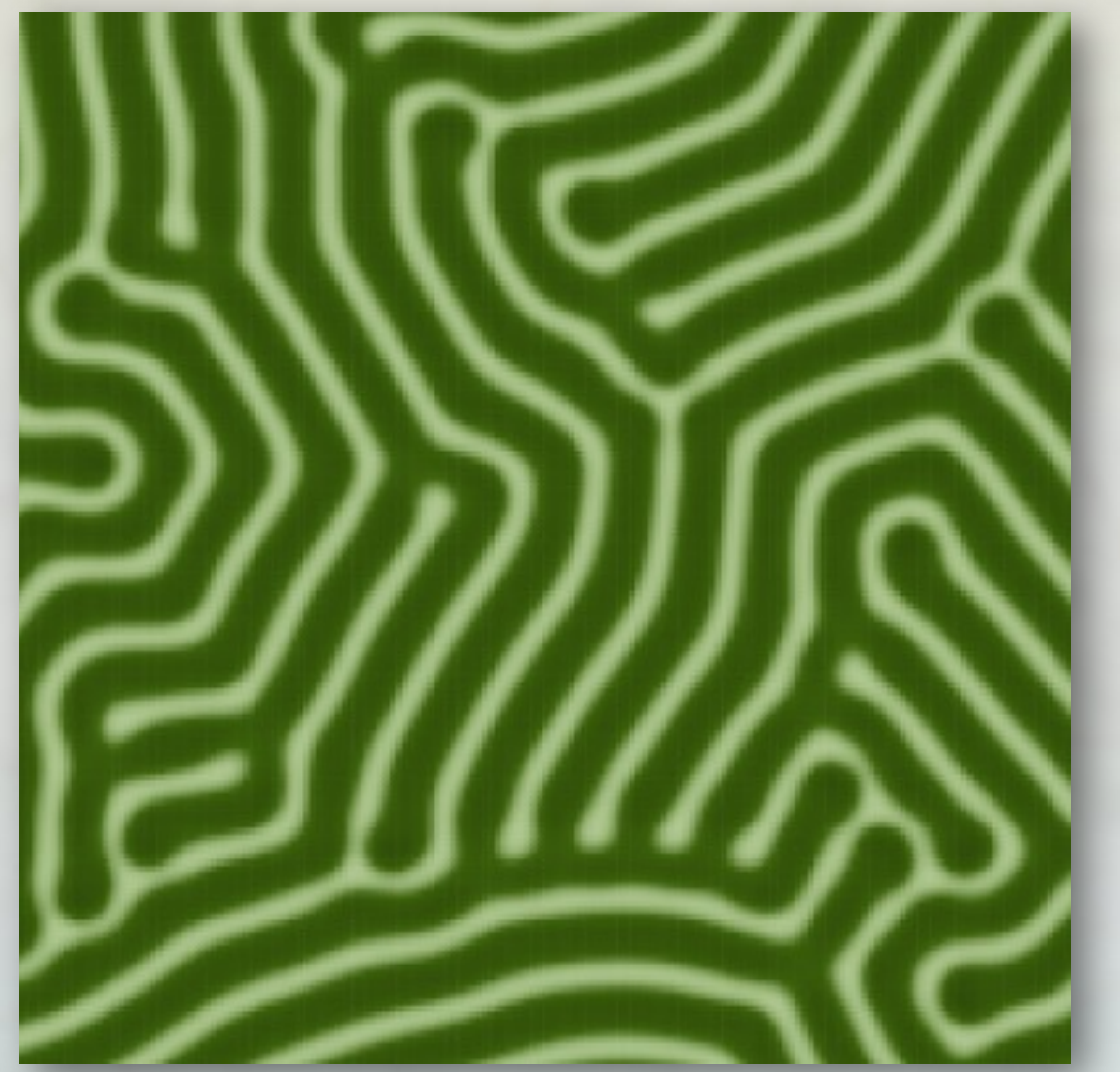

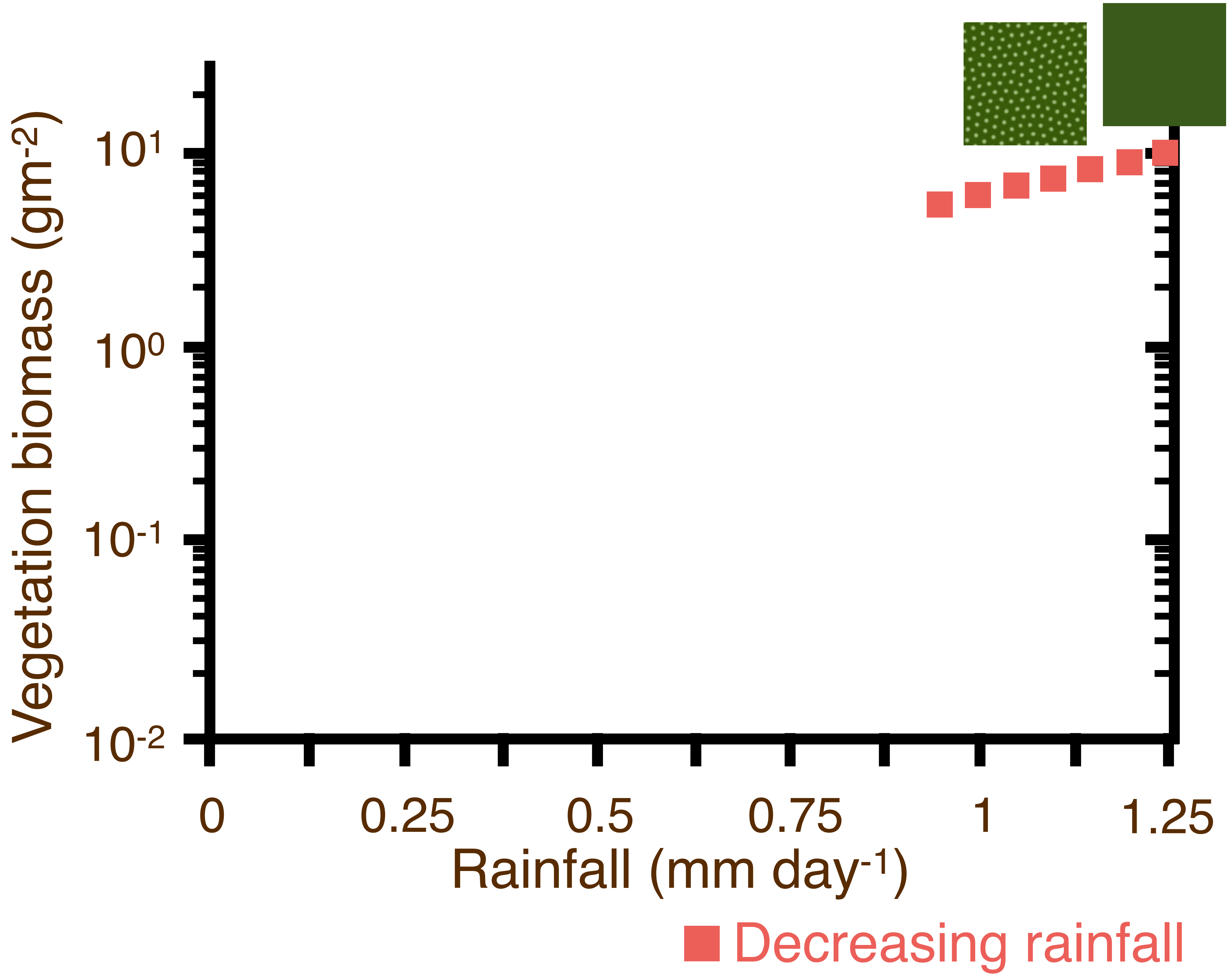

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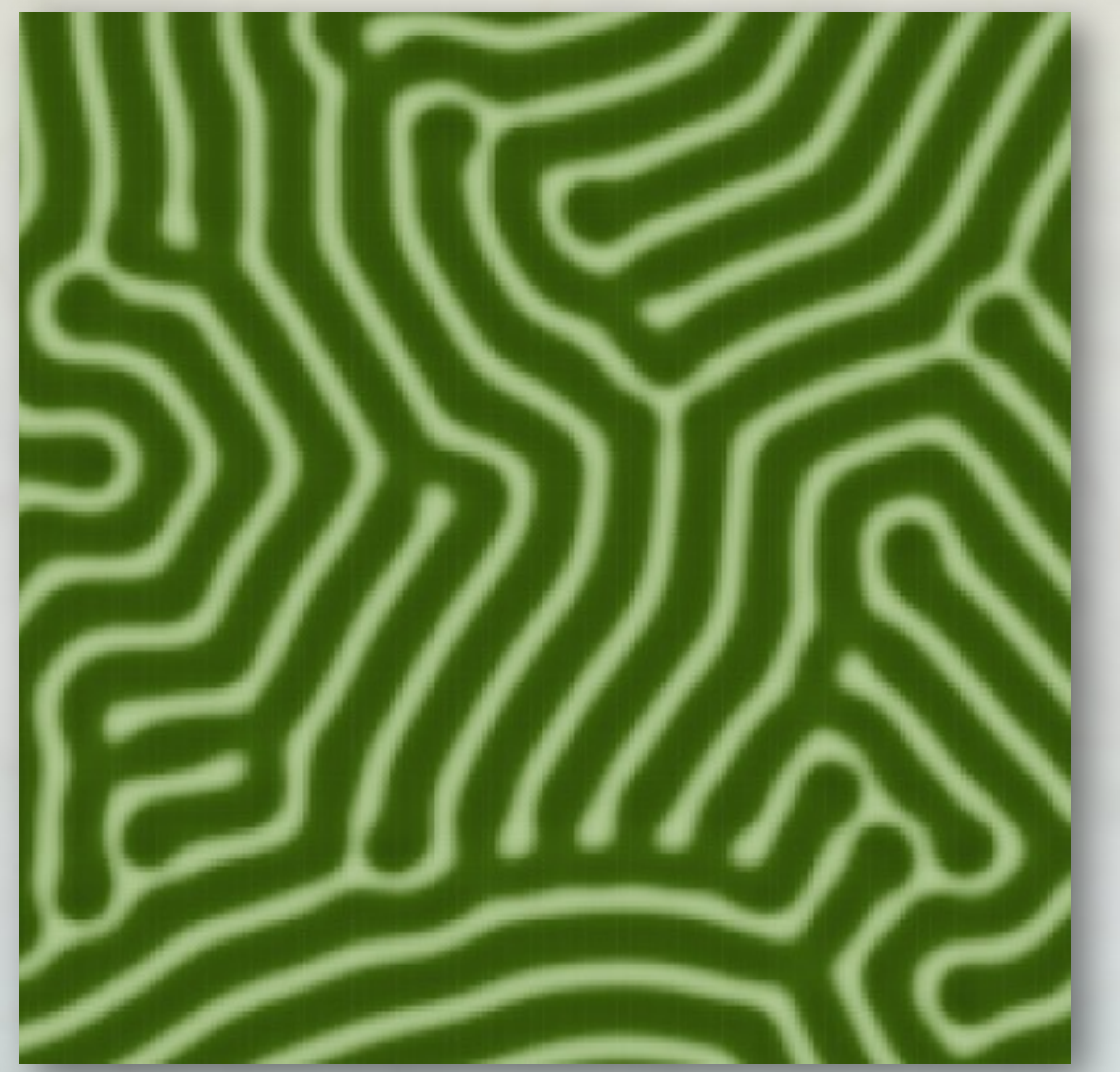

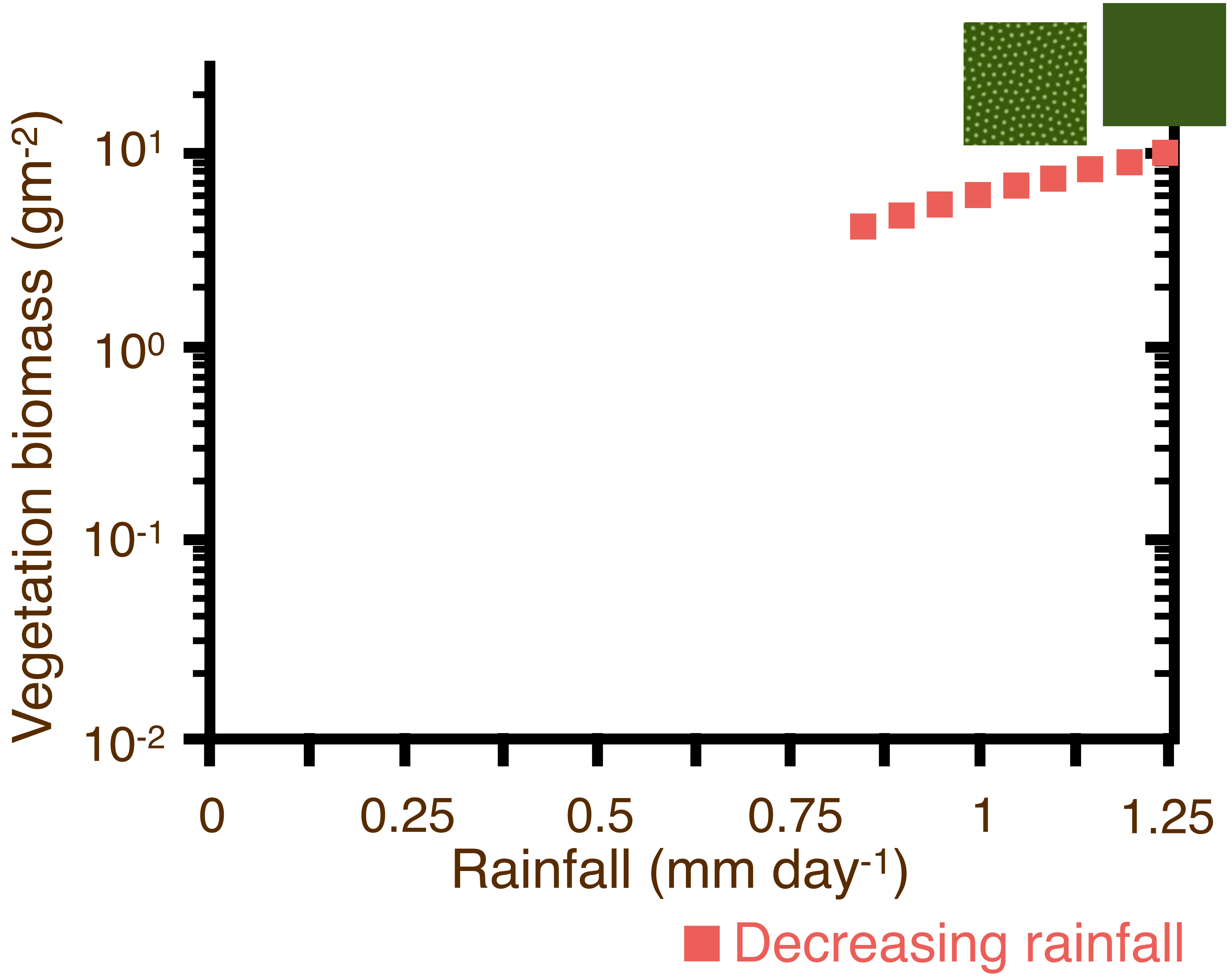

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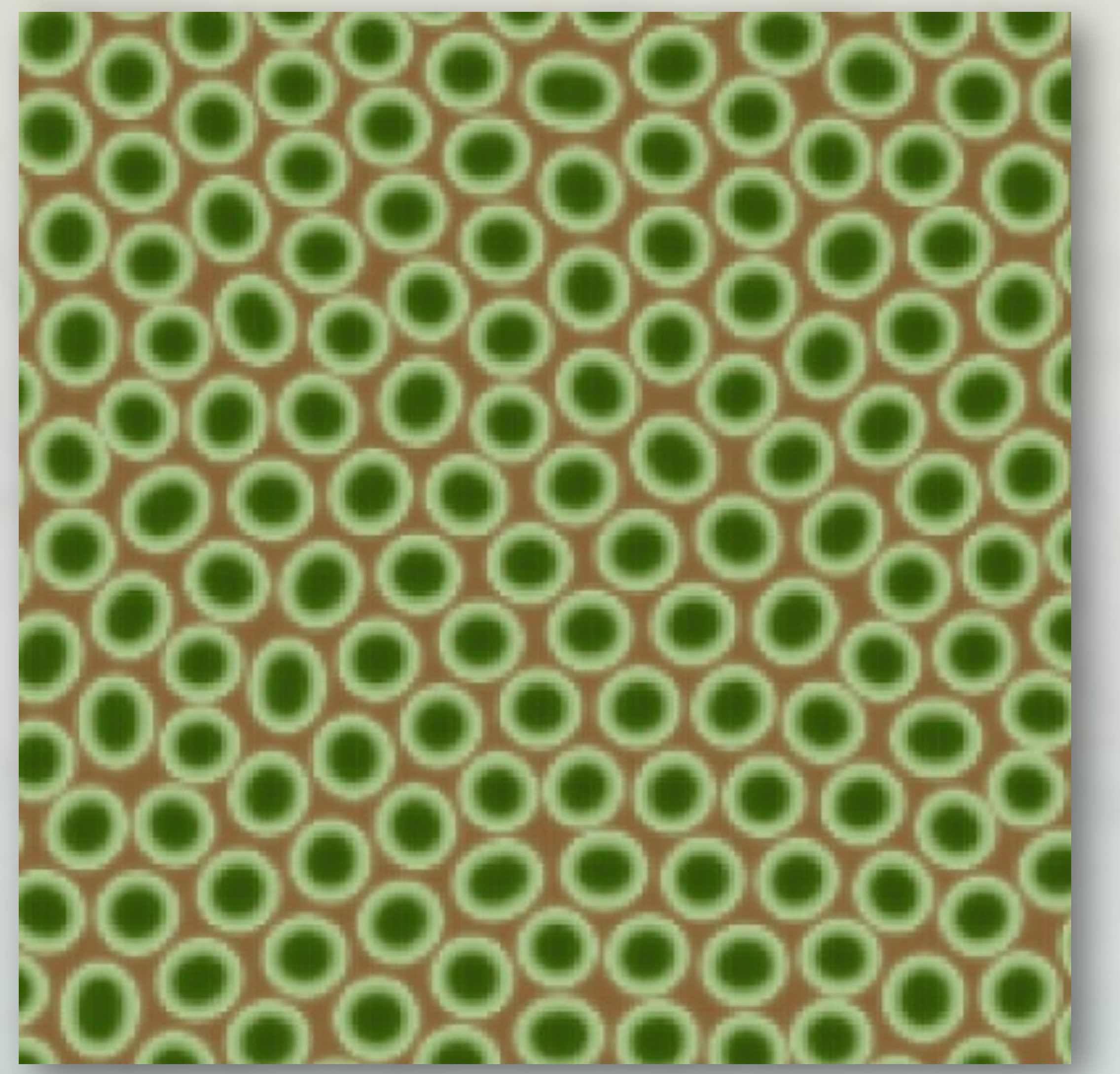

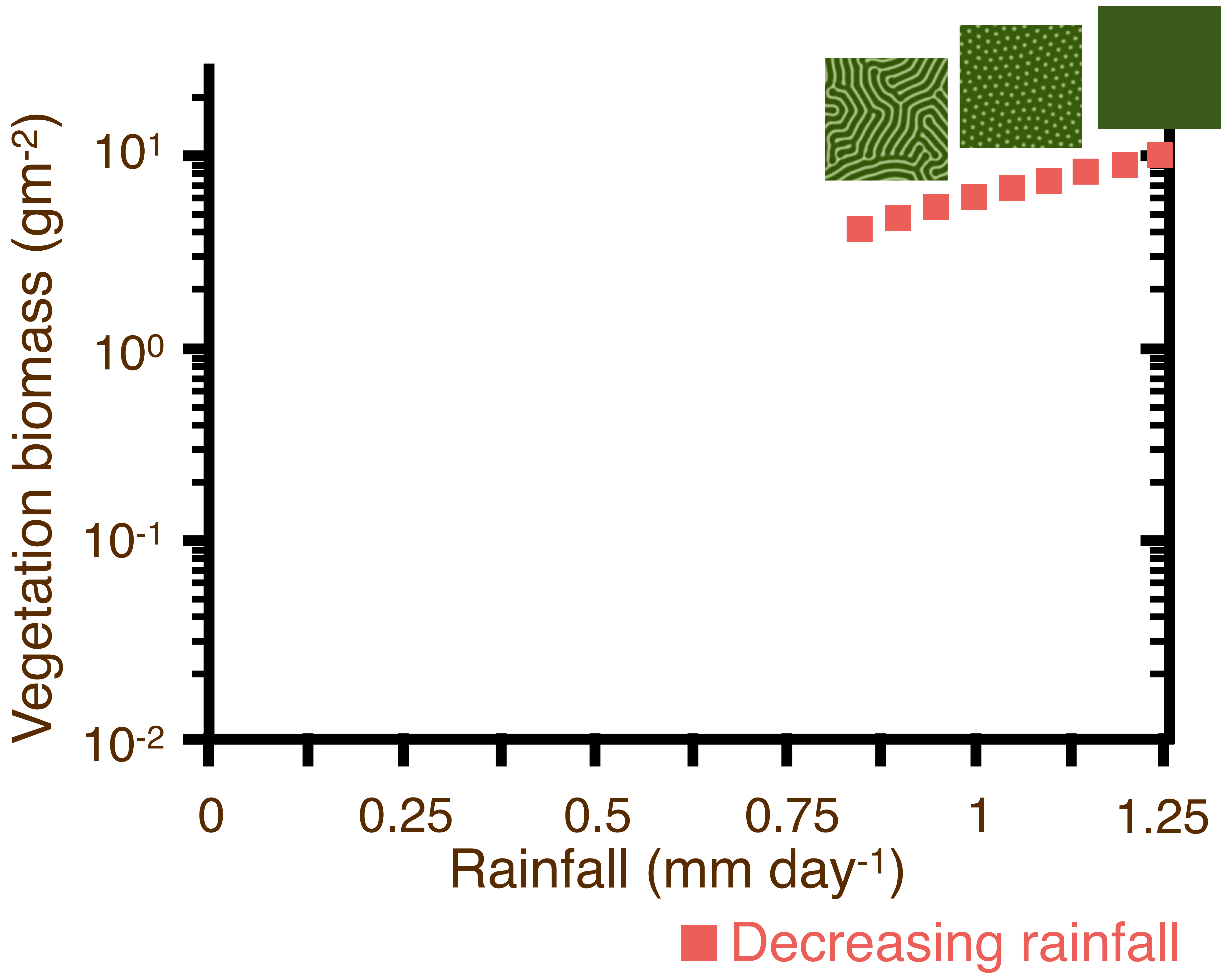

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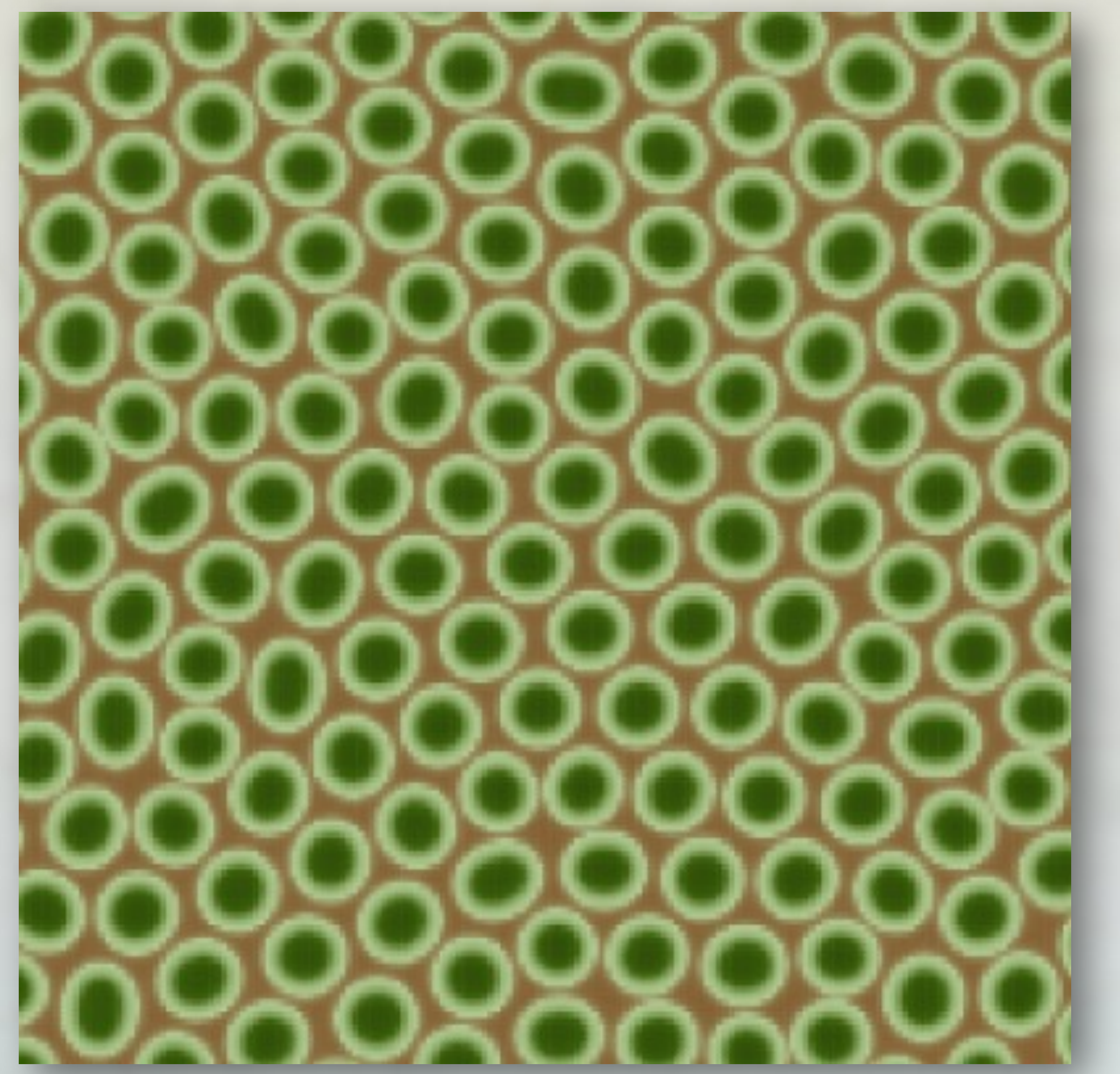

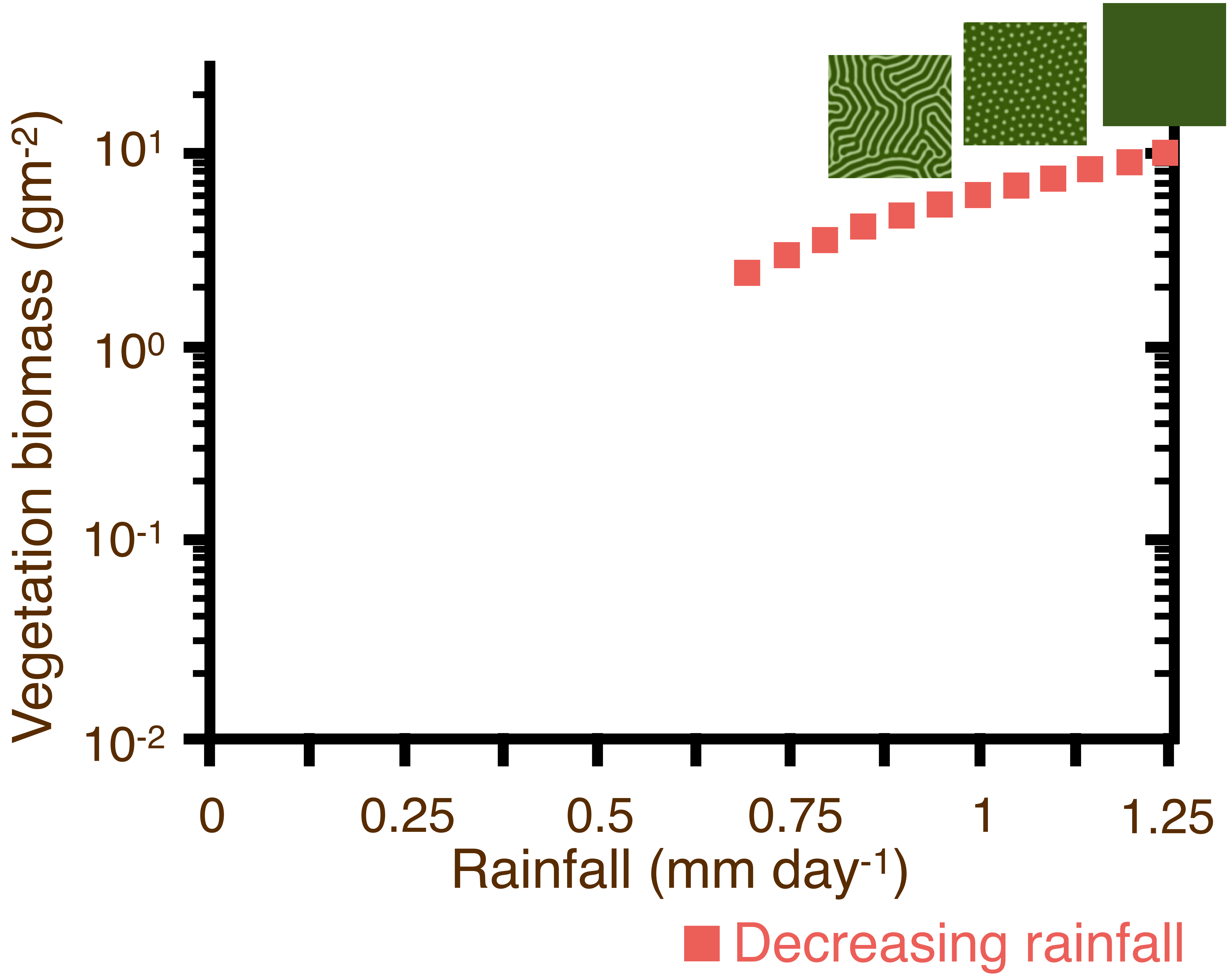

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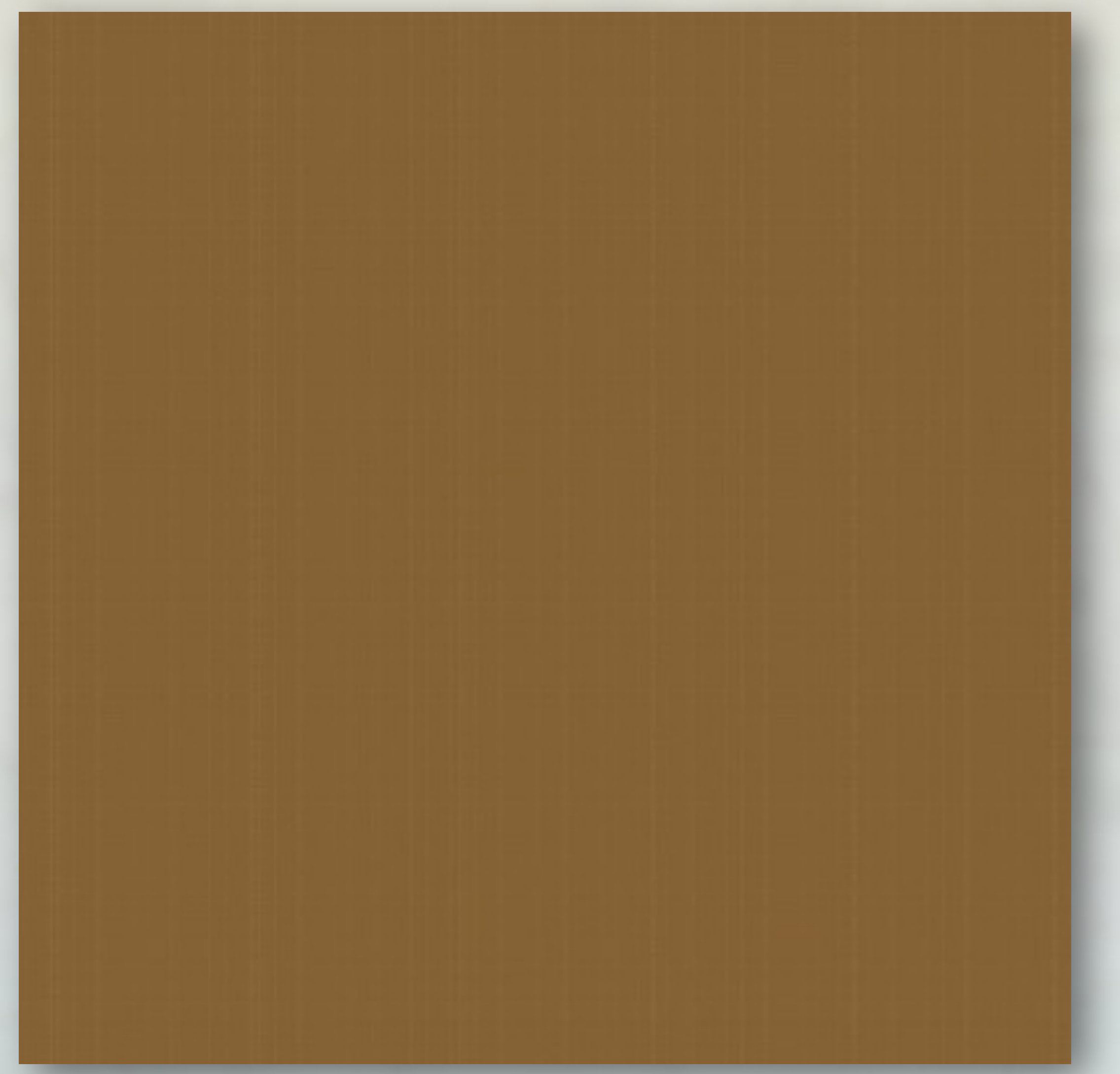

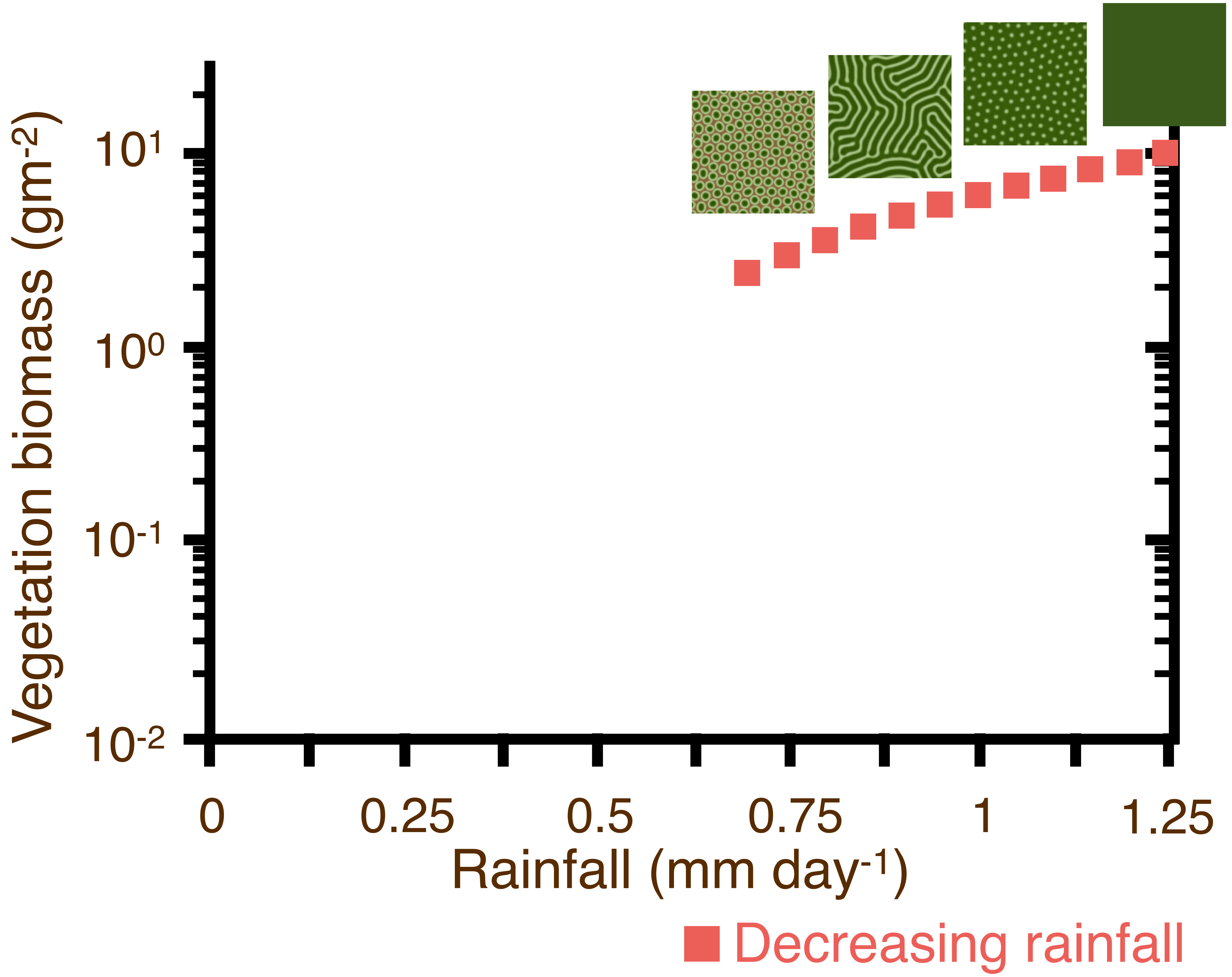

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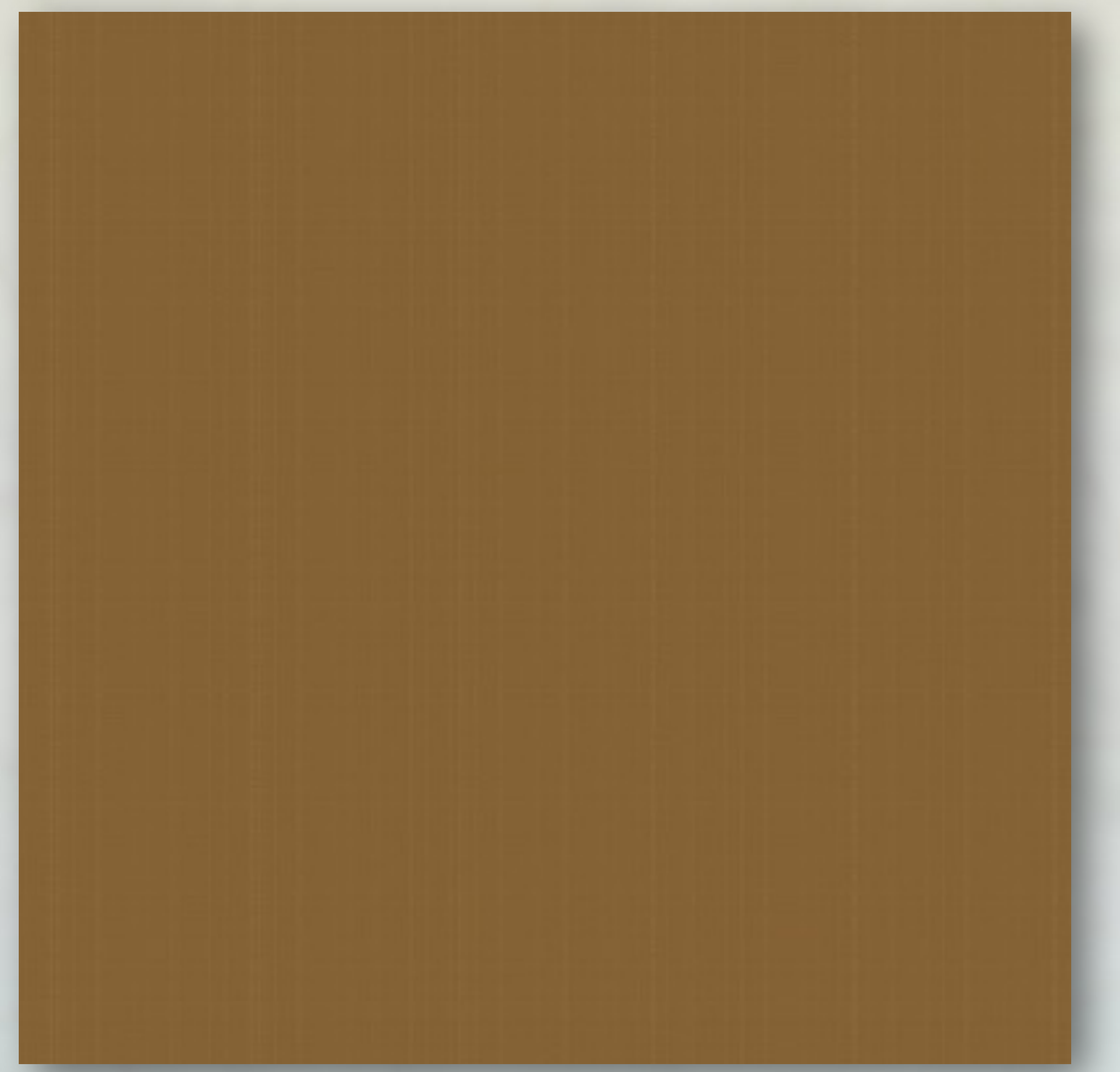

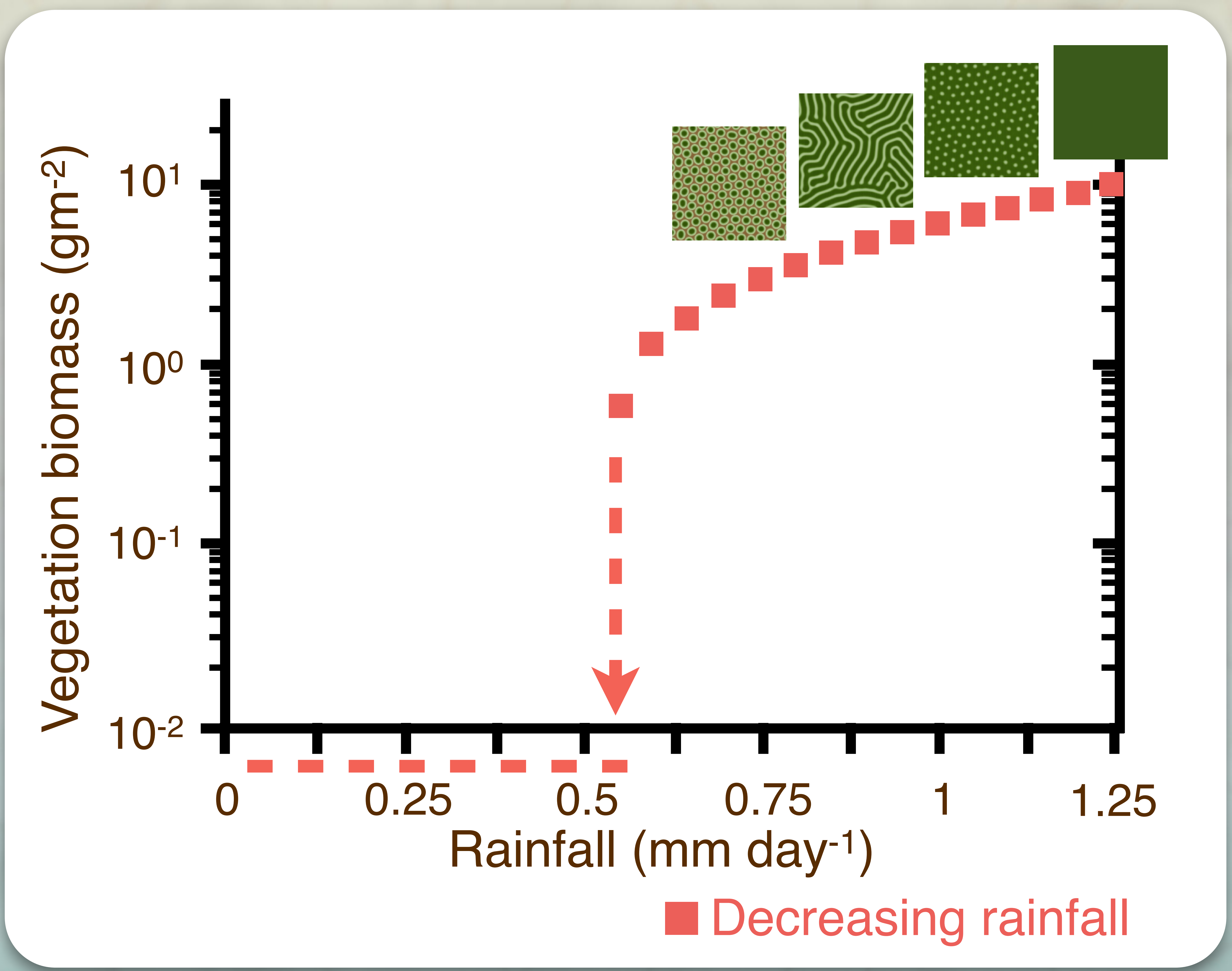

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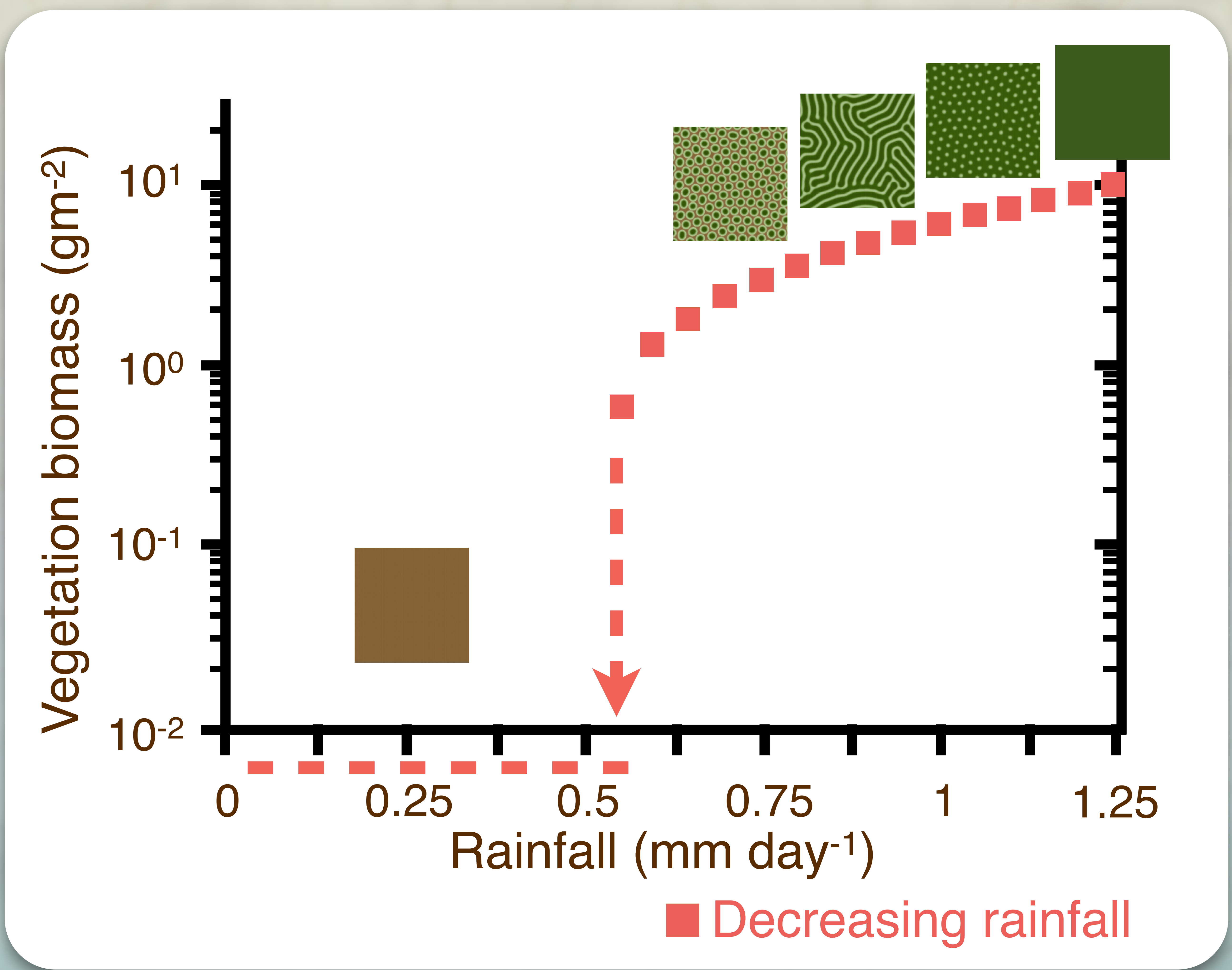
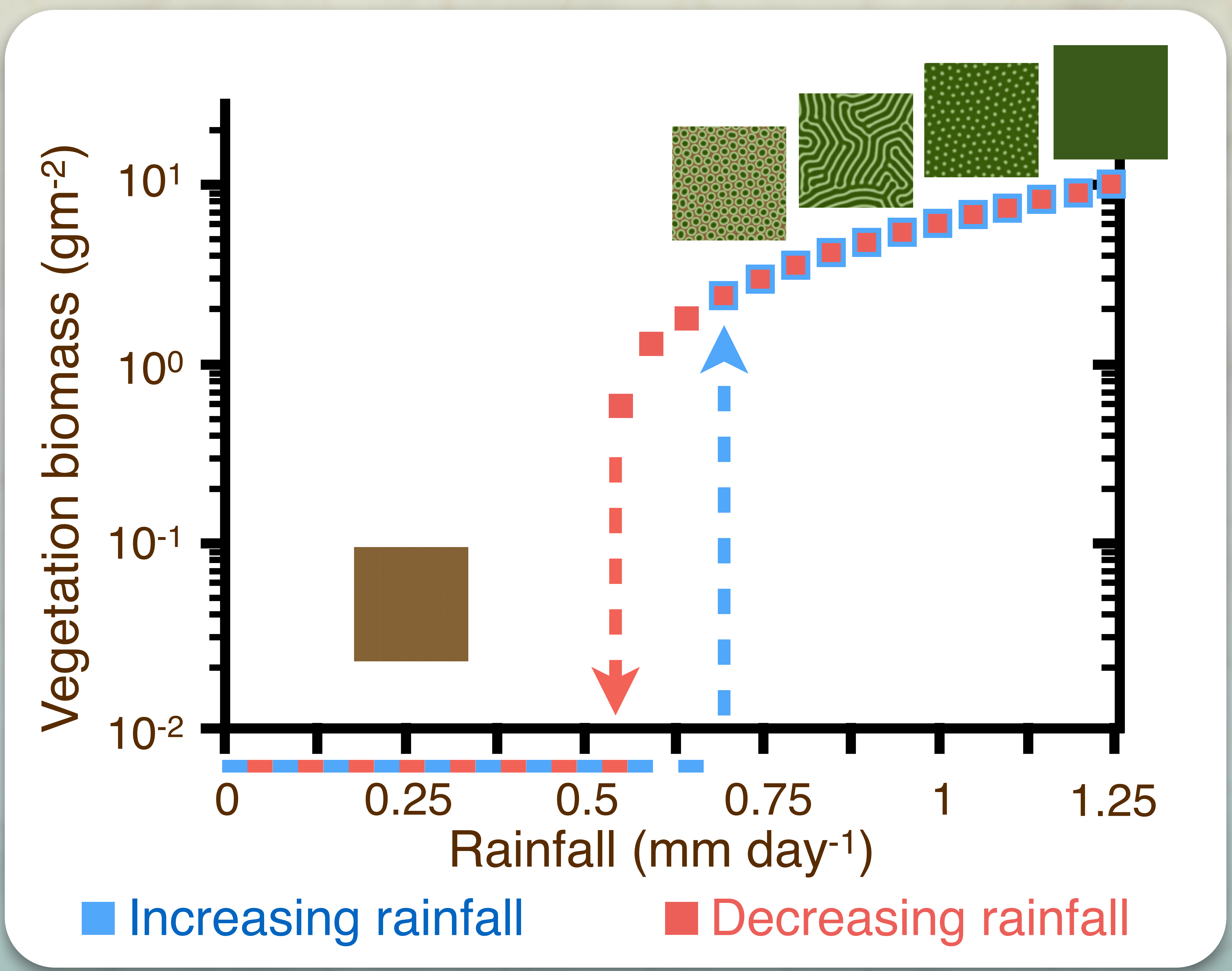
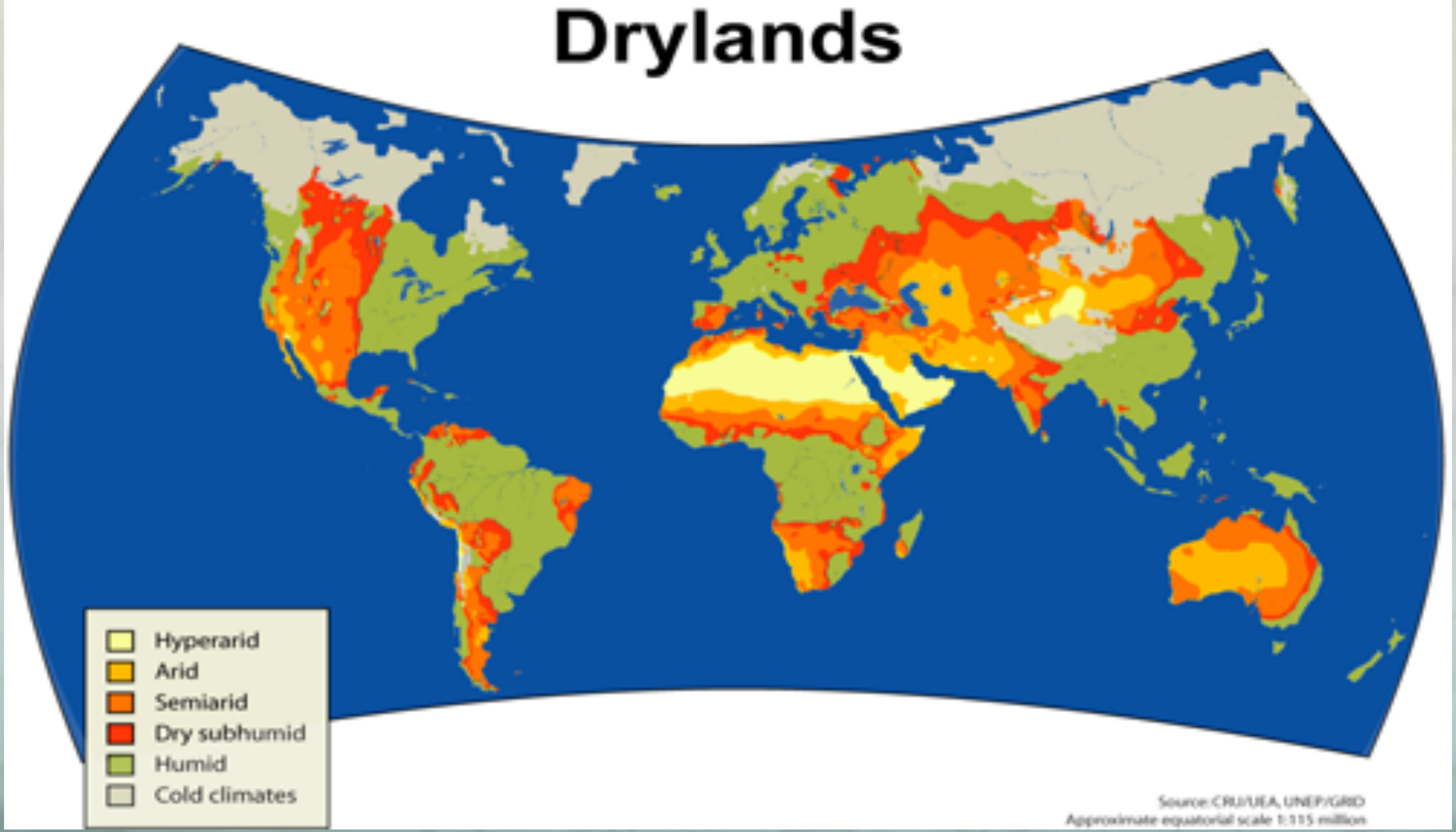


Vegetation Patterns Can Be Early-Warning Indicators



Rietkerk et al (2004), *Science*
Scheffer et al (2009), *Nature*

- Drylands cover >40% of Earth’s land surface and are home to >38% of the populace.
- The robustness/resilience of drylands is an urgent concern given the importance of these systems to human livelihoods and the increased frequency/ intensity of drought expected under climate change.



What forms these spots?

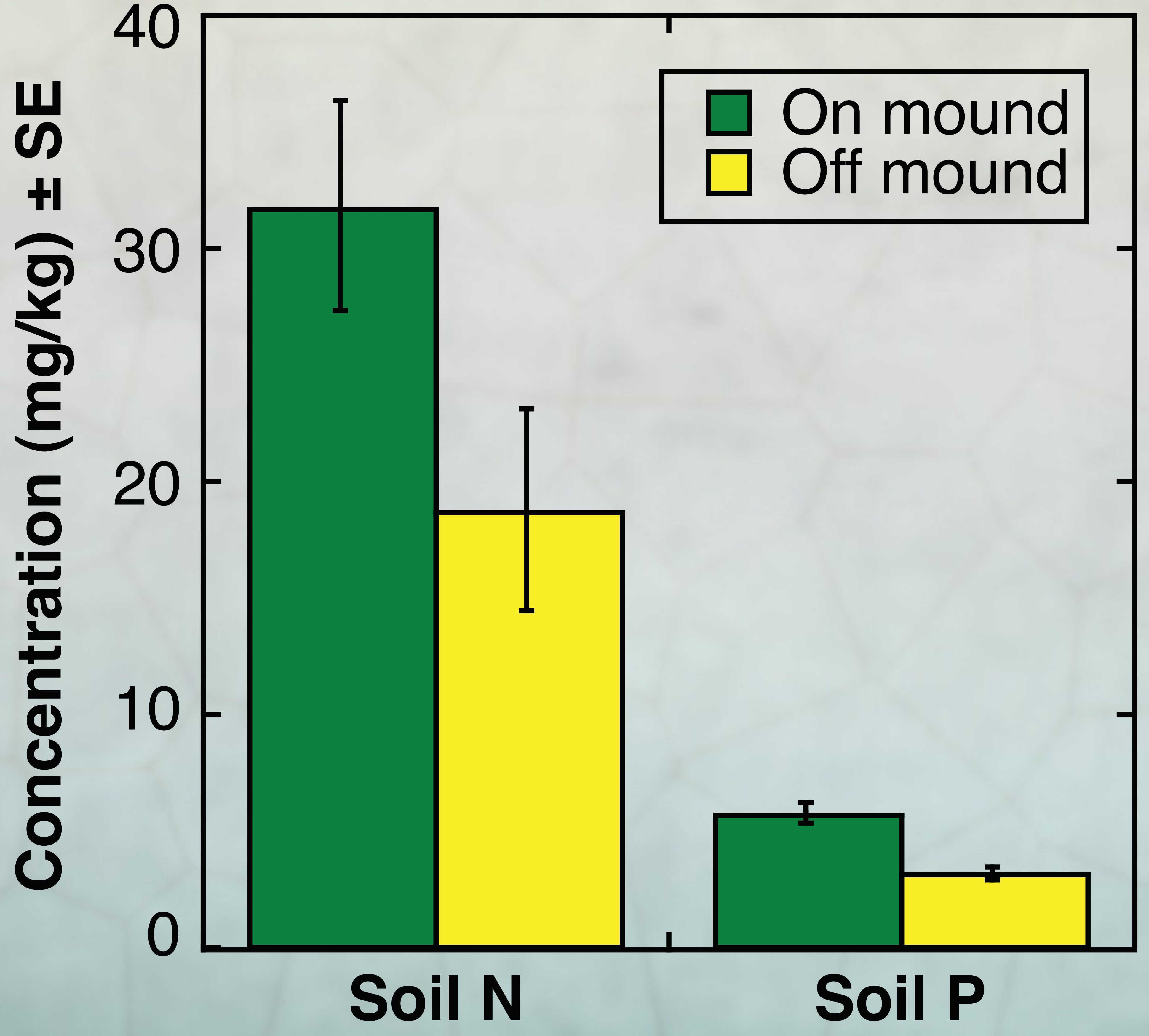
Rob Pringle

What Is Under The Vegetation Clumps?

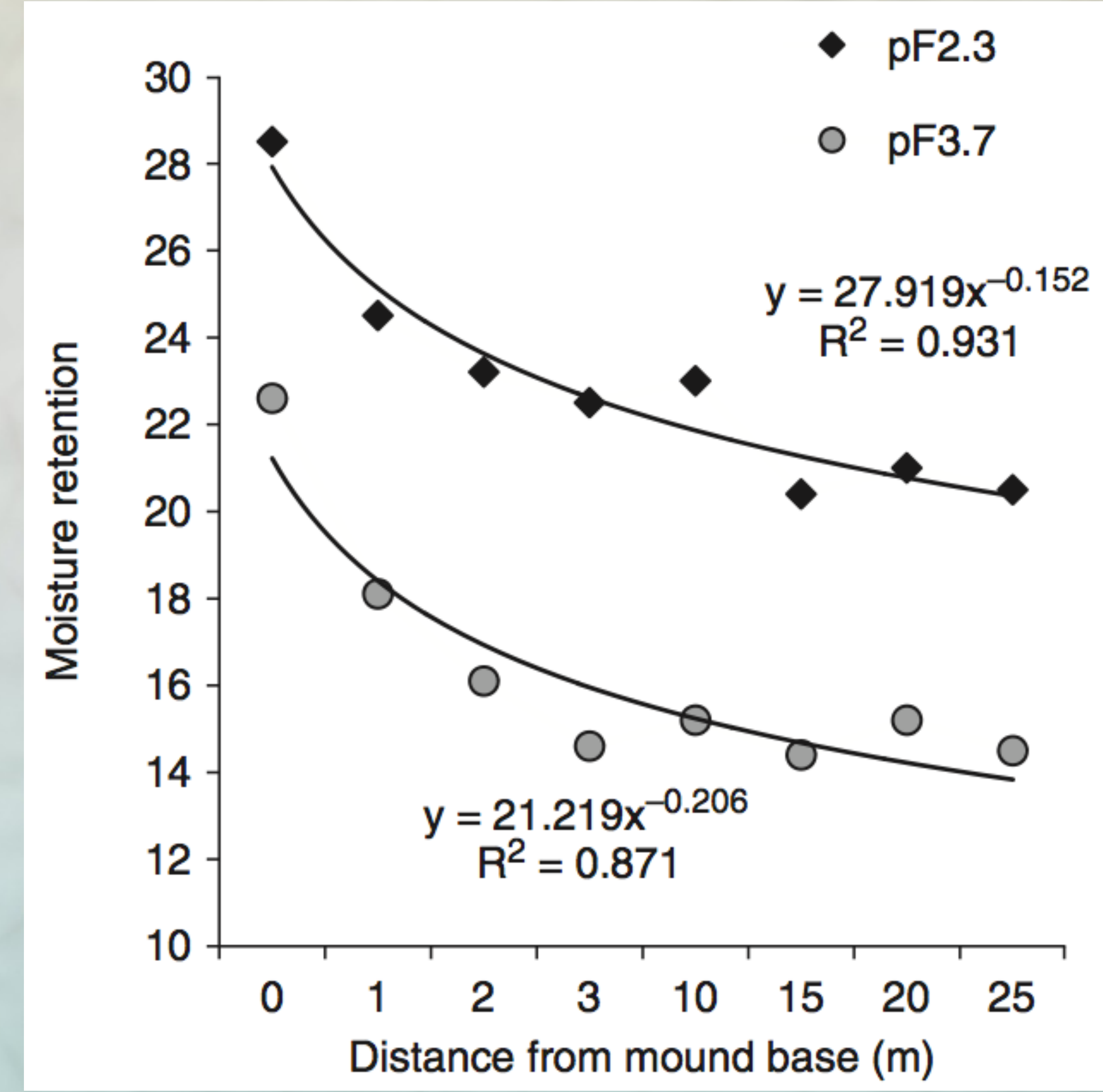
Termite-modified soil
Clay-dominated soil
Water
Organic matter
N Nitrogen
P Phosphorus
Fungi
Rain
Plants
Litter
Dung
Foraging termite
N
P

Termites modify nutrient and moisture availability

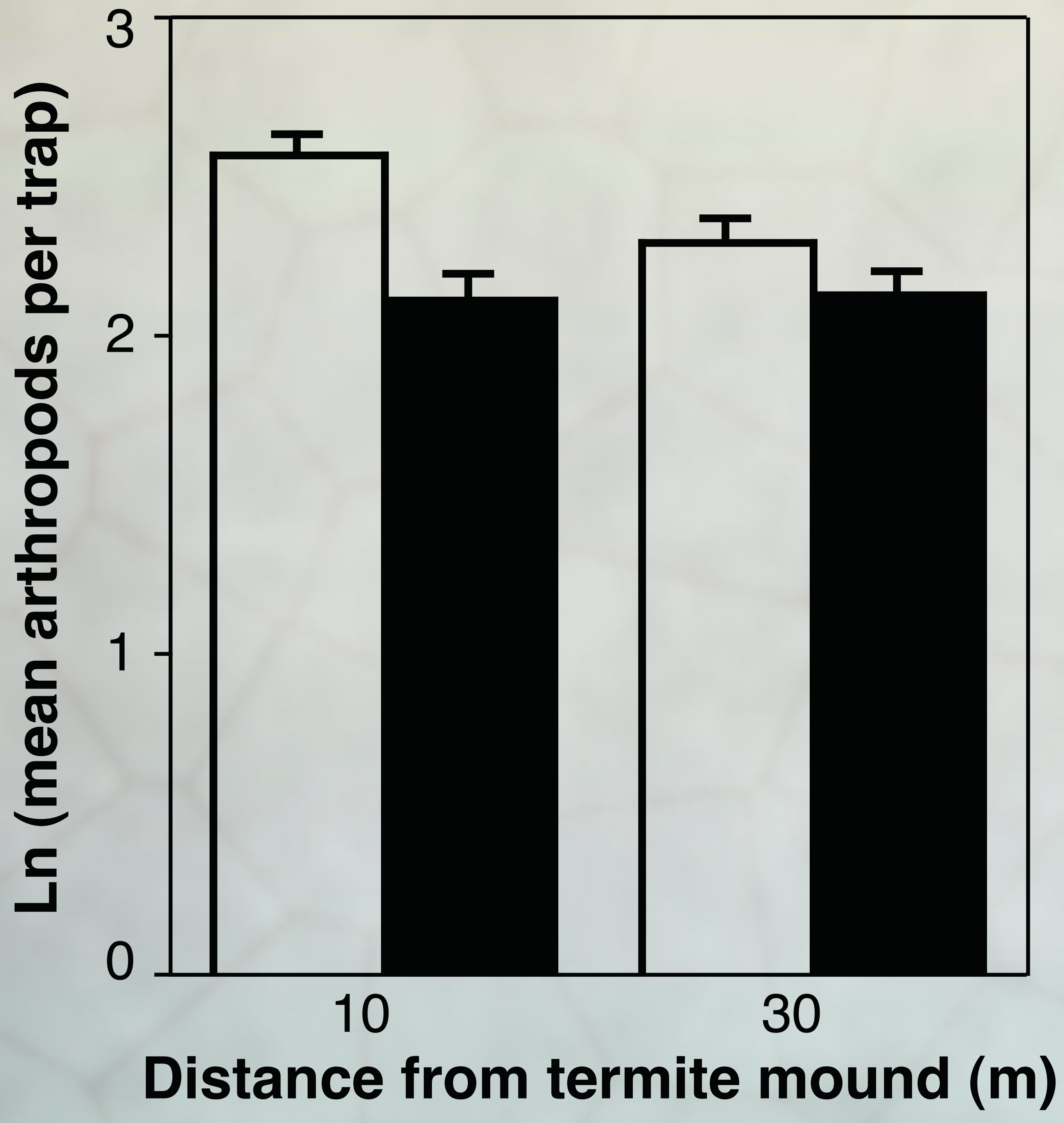
Nutrient availability

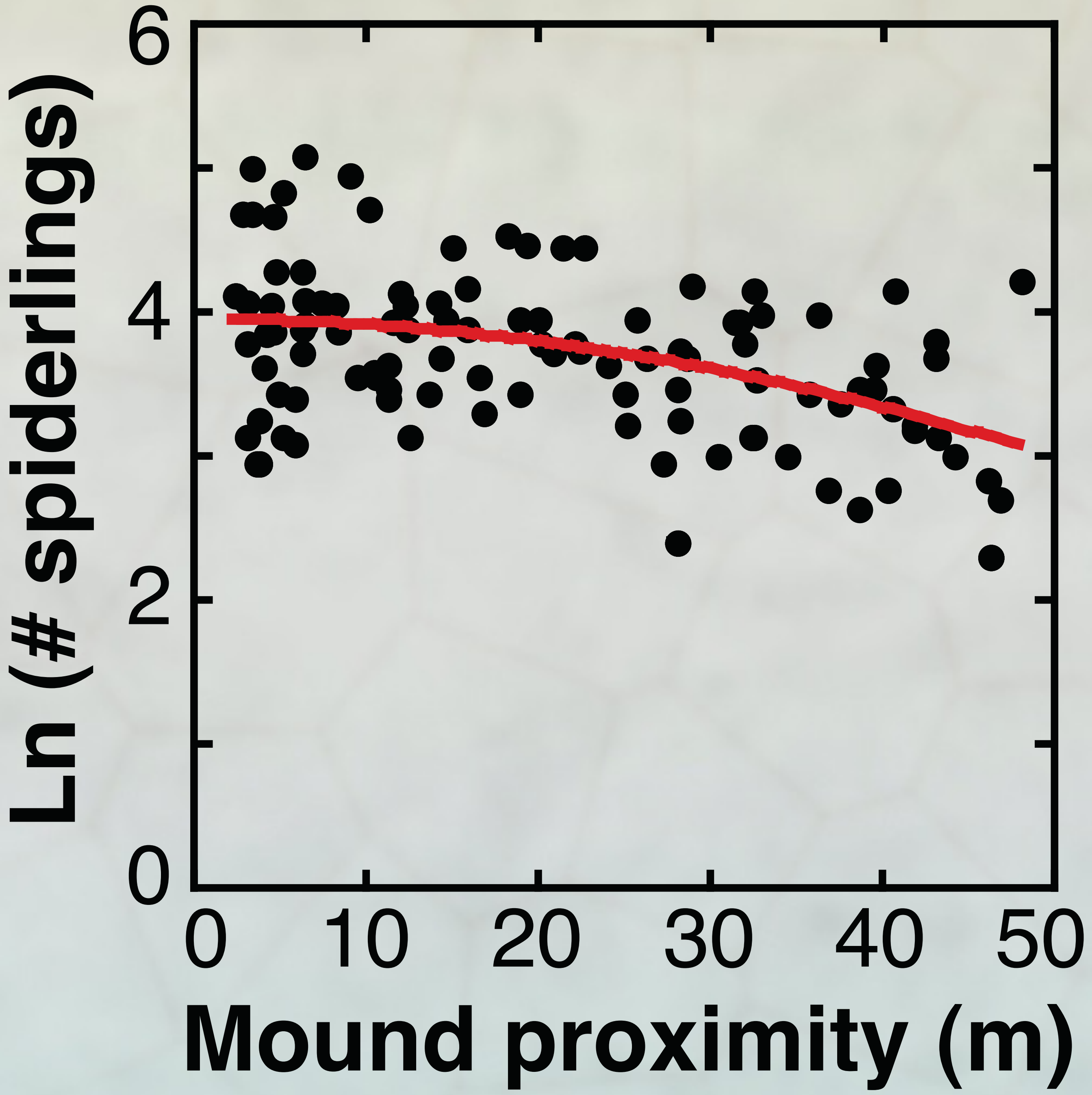


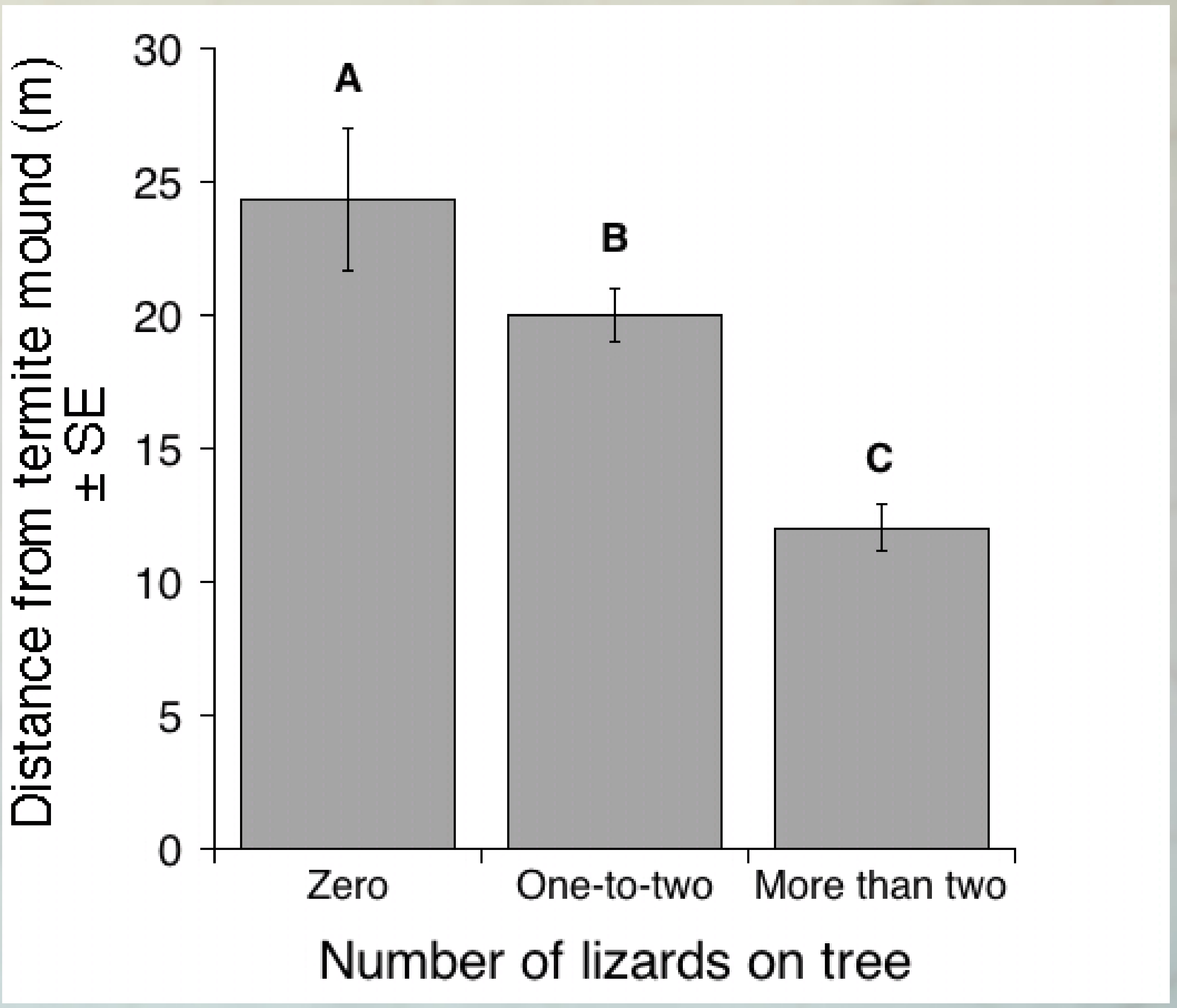
Moisture availability



Sileshi et al. (2010), *J. Veg. Sci.*







Pringle et al. (2010), *PLoS Biol*

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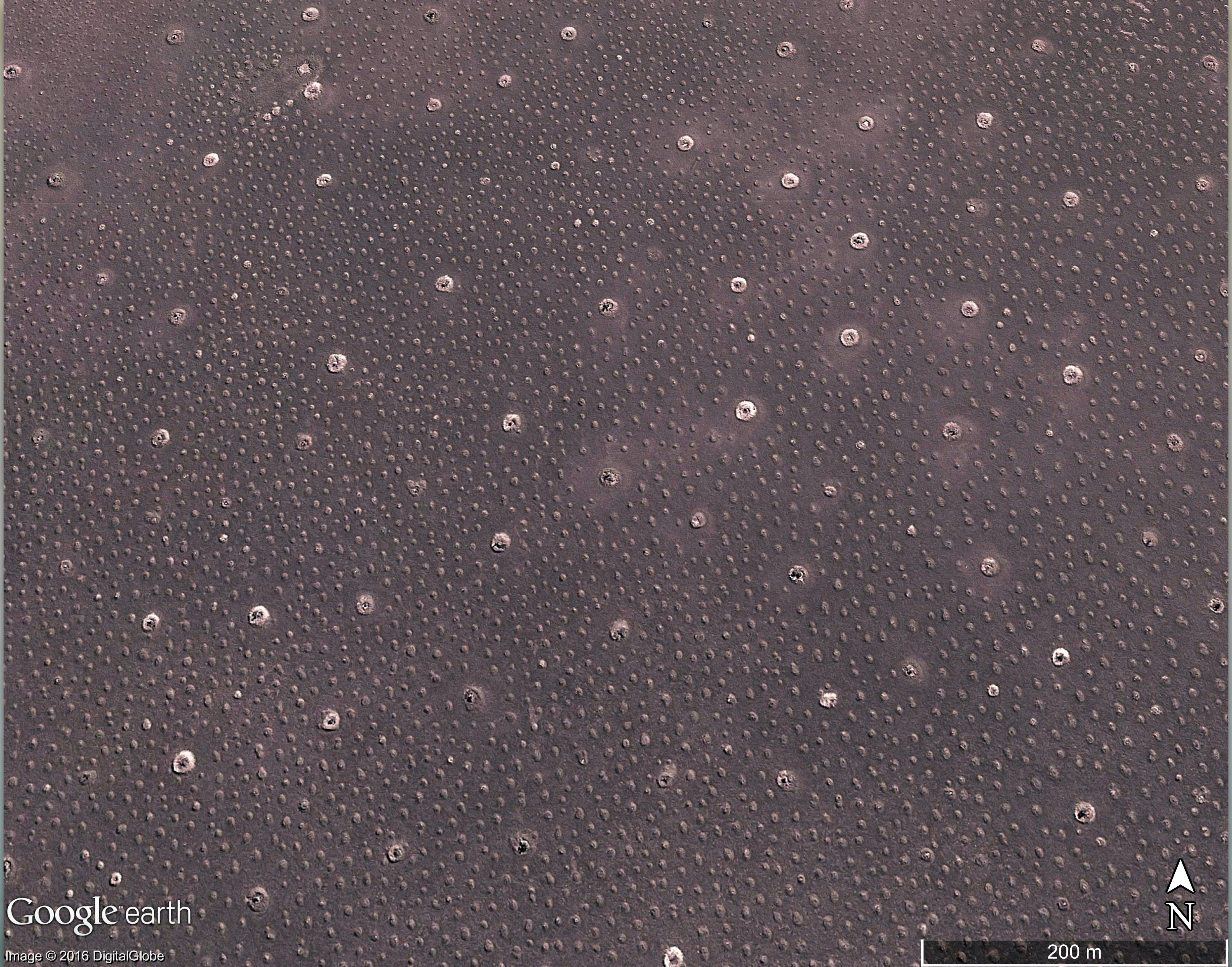
PLoS BIOLOGY

Spatial Pattern Enhances Ecosystem Functioning in an African Savanna

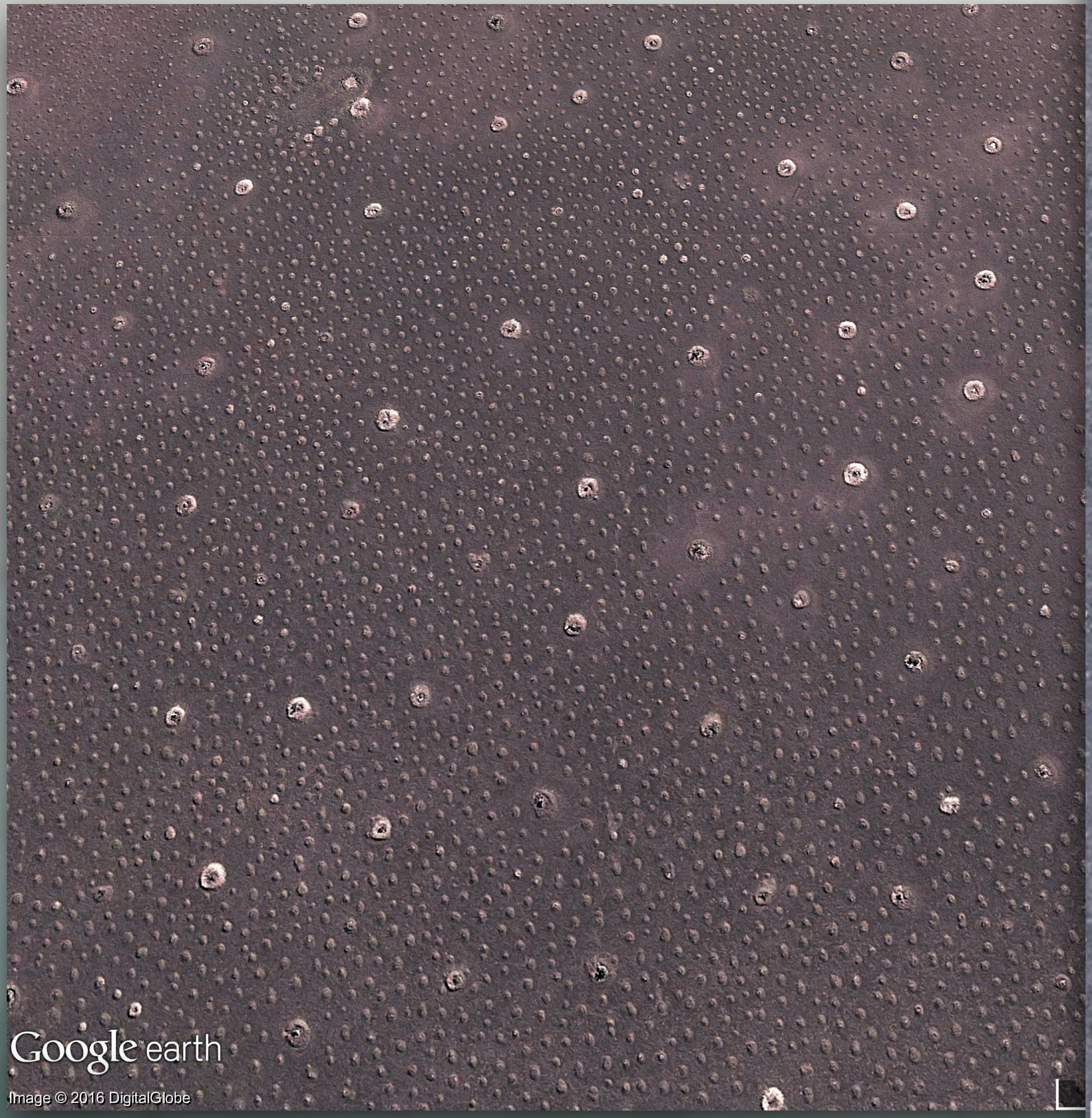
Robert M. Pringle[1,2*], **Daniel F. Doak**[2,3], **Alison K. Brody**[2,4], **Rudy Jocqué**[5], **Todd M. Palmer**[2,6]

1 Society of Fellows, Harvard University, Cambridge, Massachusetts, United States of America, **2** Mpala Research Centre, Nanyuki, Kenya, **3** Department of Zoology and Physiology, University of Wyoming, Laramie, Wyoming, United States of America, **4** Department of Biology, University of Vermont, Burlington, Vermont, United States of America, **5** Department of African Zoology, Royal Museum for Central Africa, Tervuren, Belgium, **6** Department of Biology, University of Florida, Gainesville, Florida, United States of America



Google earth
Image © 2016 DigitalGlobe
200 m
N

Agriculturalists use termite mounds to plant crops

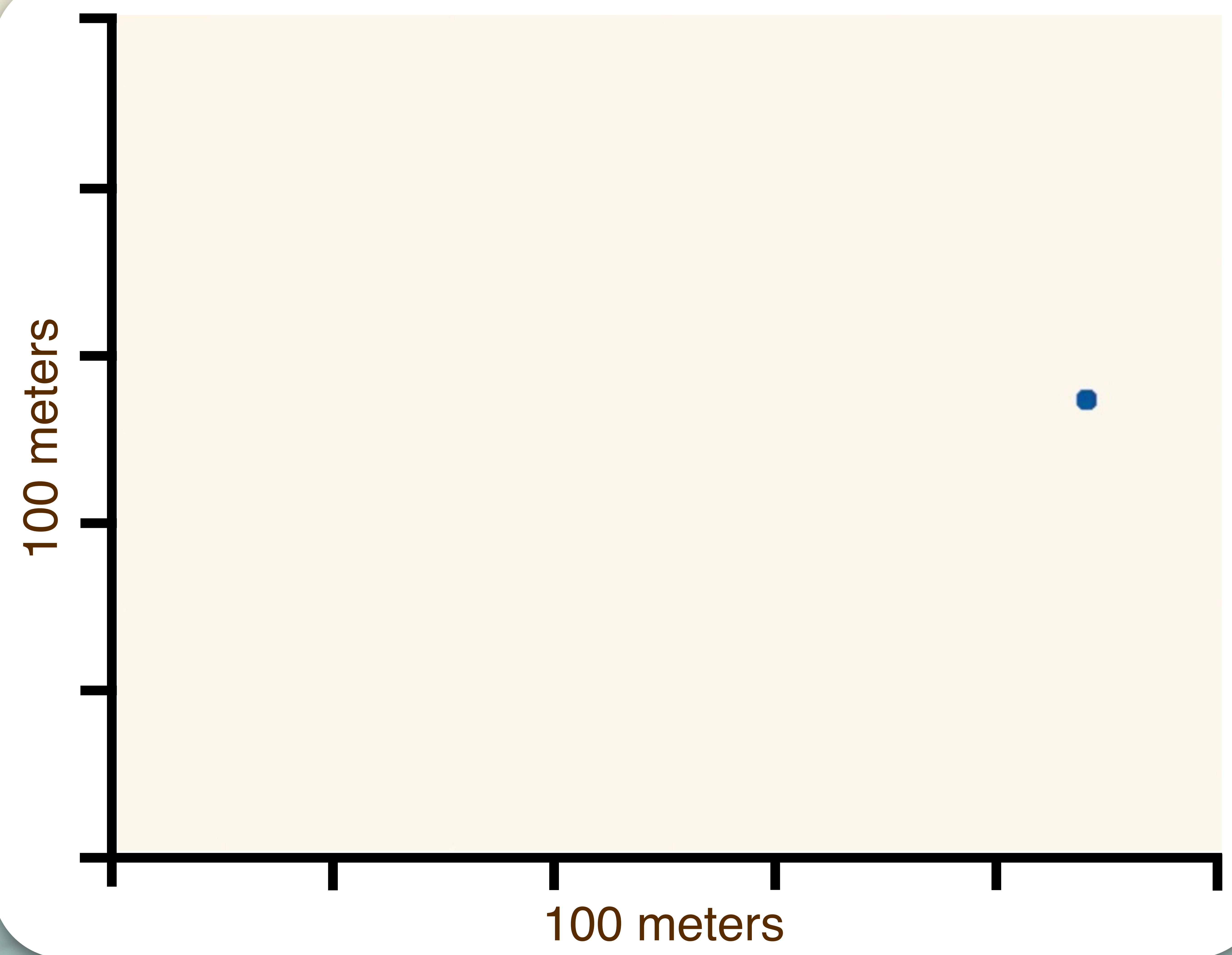


Pre-Columbian raised fields in a savanna near Sinnamary, coastal French Guiana.

What mechanism could lead to this type of pattern?

Map data: Google, © 2015 CNES/Astrium

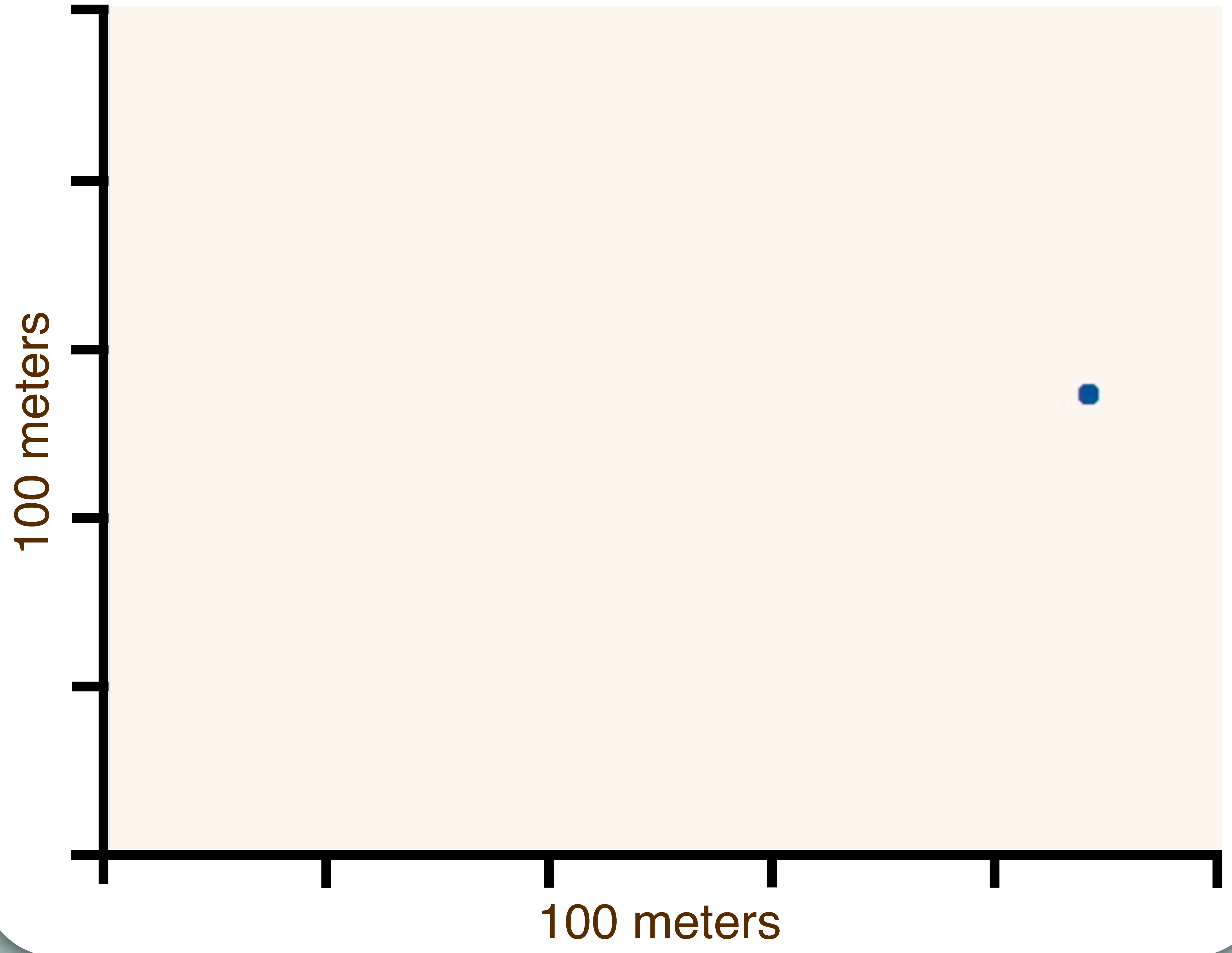
How Do Termites Organize Across the Landscape?



Juan Bonachela

Tarnita et al, *in review*

Colony Growth



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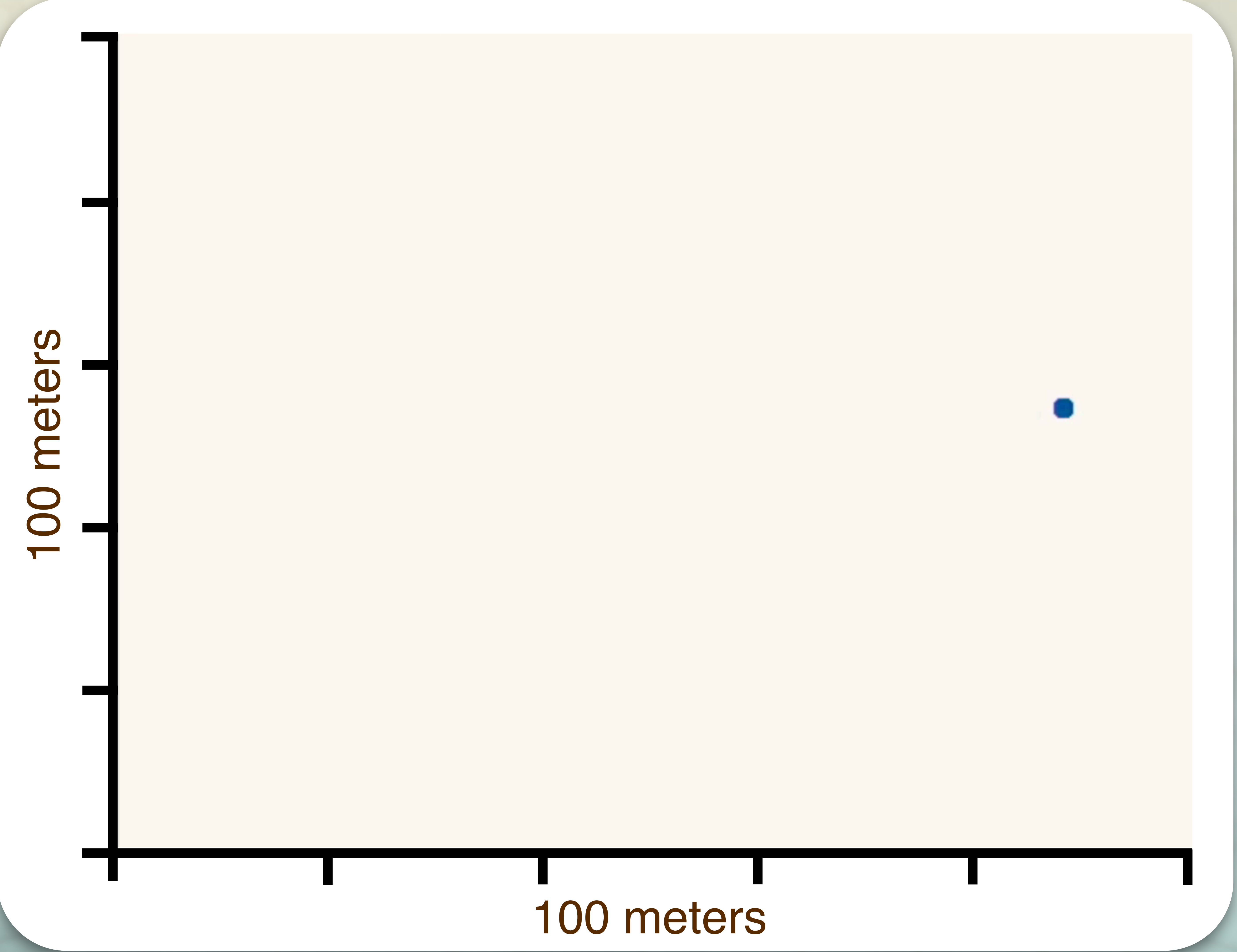
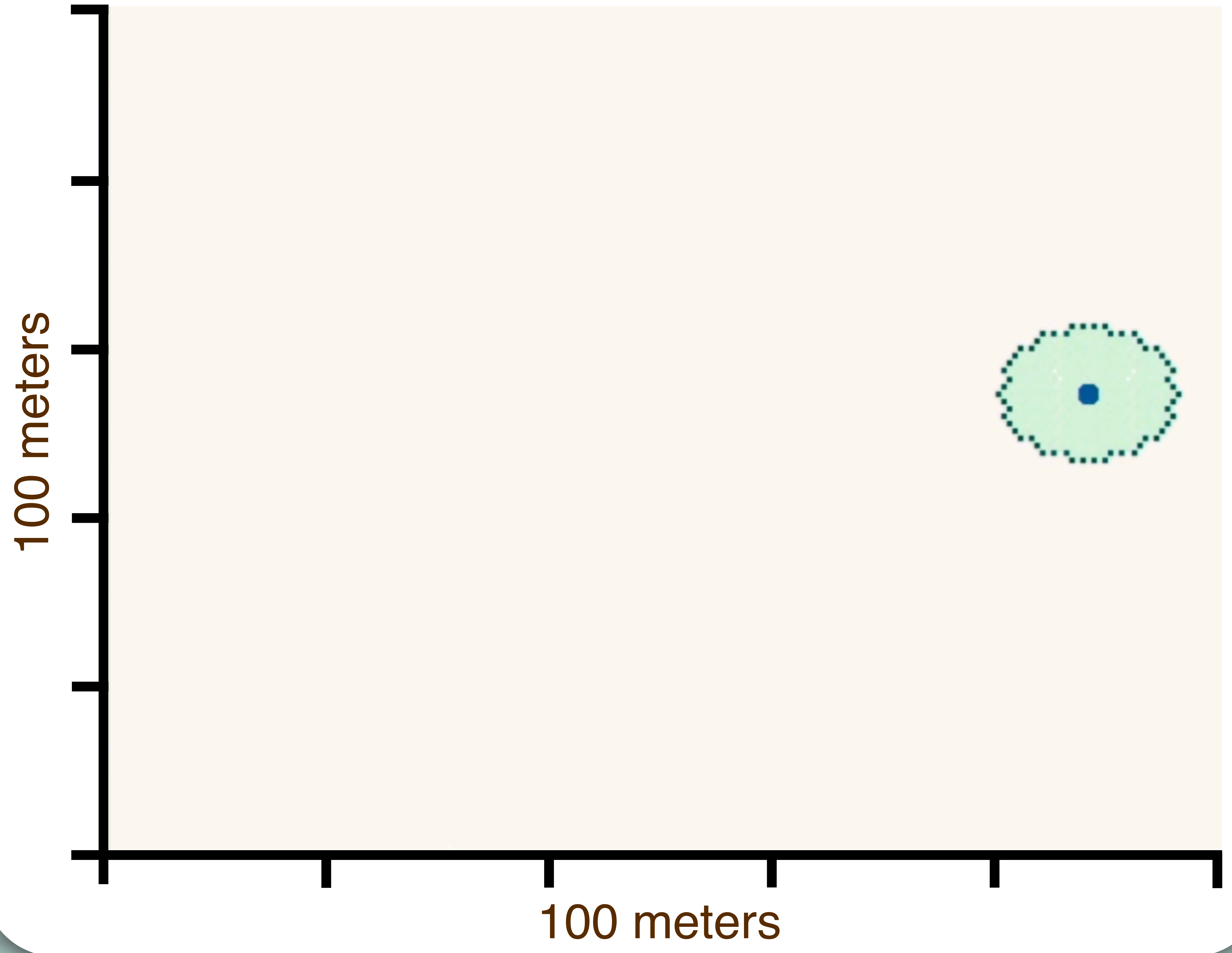


Colony Reproduction



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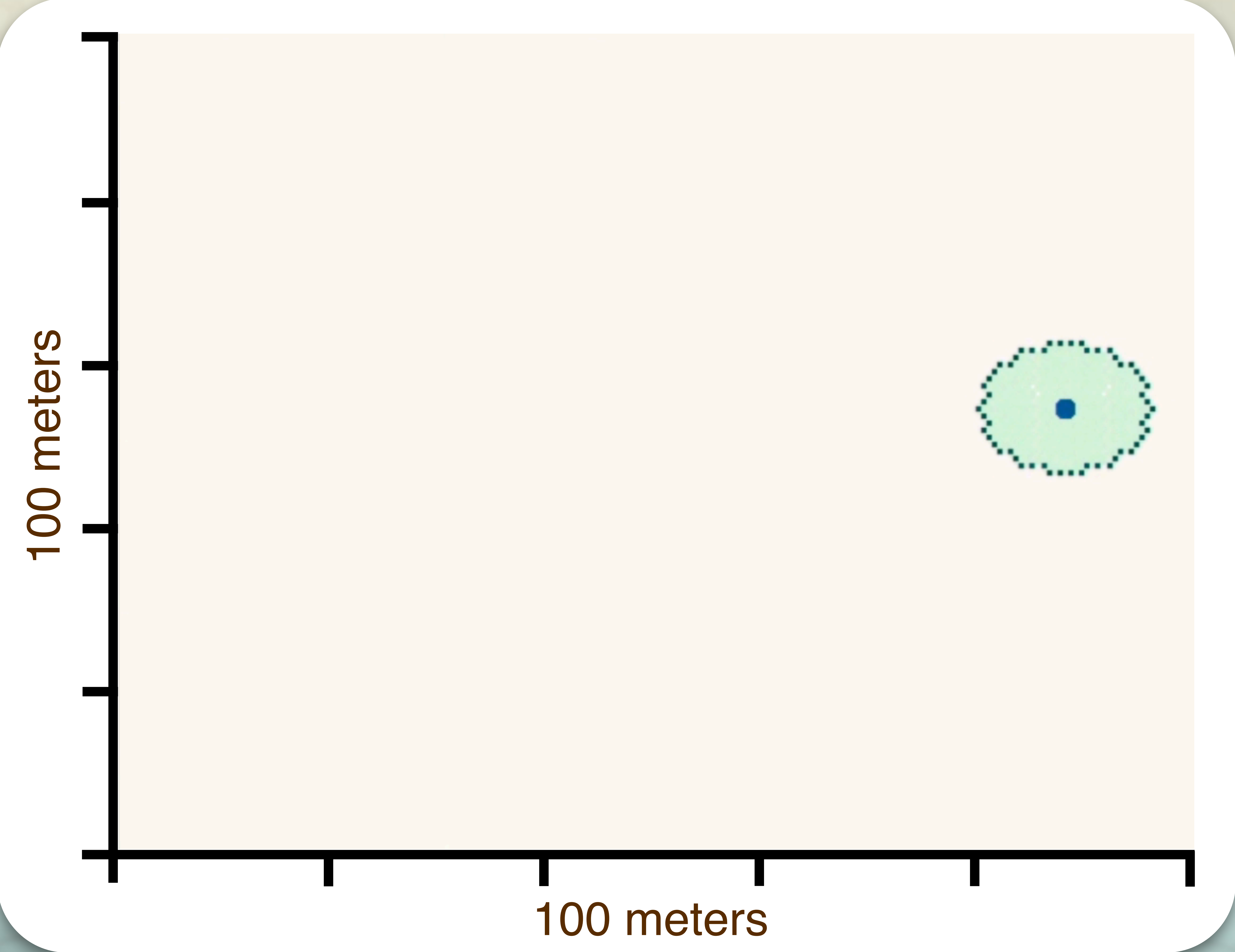
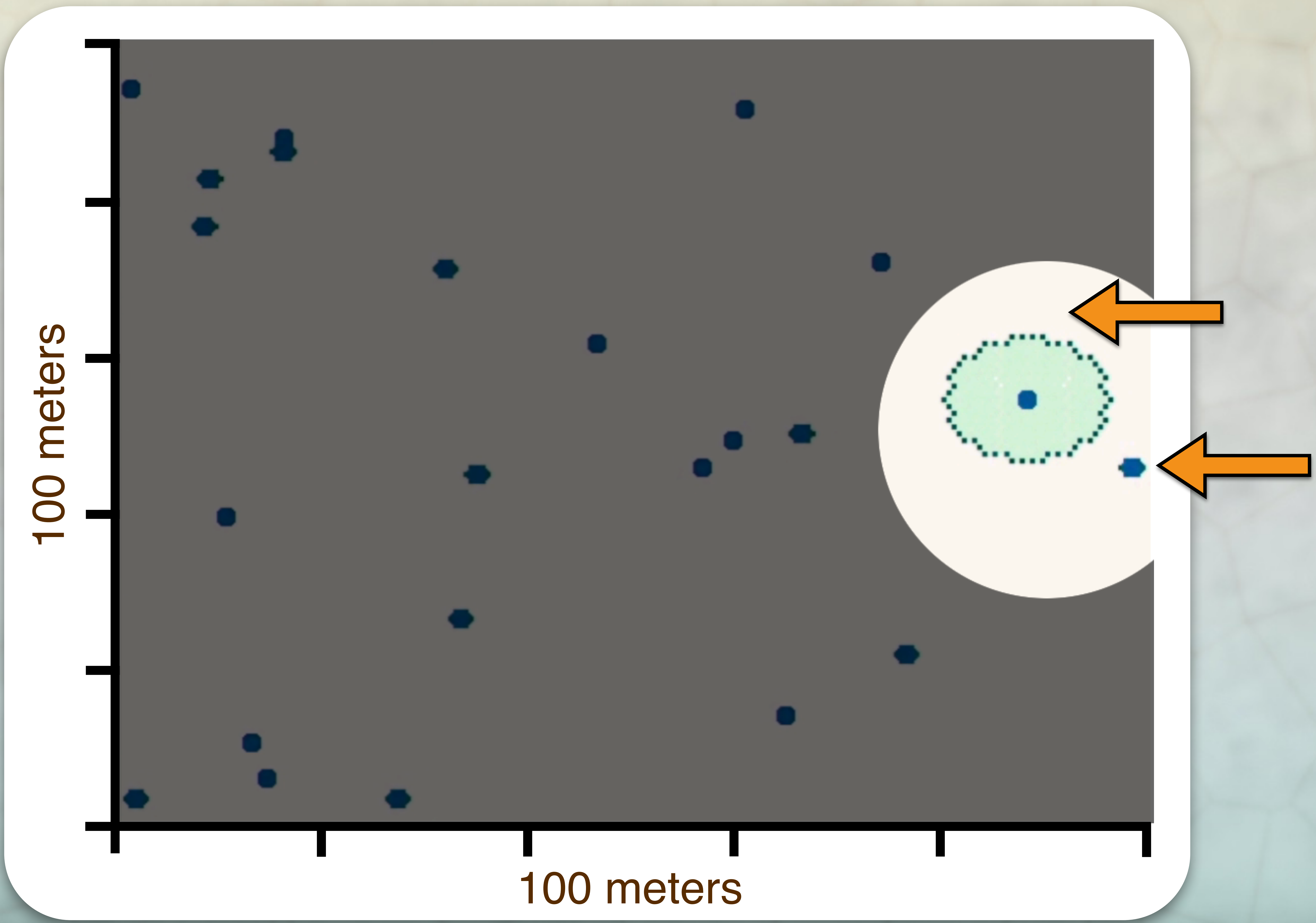


Competition



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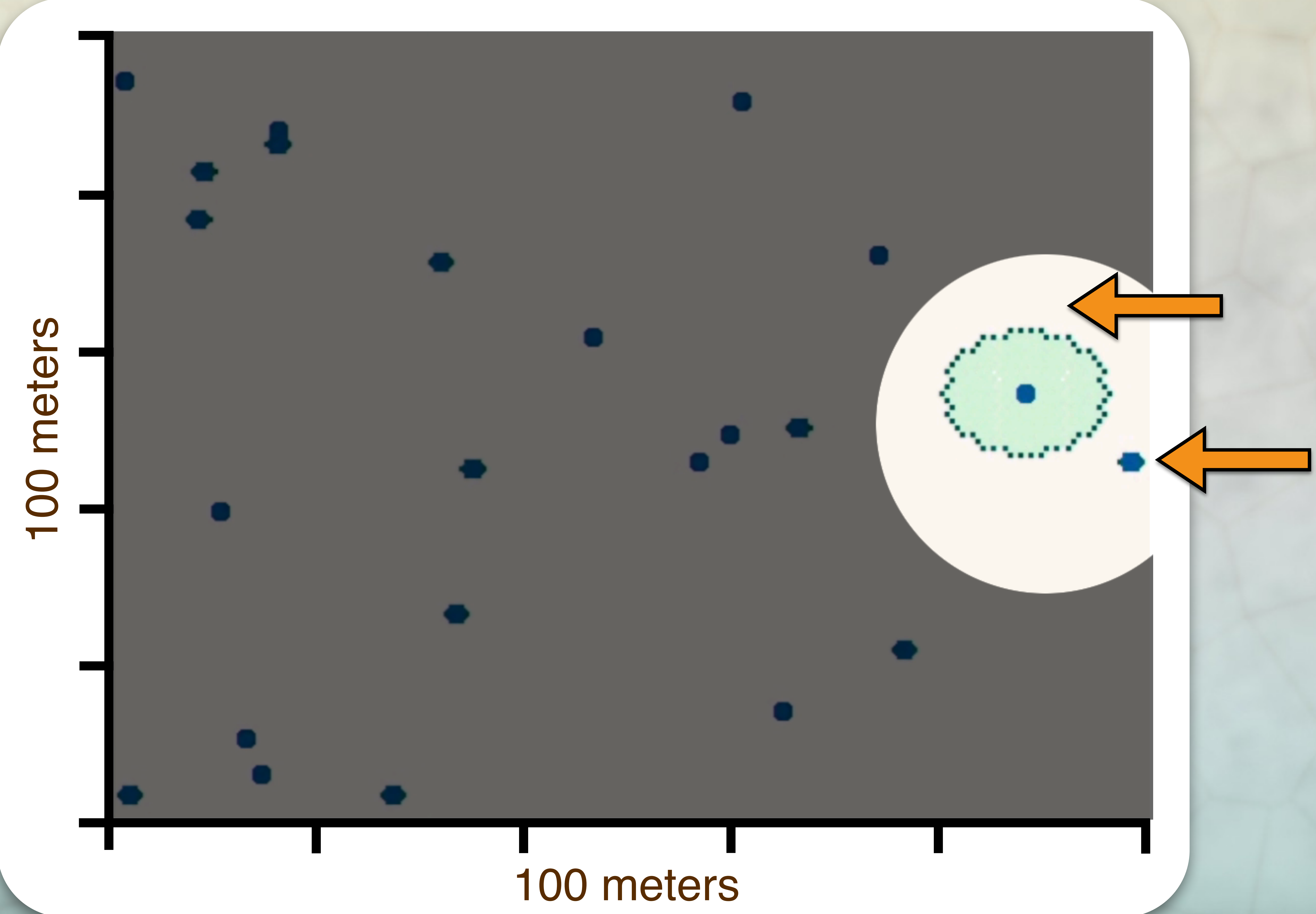
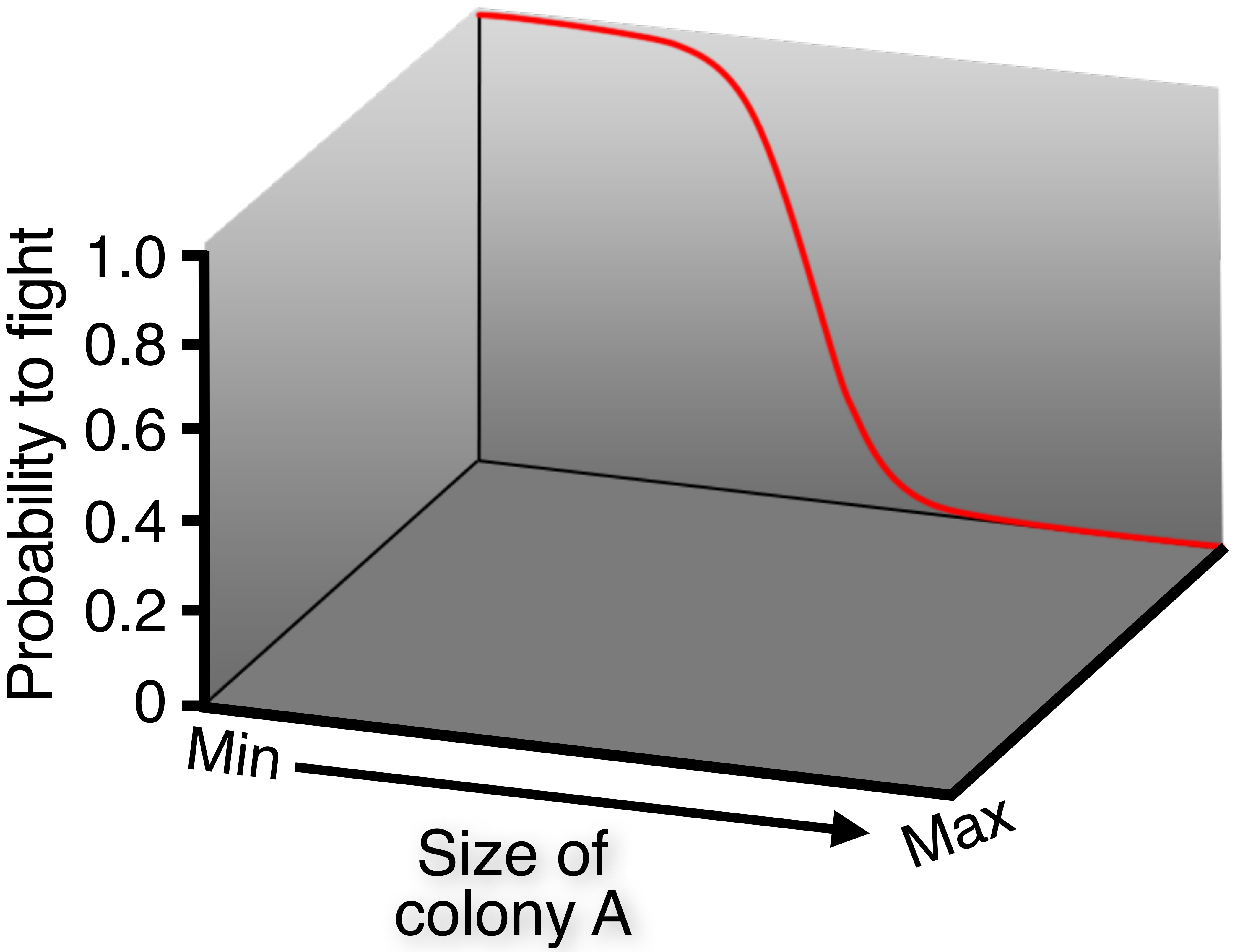


Modeling Termite Colony Competition: When Do Conflicts Occur?



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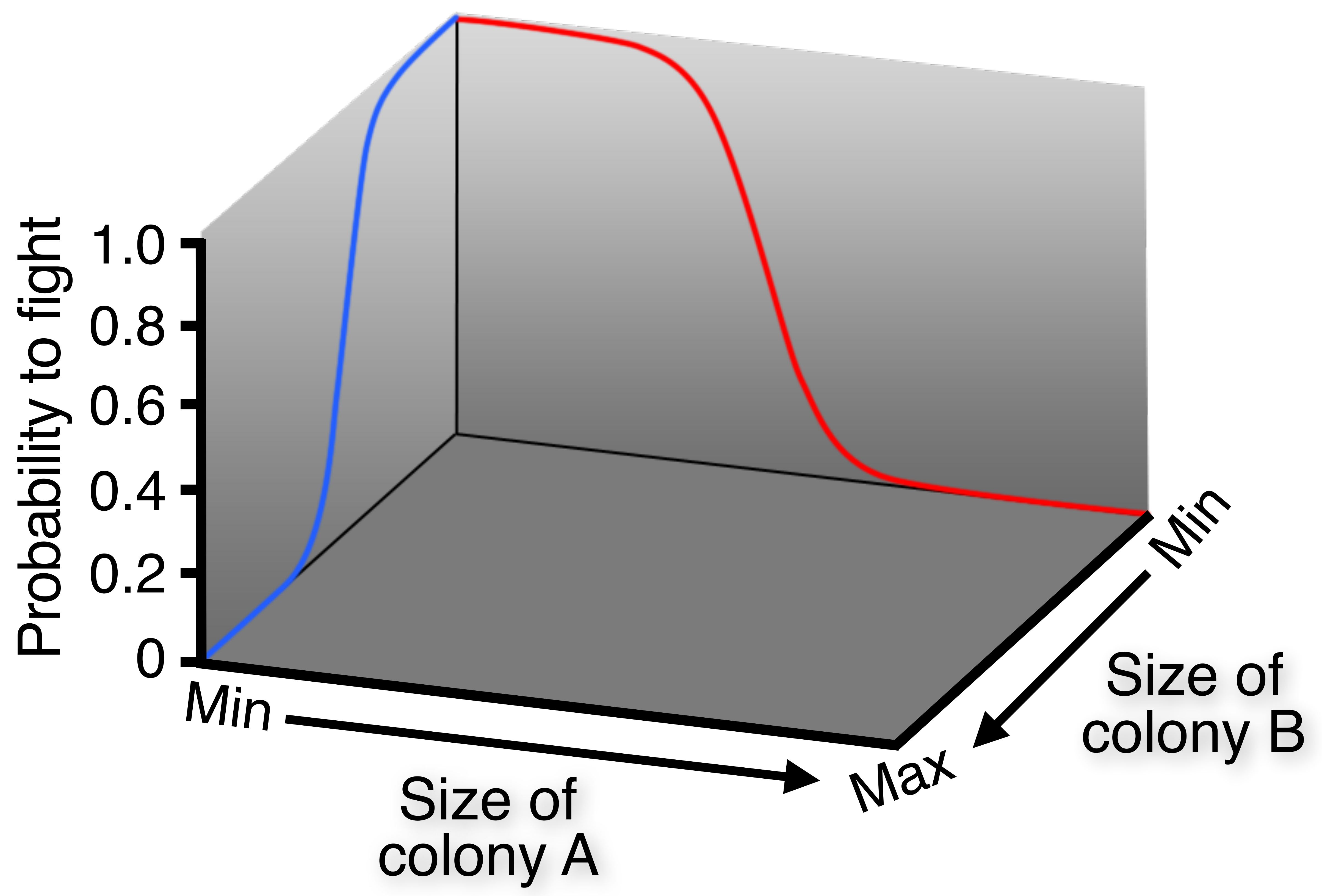

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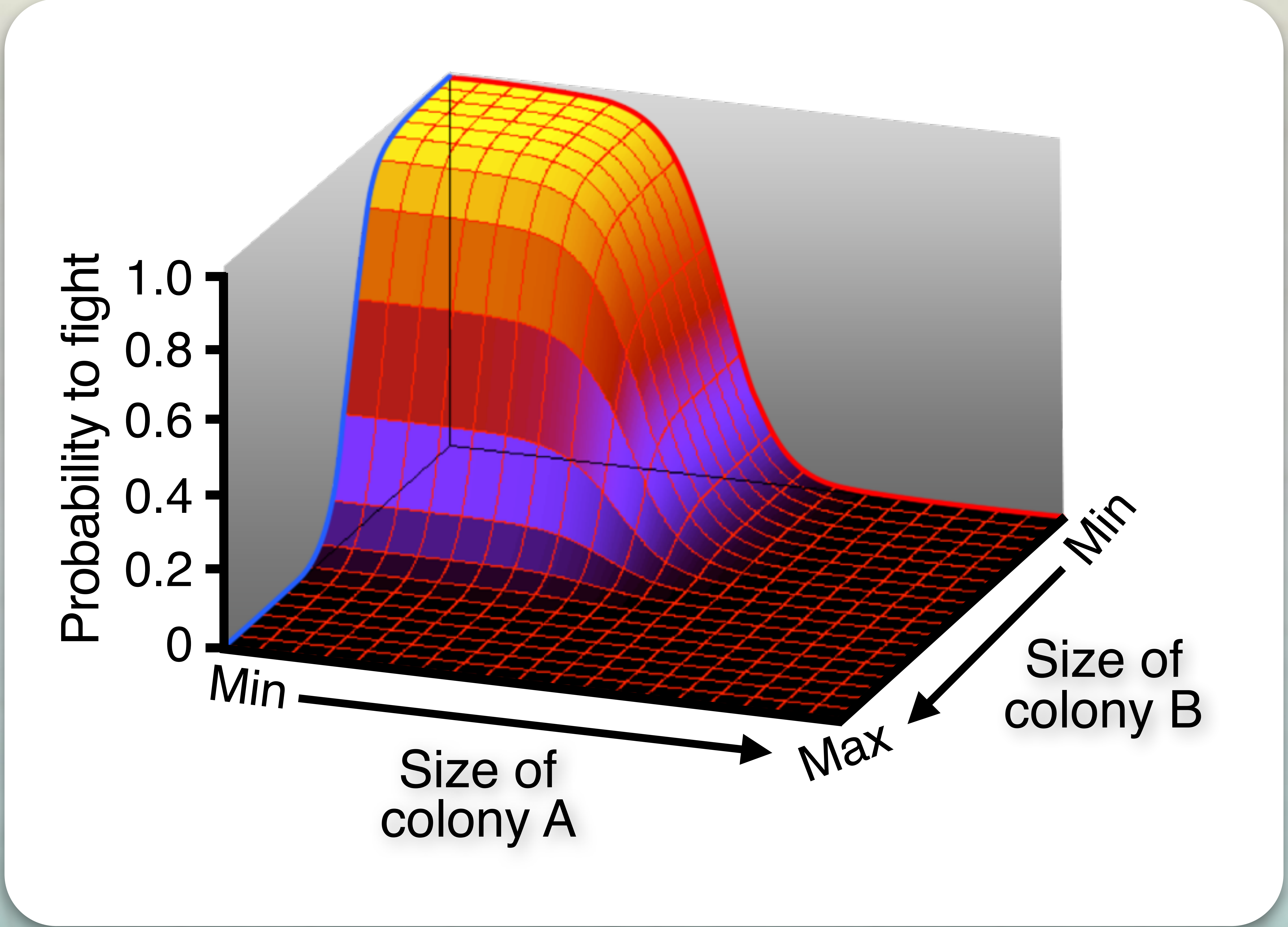

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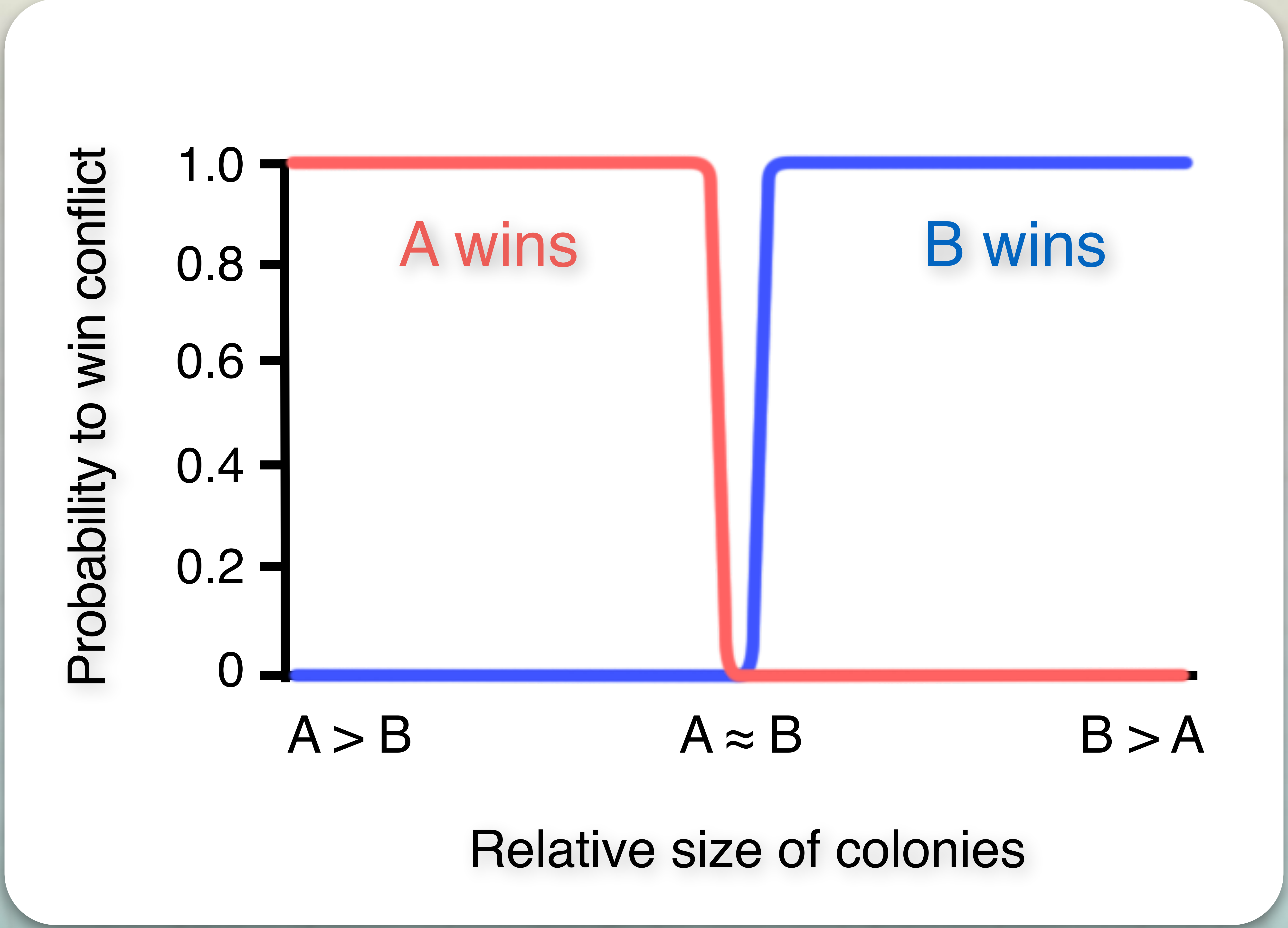

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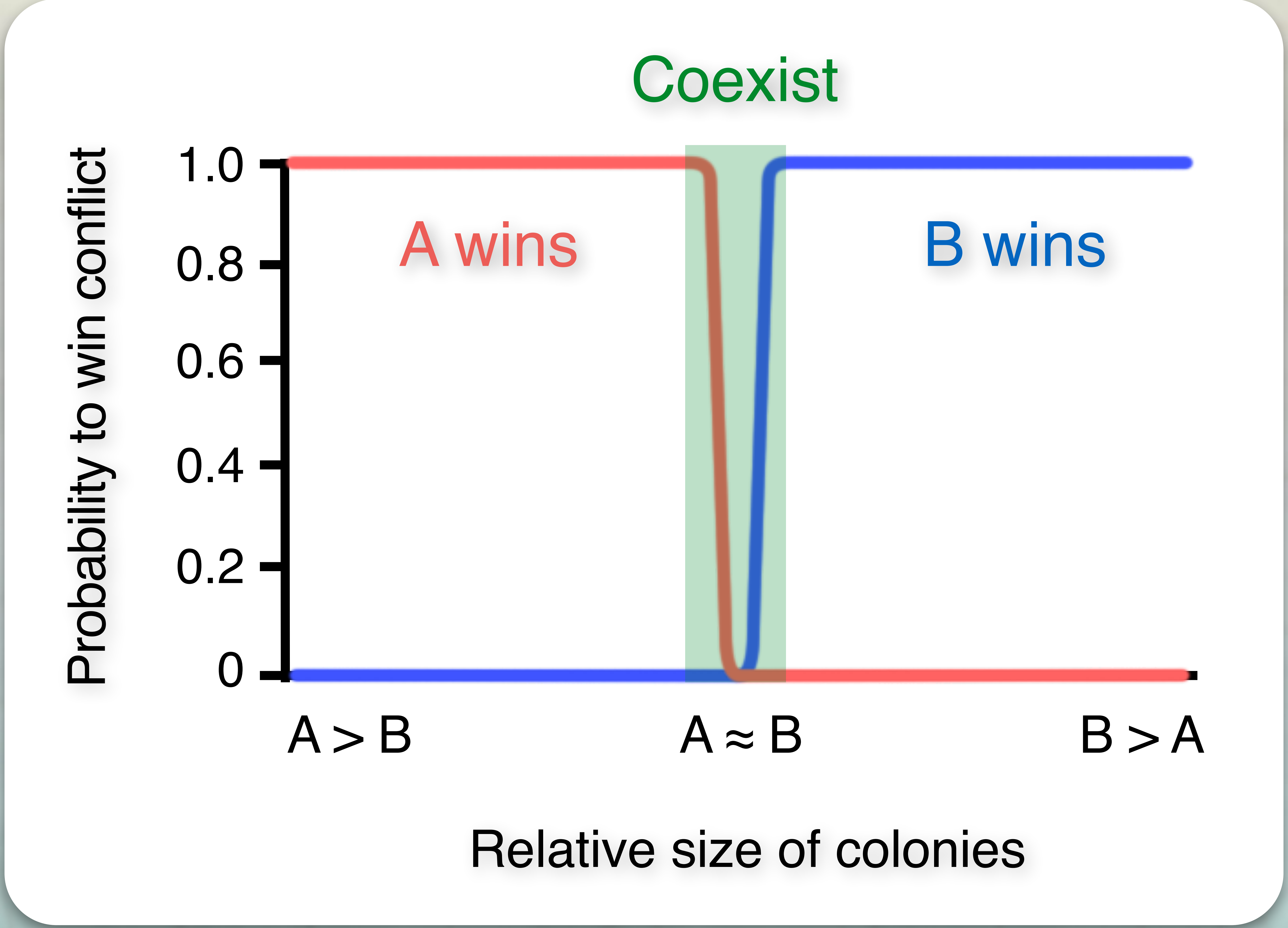
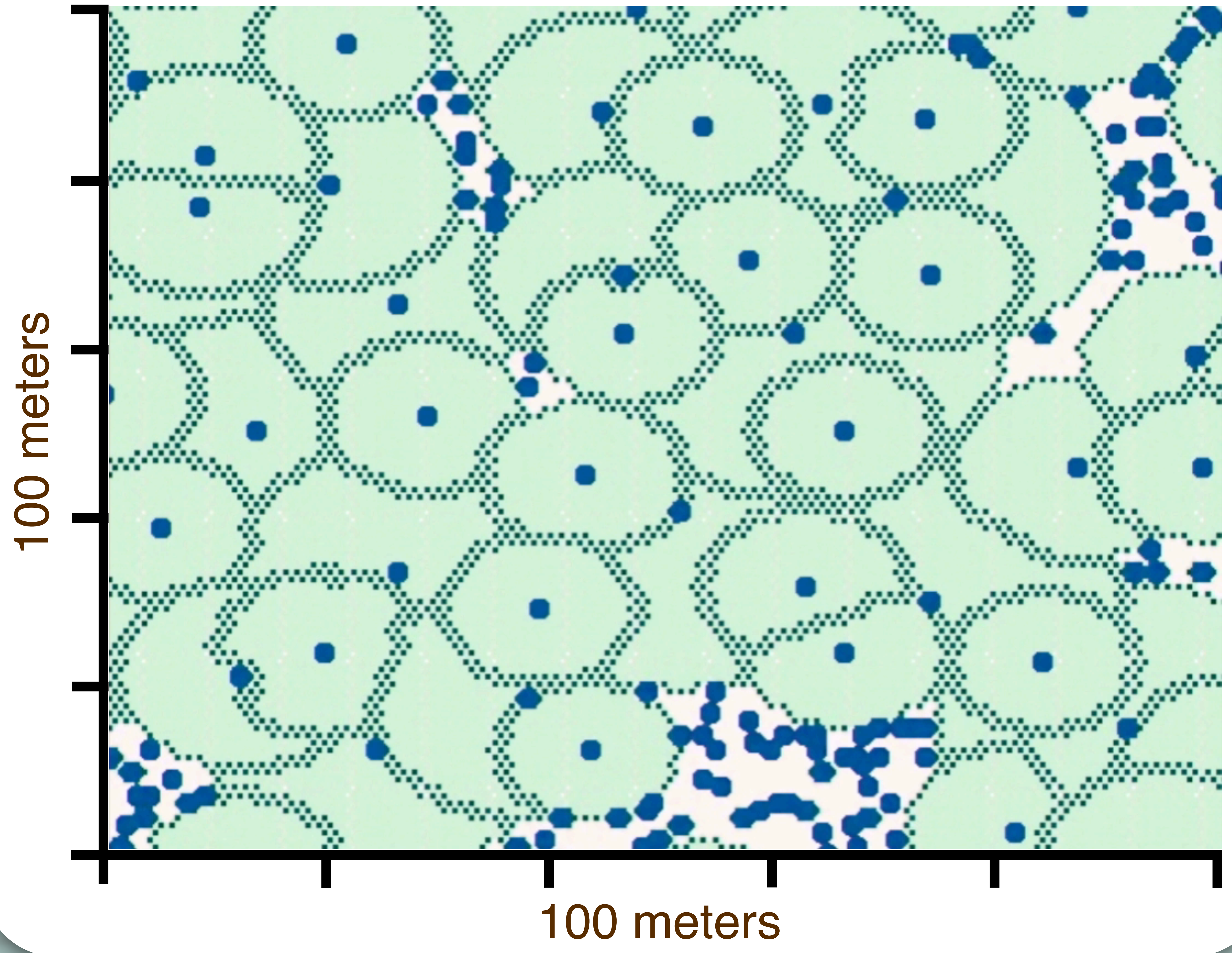
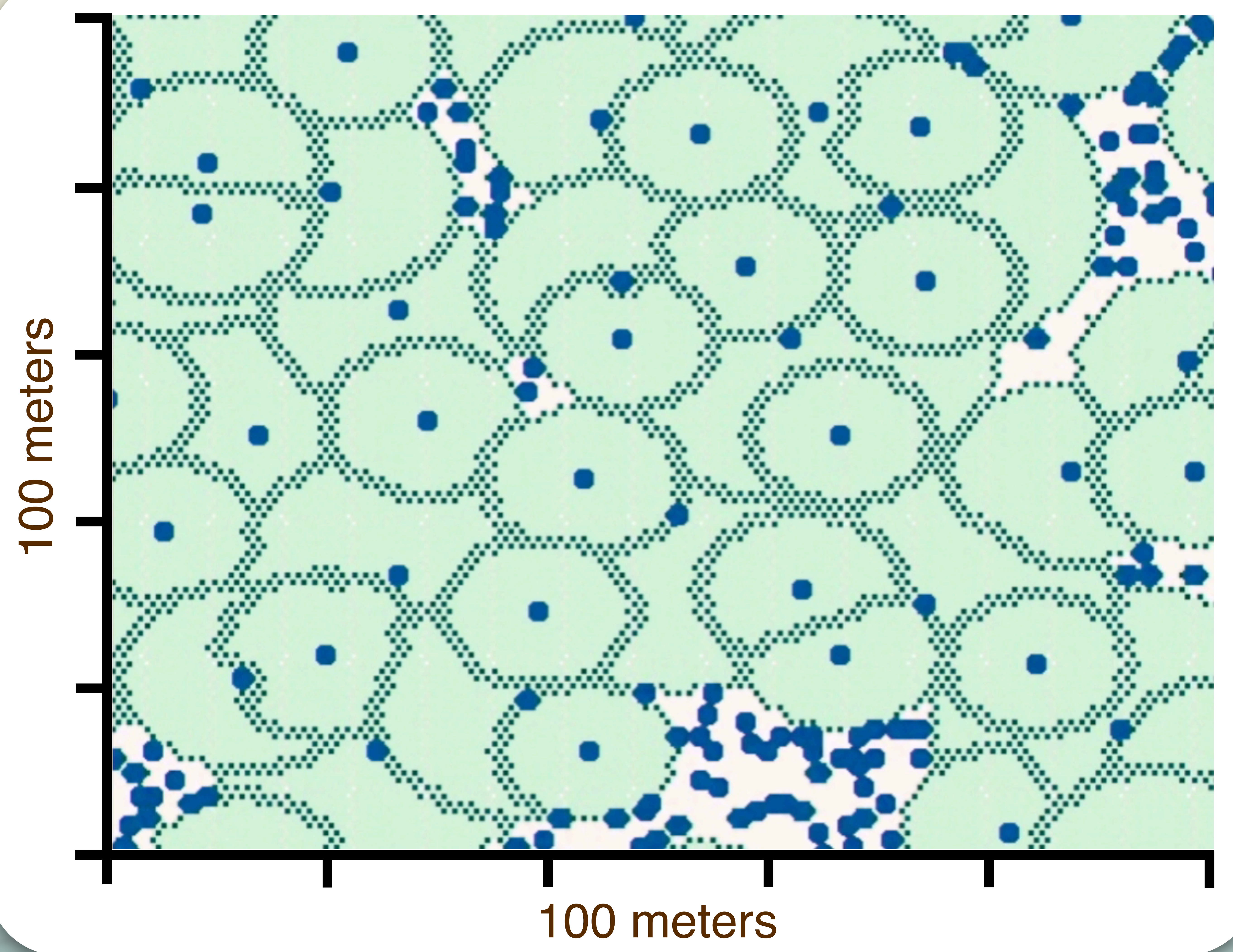


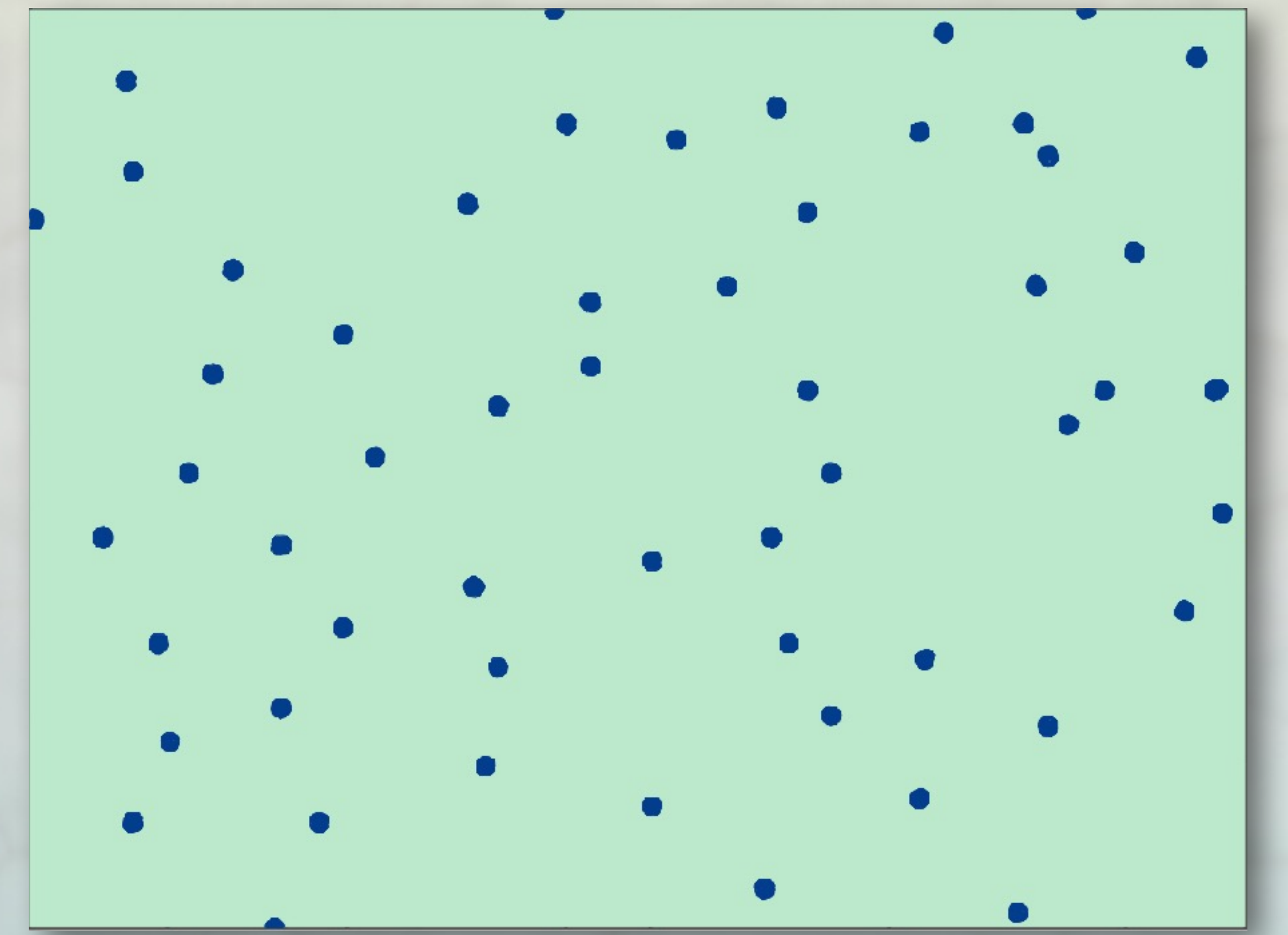
Dynamics

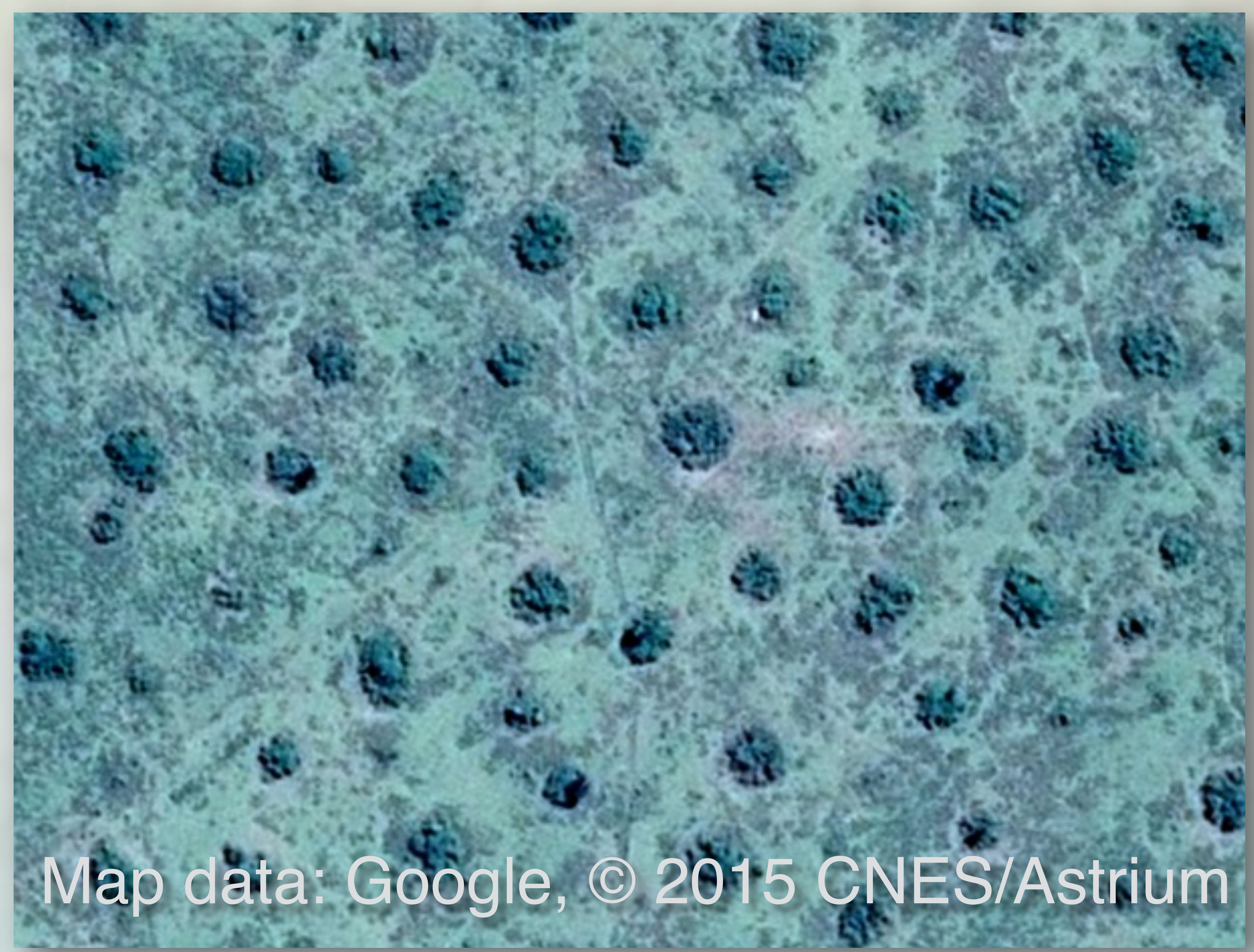


Dynamics

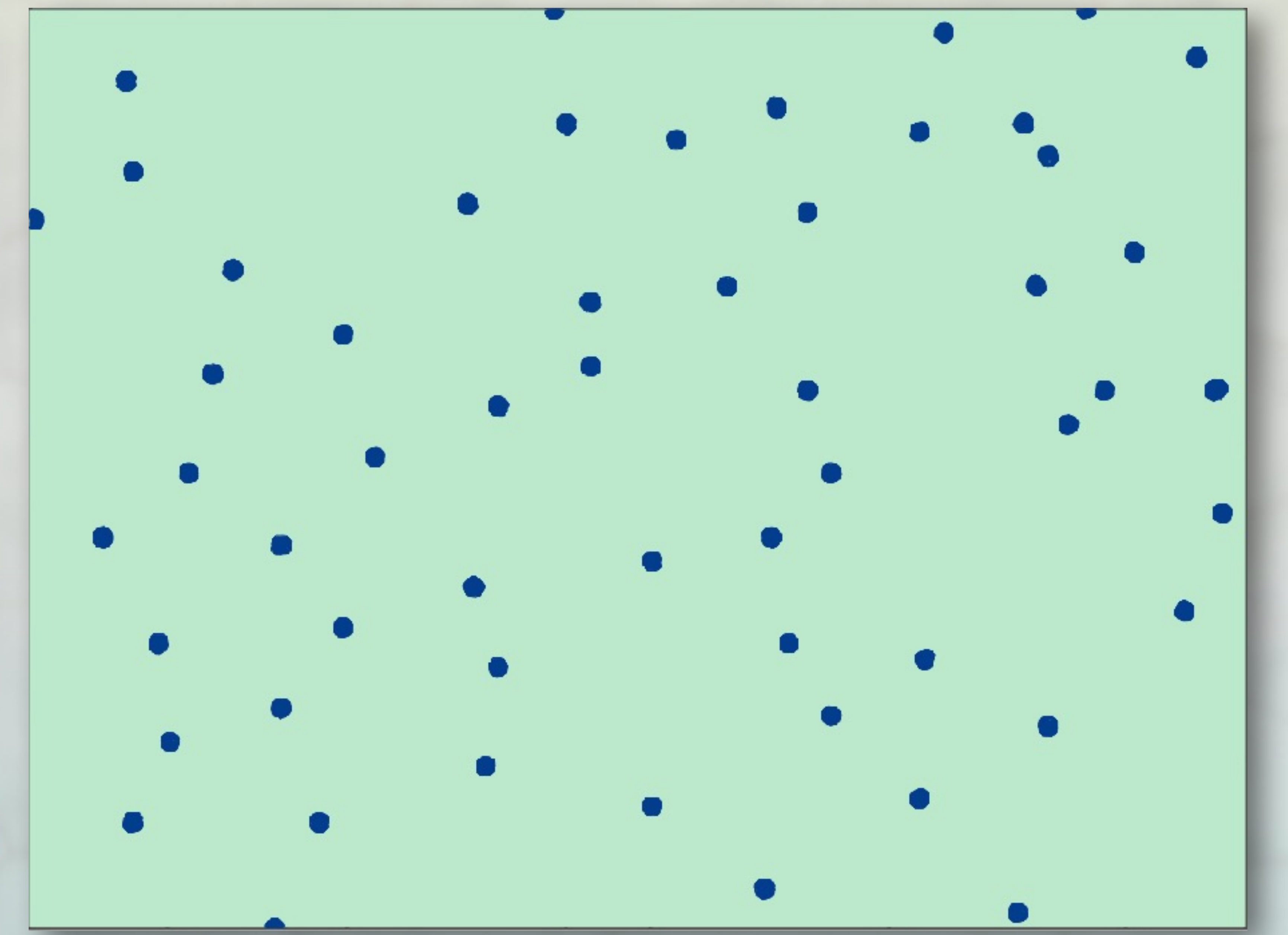


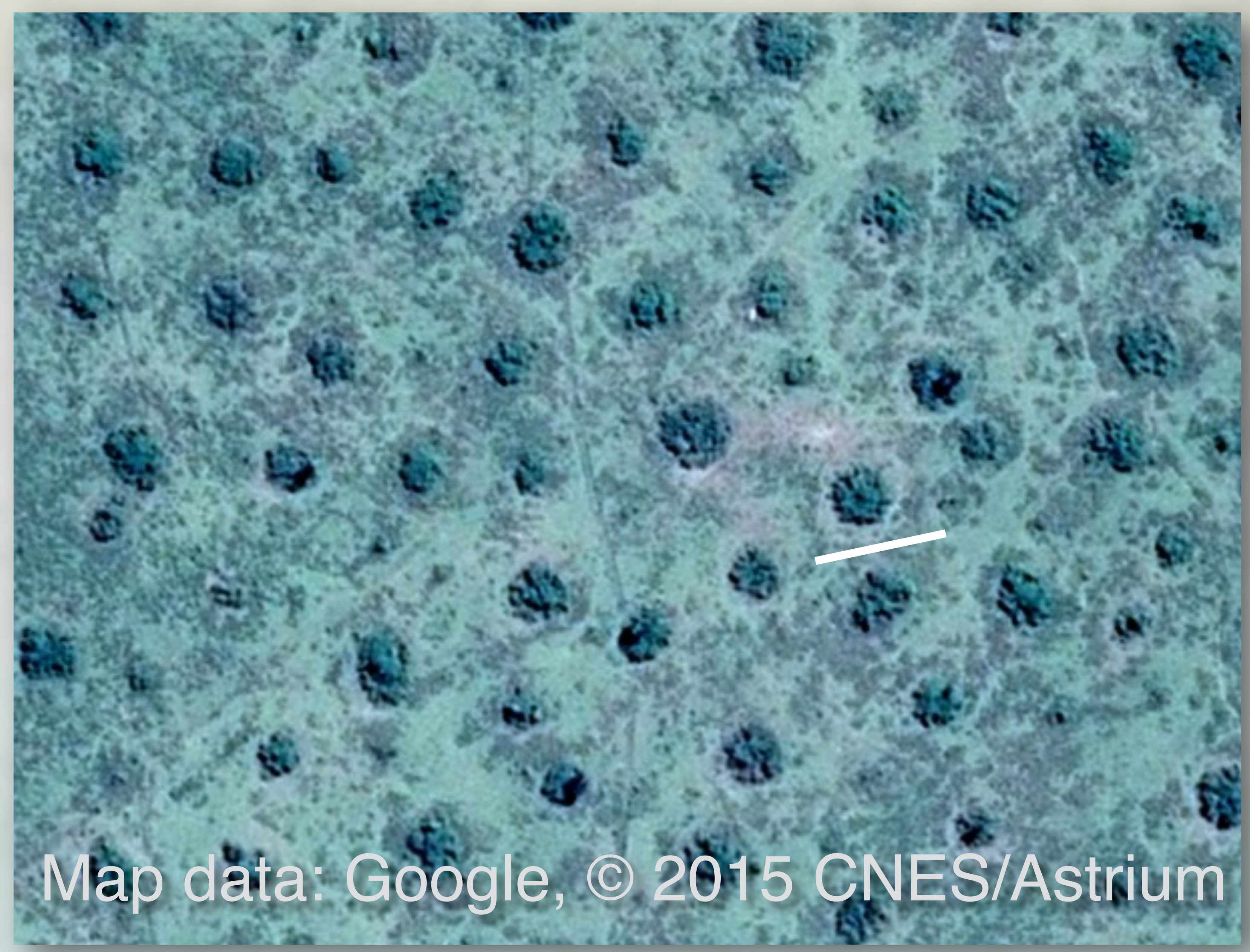
Competition and Conflict Result in Pattern: But Is It Similar To The Natural Pattern?





Spatial Statistics: A Voronoi Diagram Allows Comparison Between Patterns





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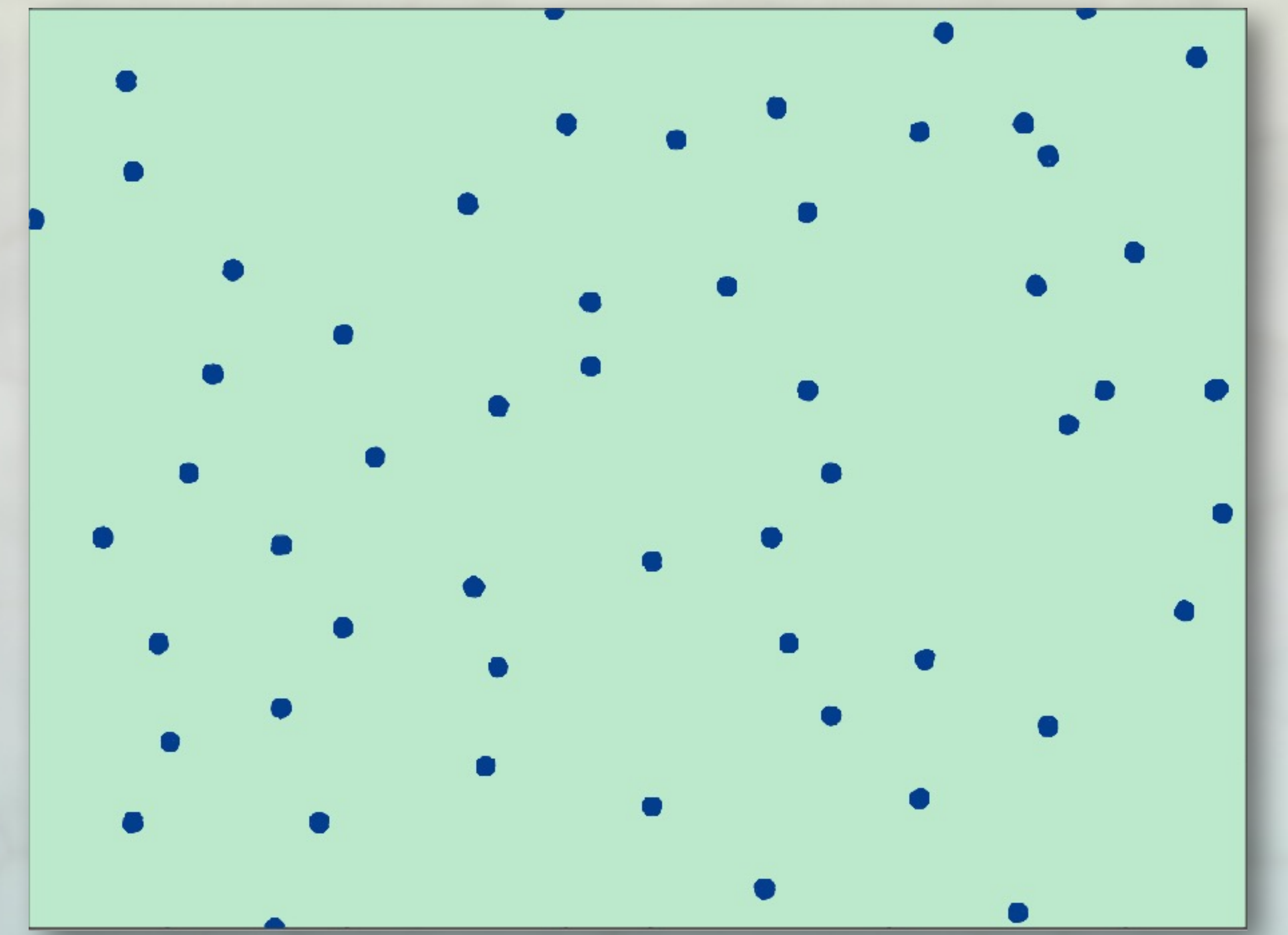

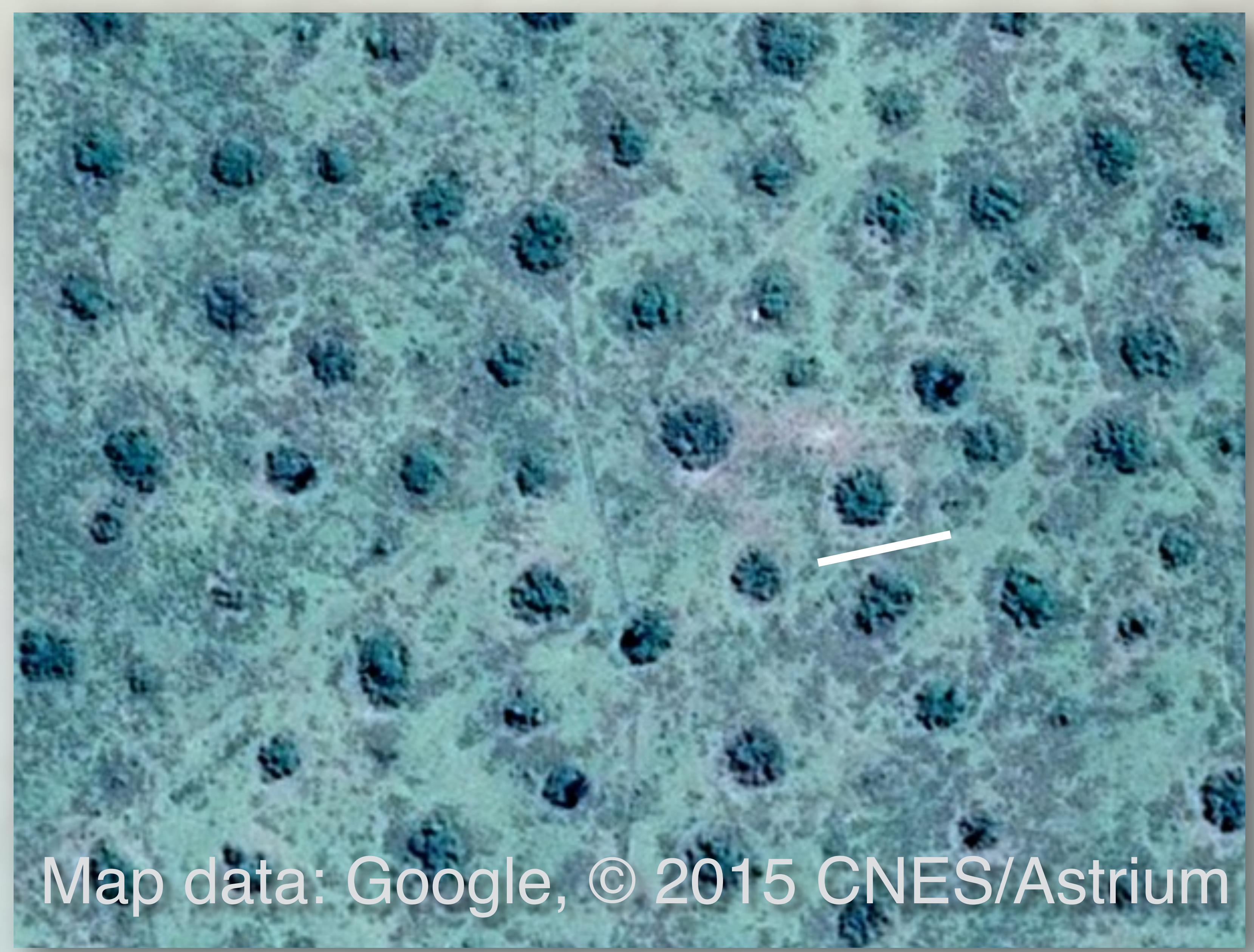

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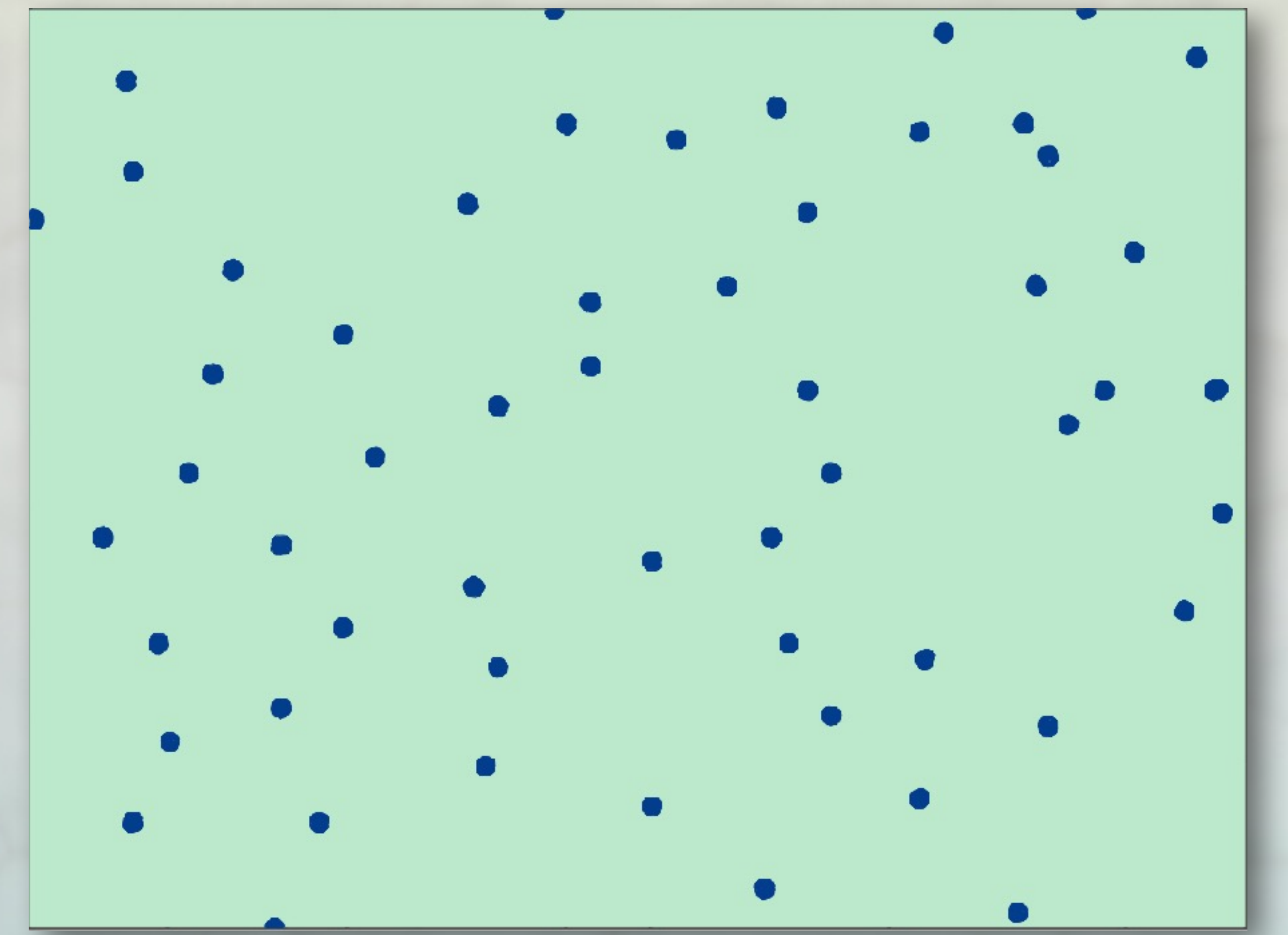

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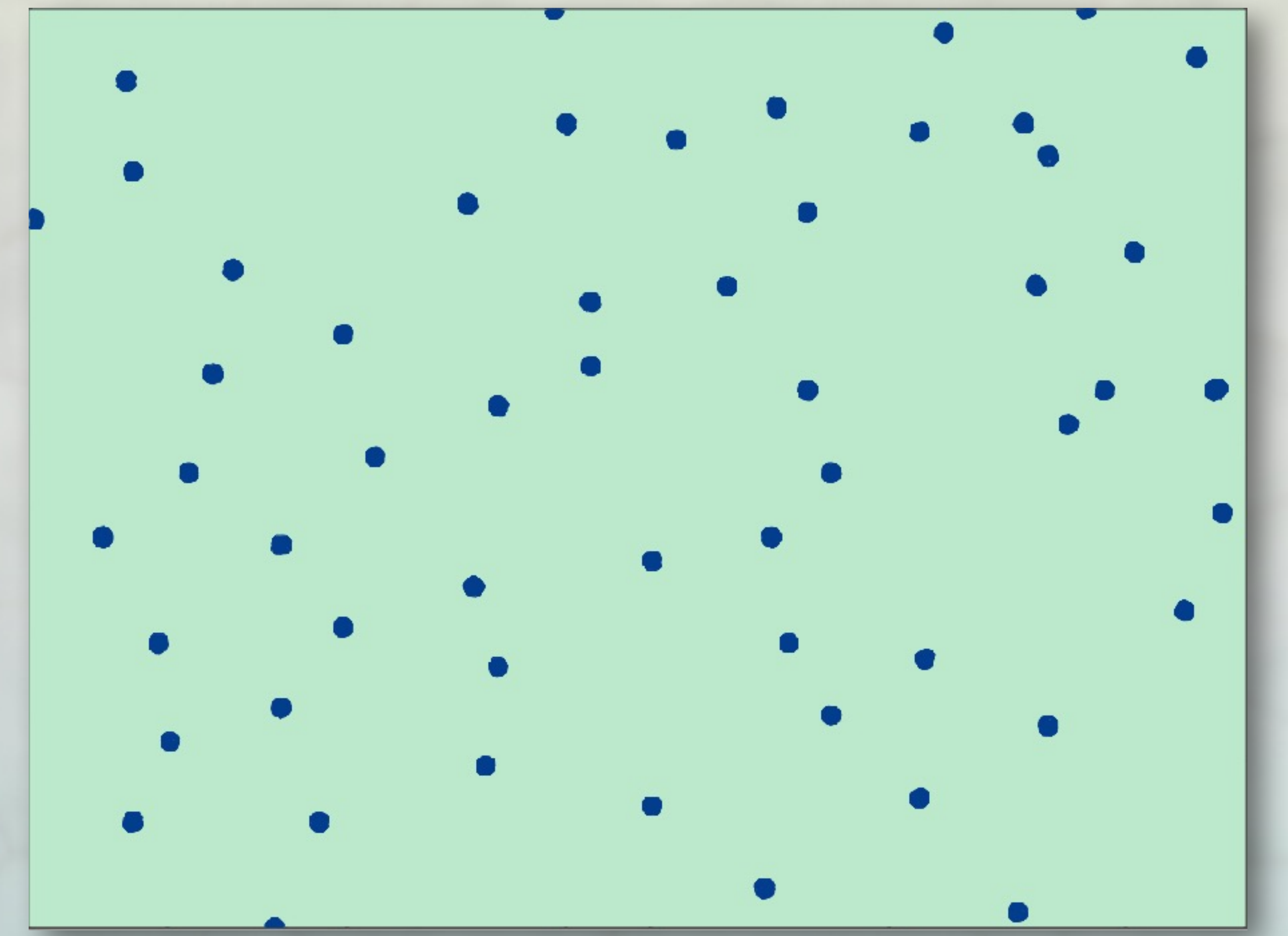

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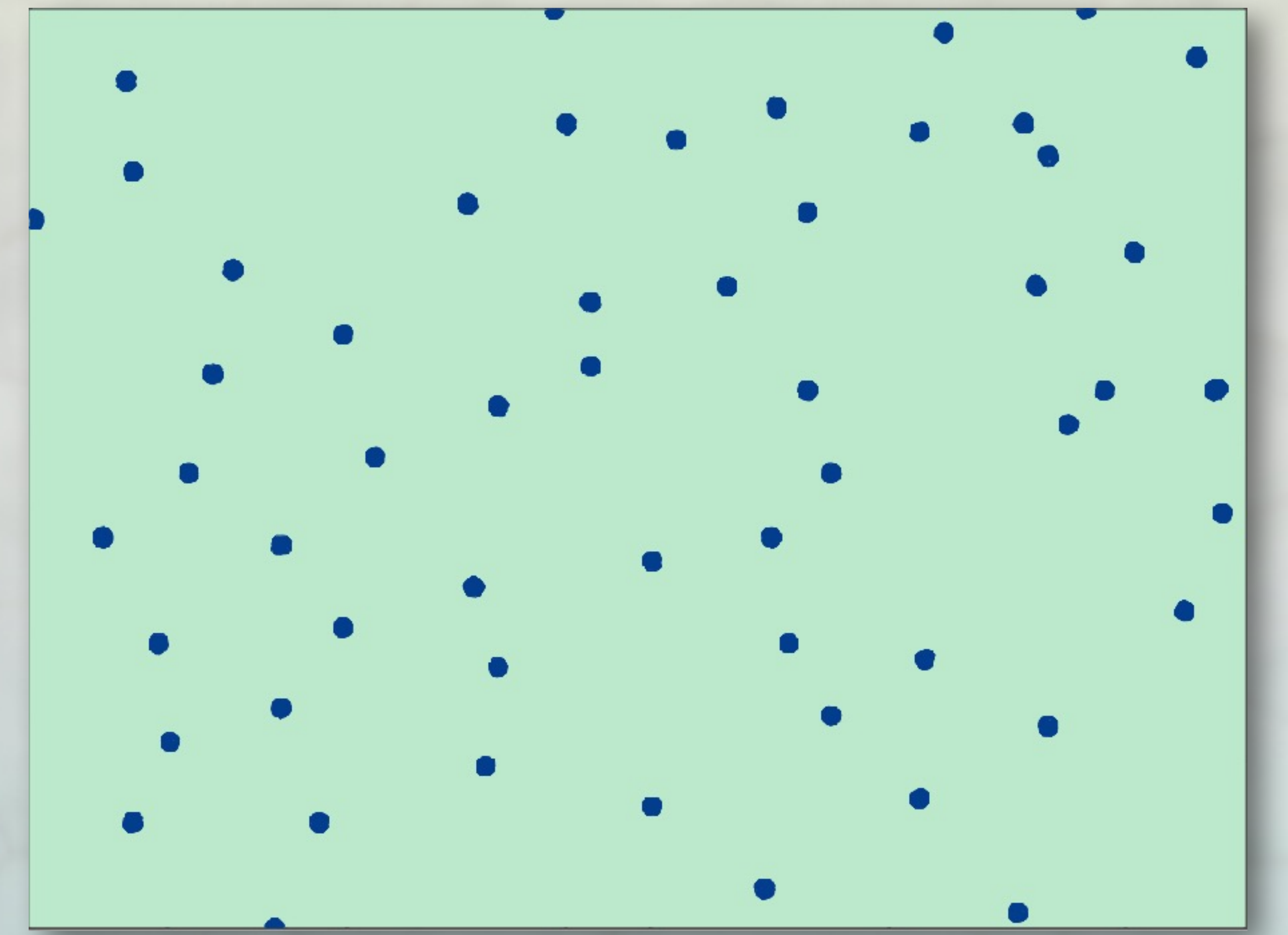

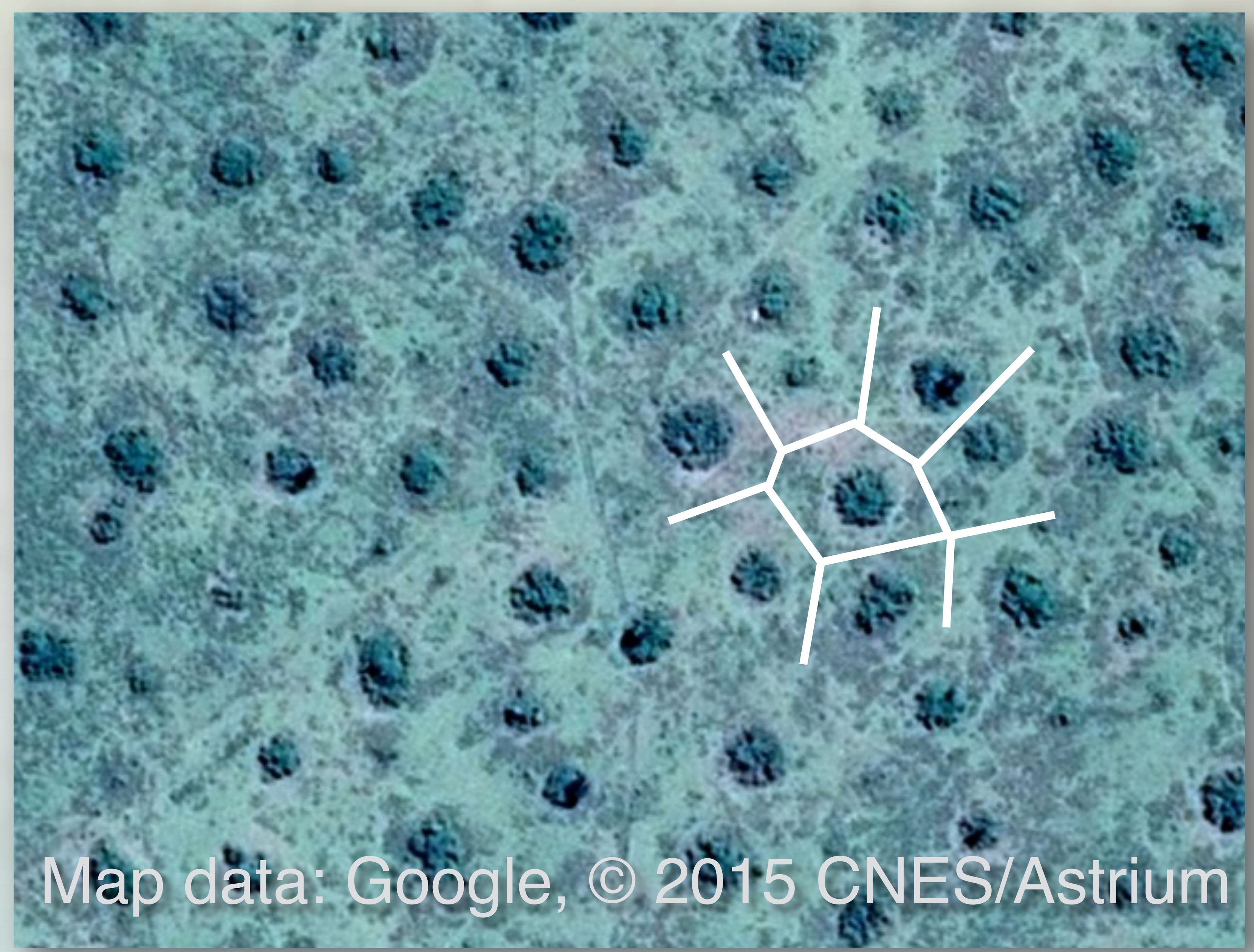

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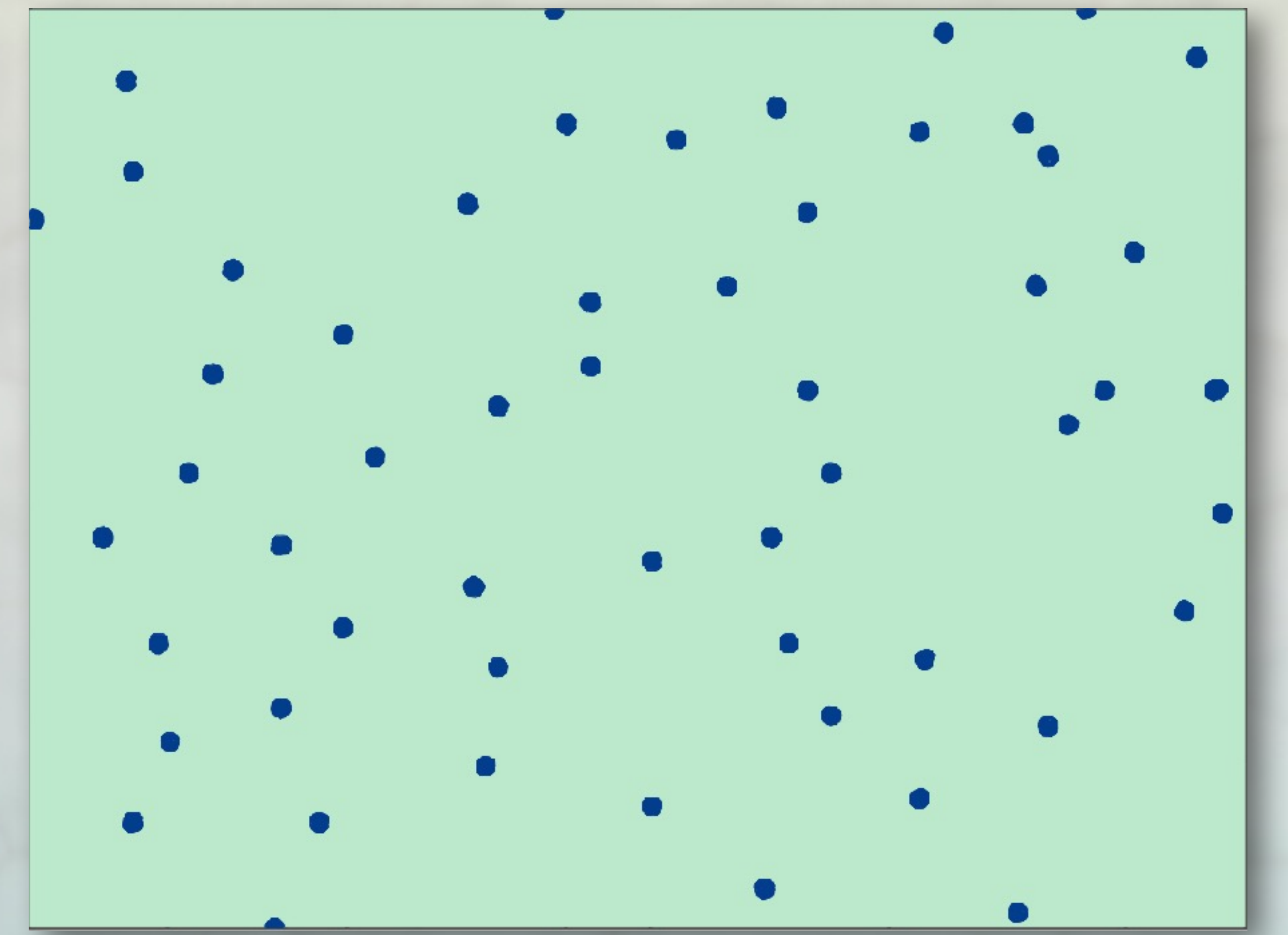

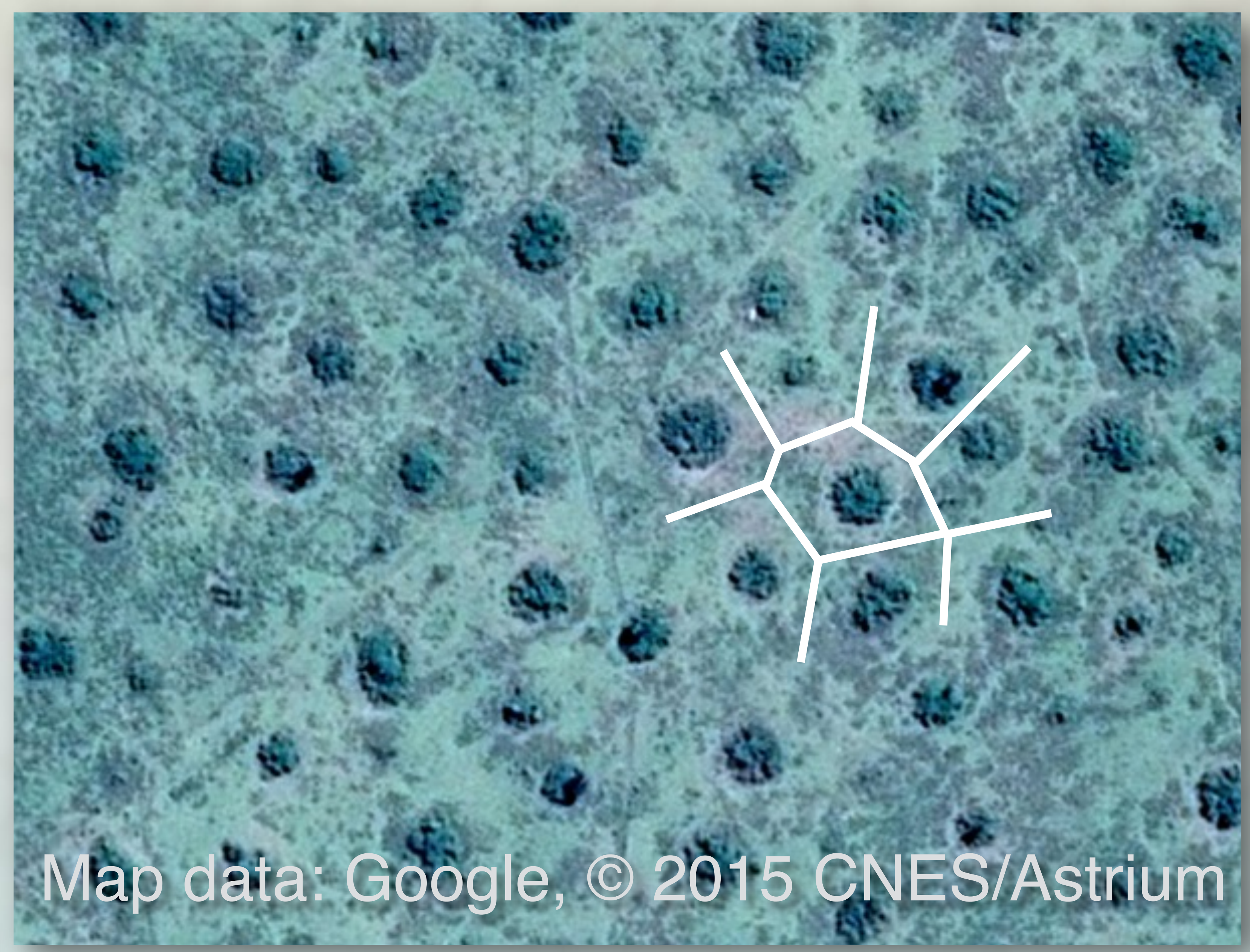

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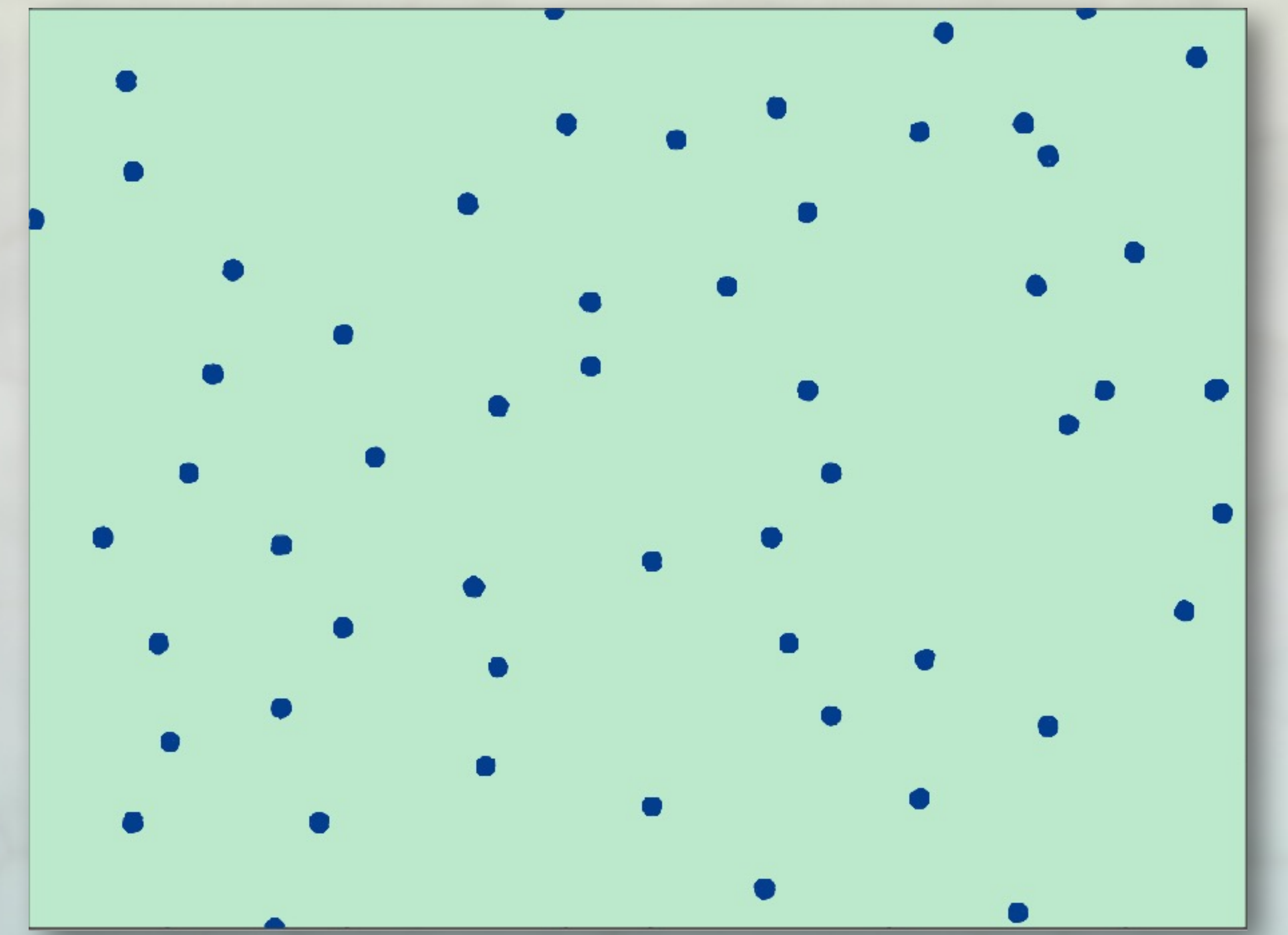

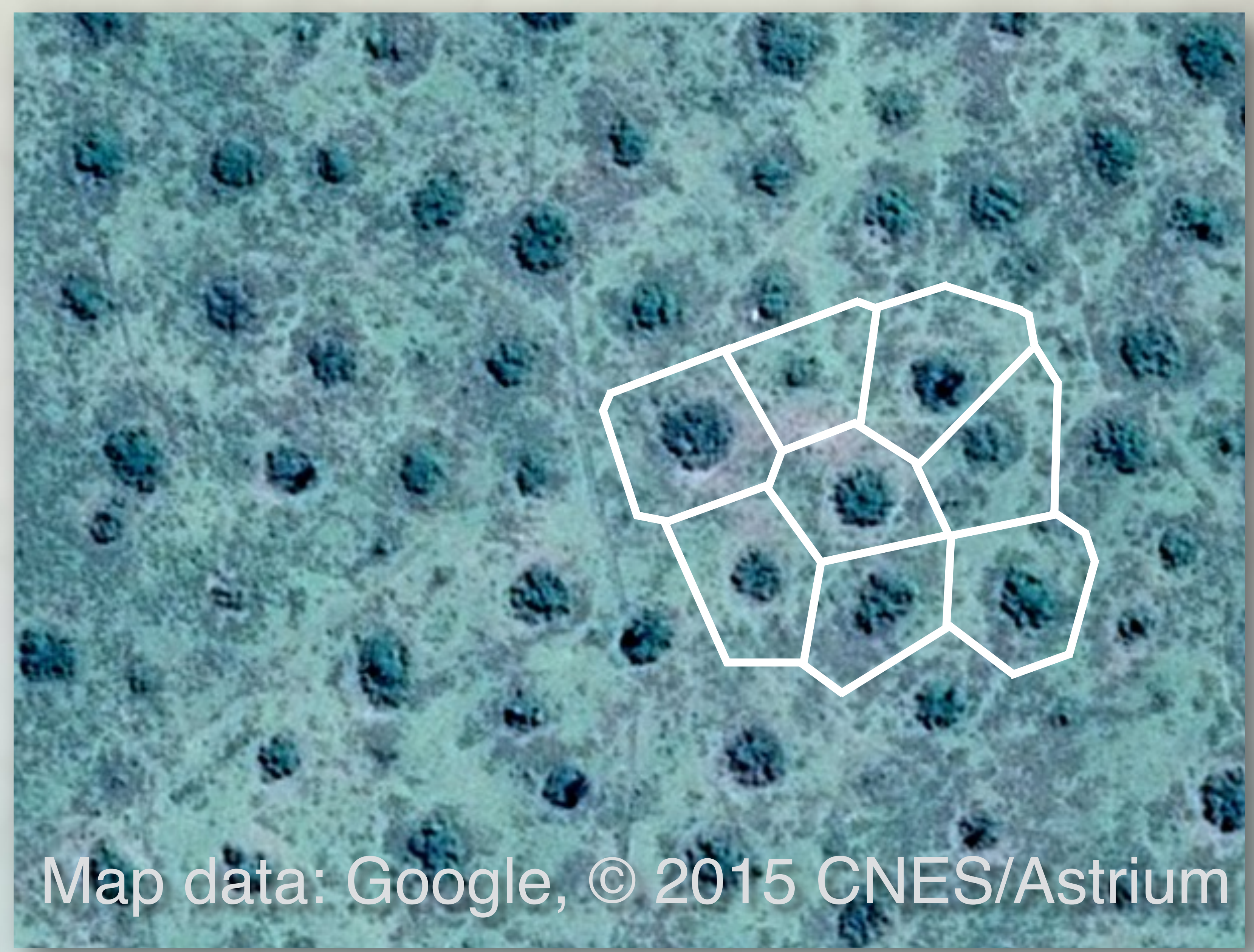

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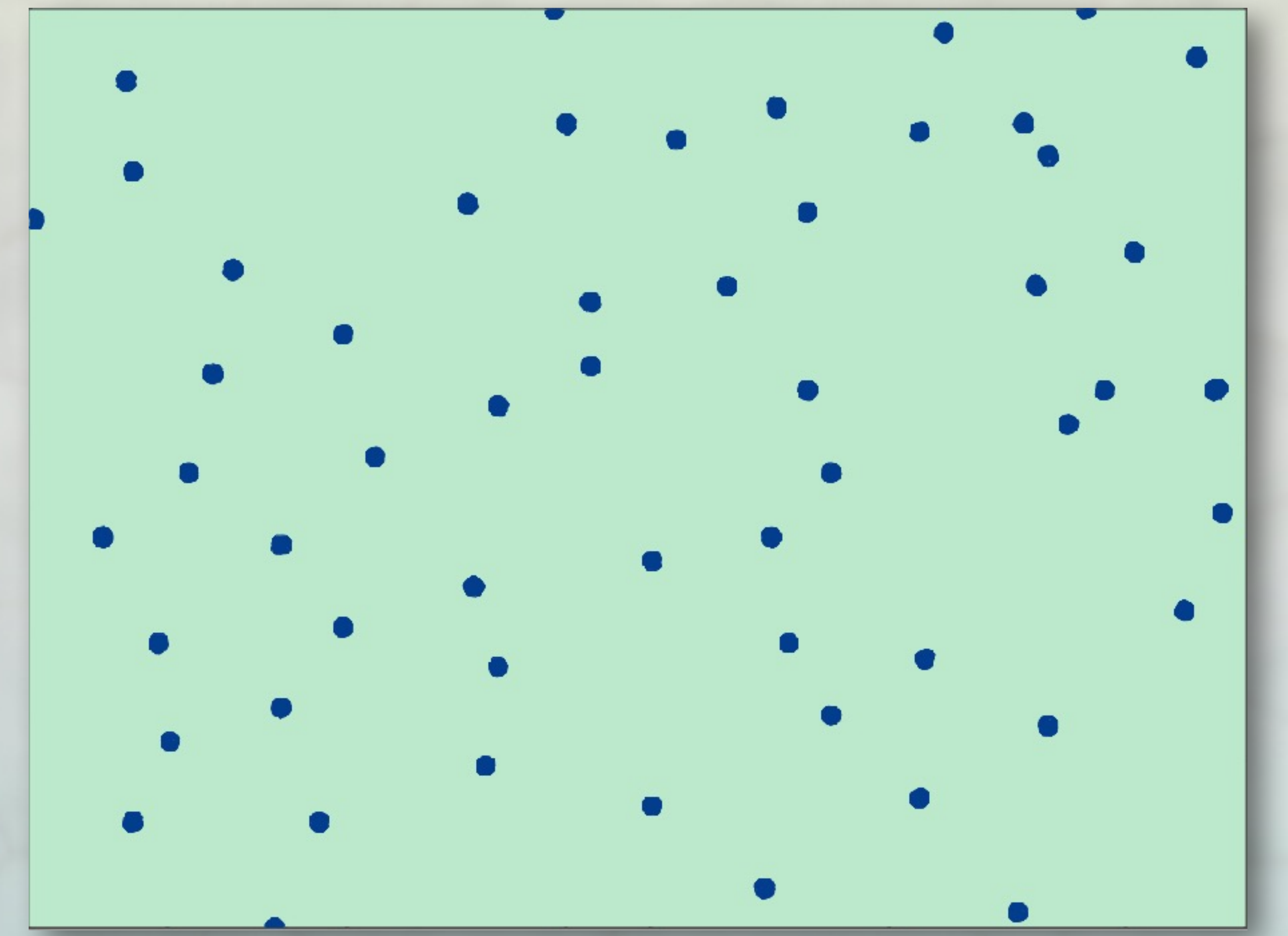
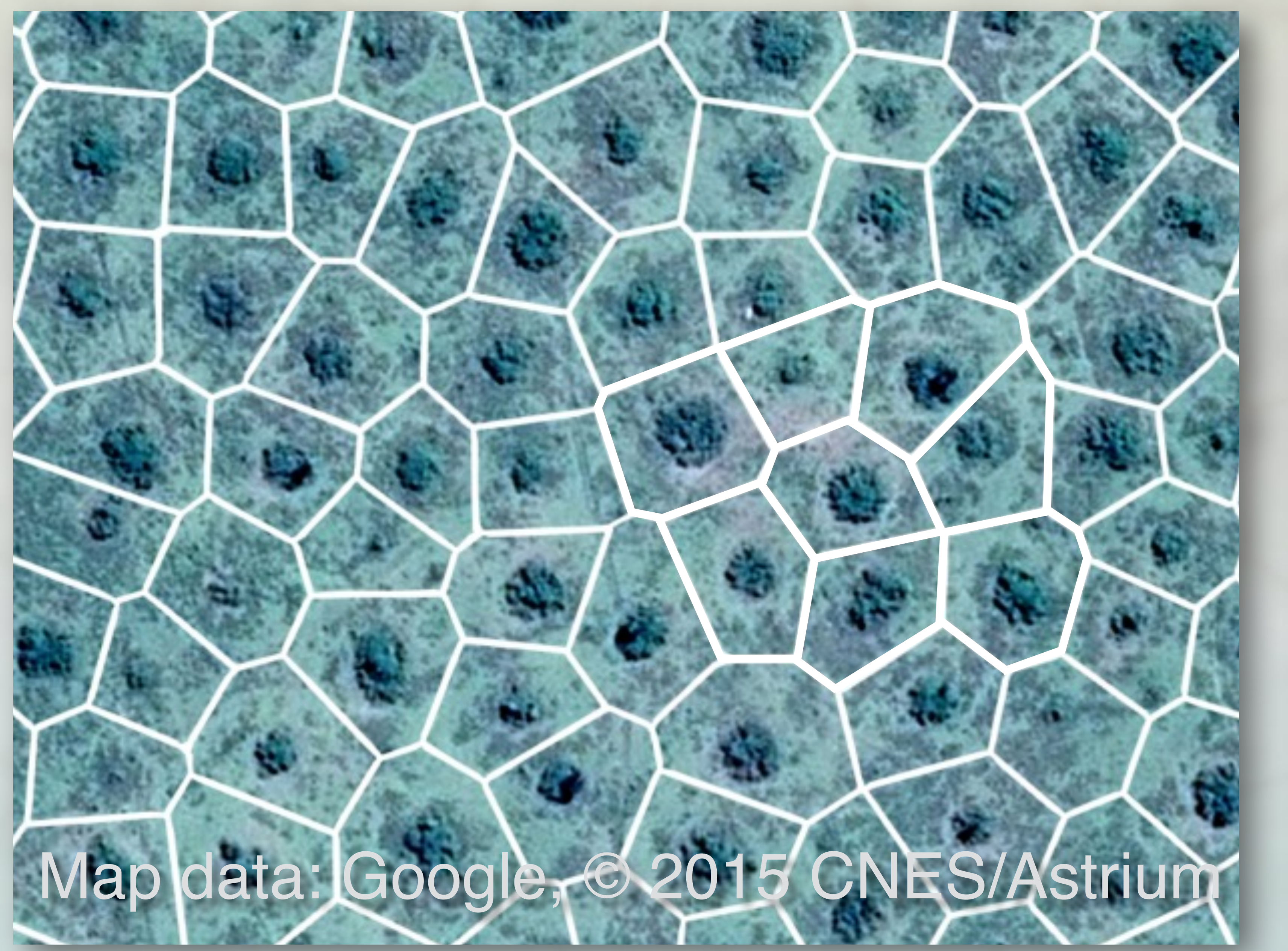
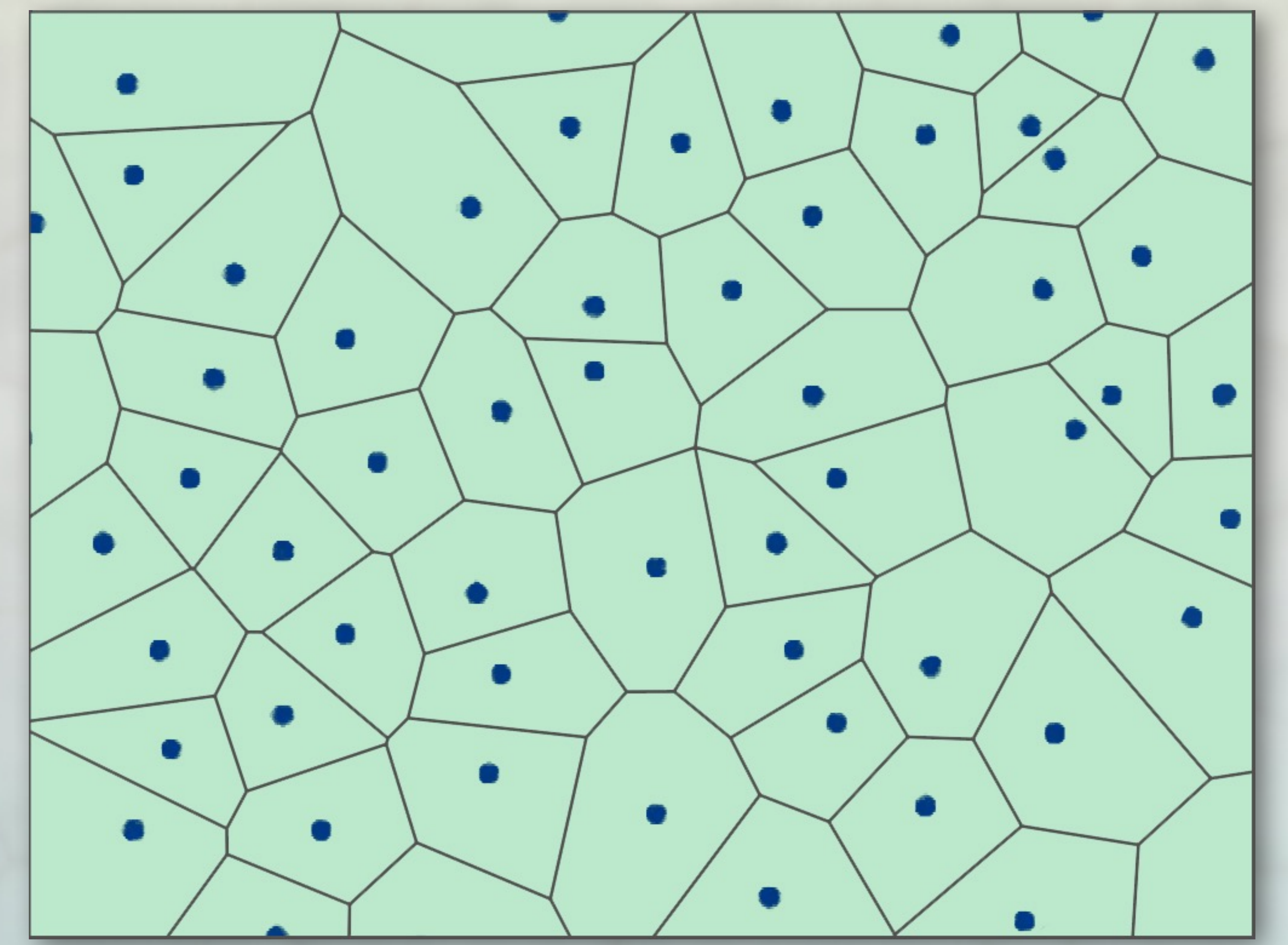
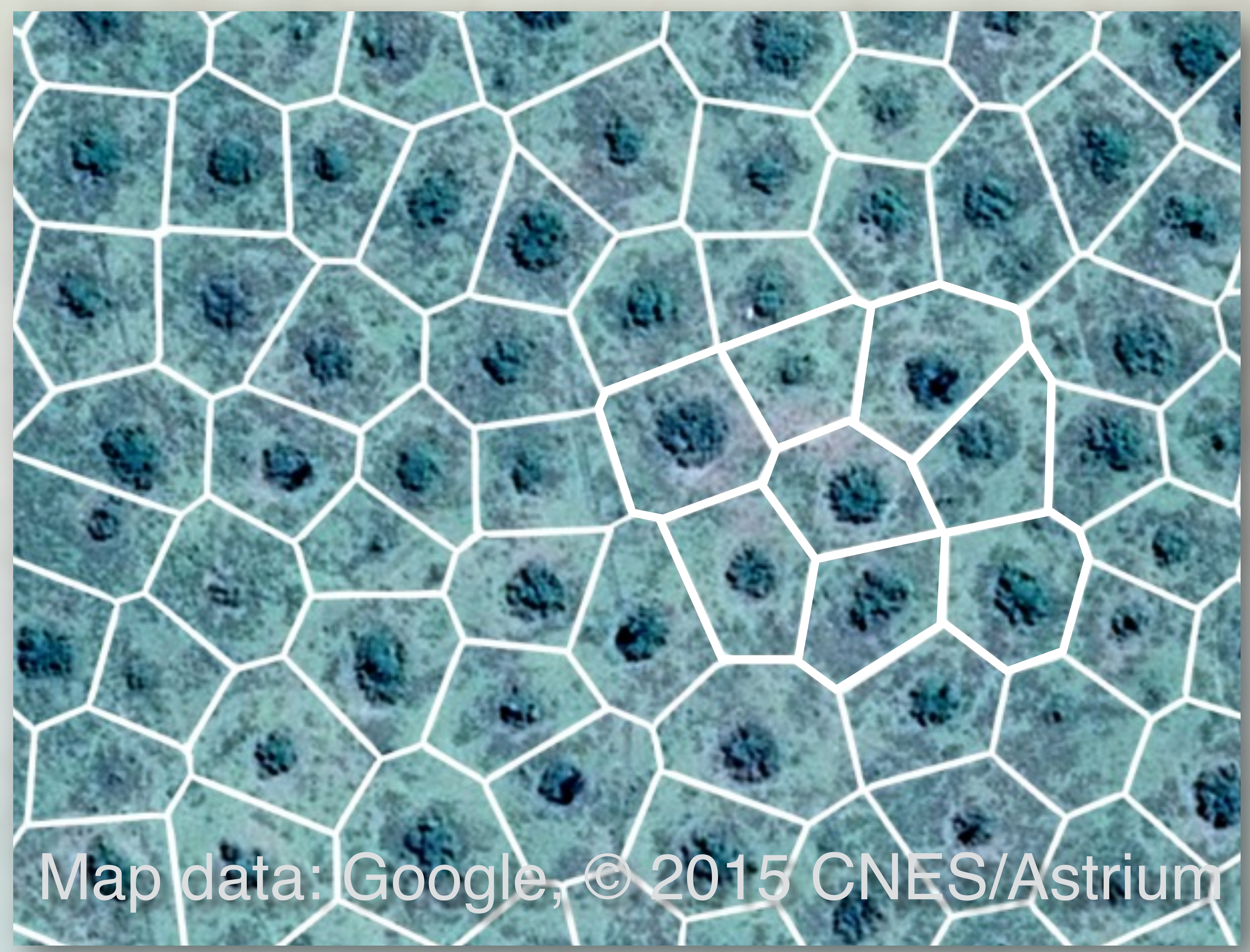




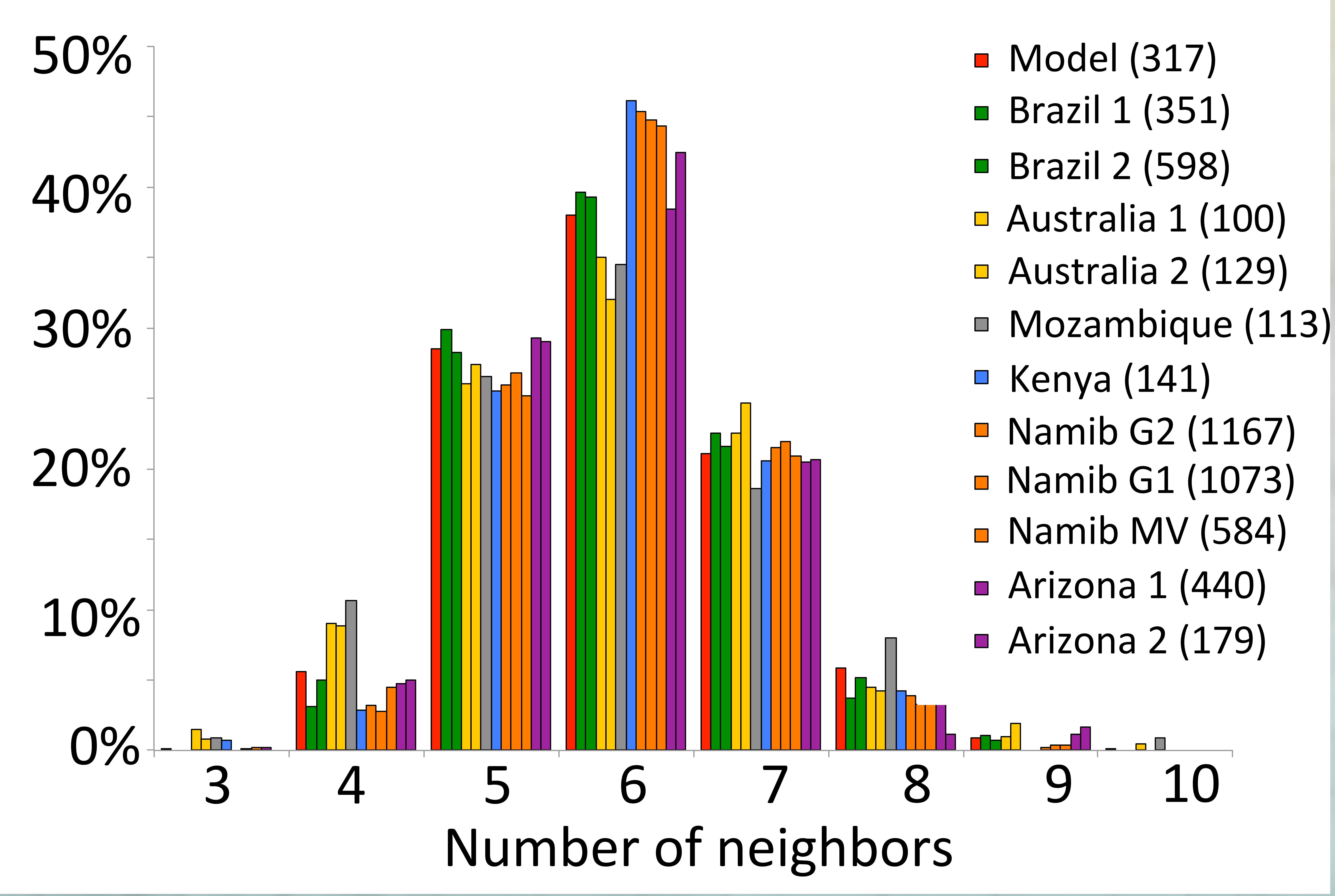
The Regular Pattern of Termite Mounds Arises from Competition and Conflict





Tarnita et al, *in review*

In general, same is true across several continents and different species of social insects



Tarnita et al, *in review*

Does the termite pattern tell us anything about robustness?

Does the termite pattern tell us anything about robustness?

And what happens if both mechanisms coexist?

$$\frac{\partial P}{\partial t} = c \times g_{\max} \times \frac{W}{W + k_1} \times P - d \times P + D_p \Delta P,$$

$$\frac{\partial W}{\partial t} = \alpha \times O \frac{P + k_2 \times W_0}{P + k_2} - g_{\max} \times \frac{W}{W + k_1} \times P - r_w \times W + D_w \Delta W,$$

$$\frac{\partial O}{\partial t} = R - \alpha \times O \frac{P + k_2 \times W_0}{P + k_2} + D_o \Delta O,$$

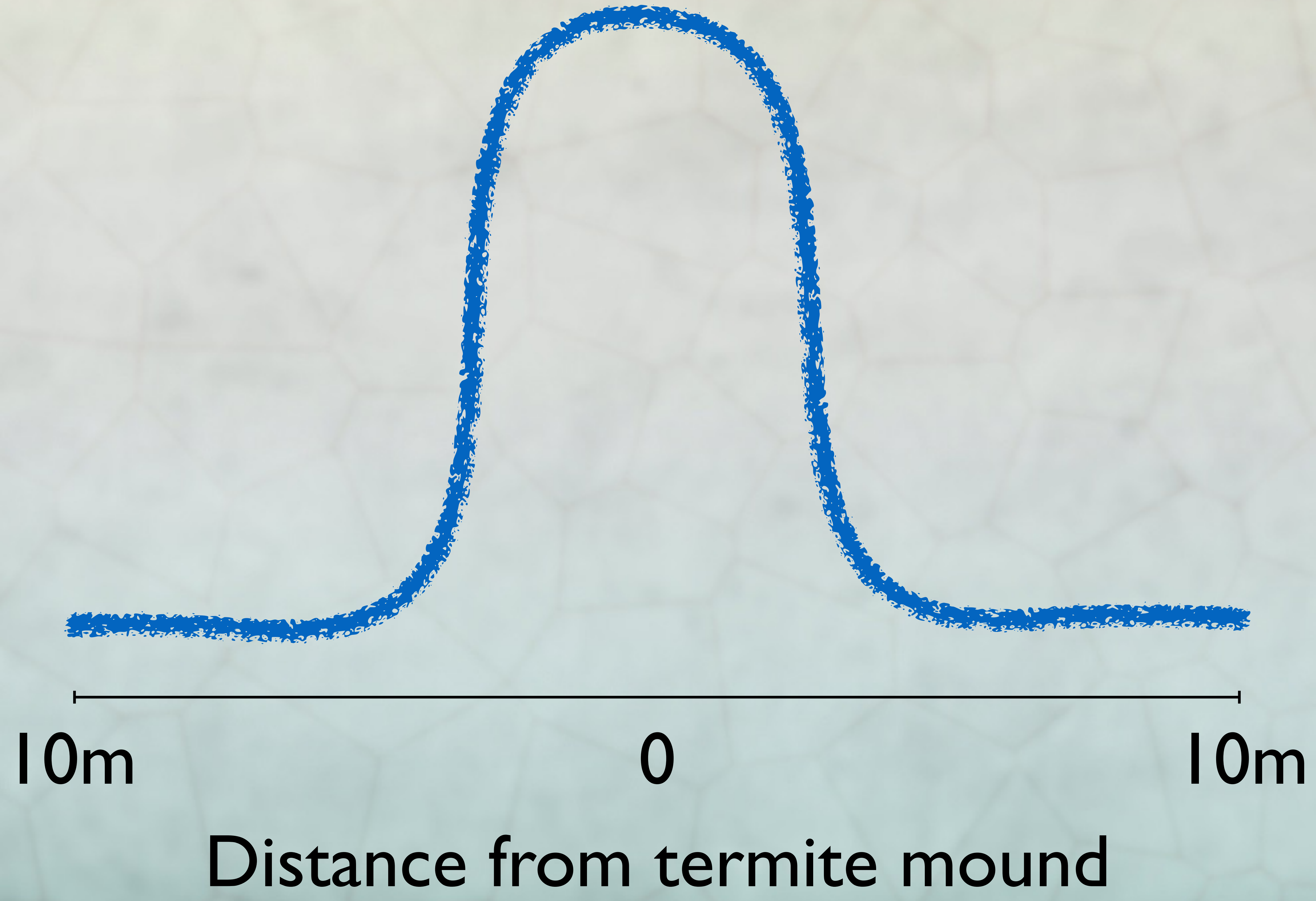
Rietkerk et al 2002, *Am. Nat.*

- c = Yield coefficient for plants (water use efficiency)
- g_{max} = Maximum plant growth rate.
- k_1 = Growth efficiency for plants growing on water as limiting nutrient.
- d = Plant mortality rate.
- r_w = Evaporation/loss rate for underground water.
- alpha = Maximum infiltration rate for the soil.
- k_2 = Infiltration efficiency of the soil.
- W_0 = With alpha and O, minimum water infiltration in the absence of vegetation
- D_p = Plant dispersion rate.
- D_w = Diffusivity of soil water
- D_o = Diffusivity of surface water

Termite induced heterogeneity in water use efficiency (increase 0-50%) and infiltration efficiency (increase 0-67%)

Simon Levin

Kelly Caylor



Juan Bonachela

$$\frac{\partial P}{\partial t} = c \times g_{max} \times \frac{W}{W + k_1} \times P - d \times P + D_p \Delta P,$$

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Rietkerk et al 2002, *Am. Nat.*

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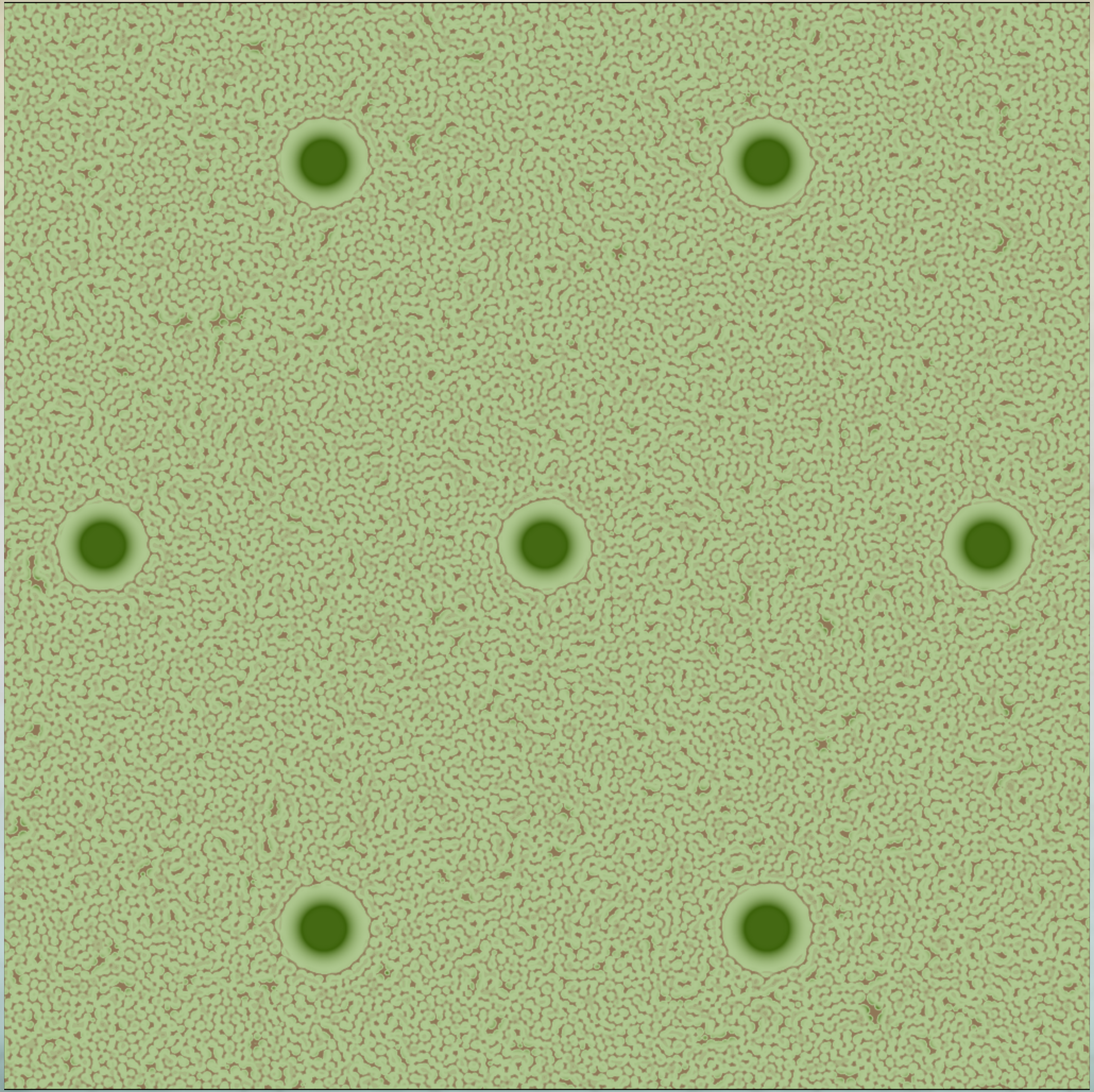
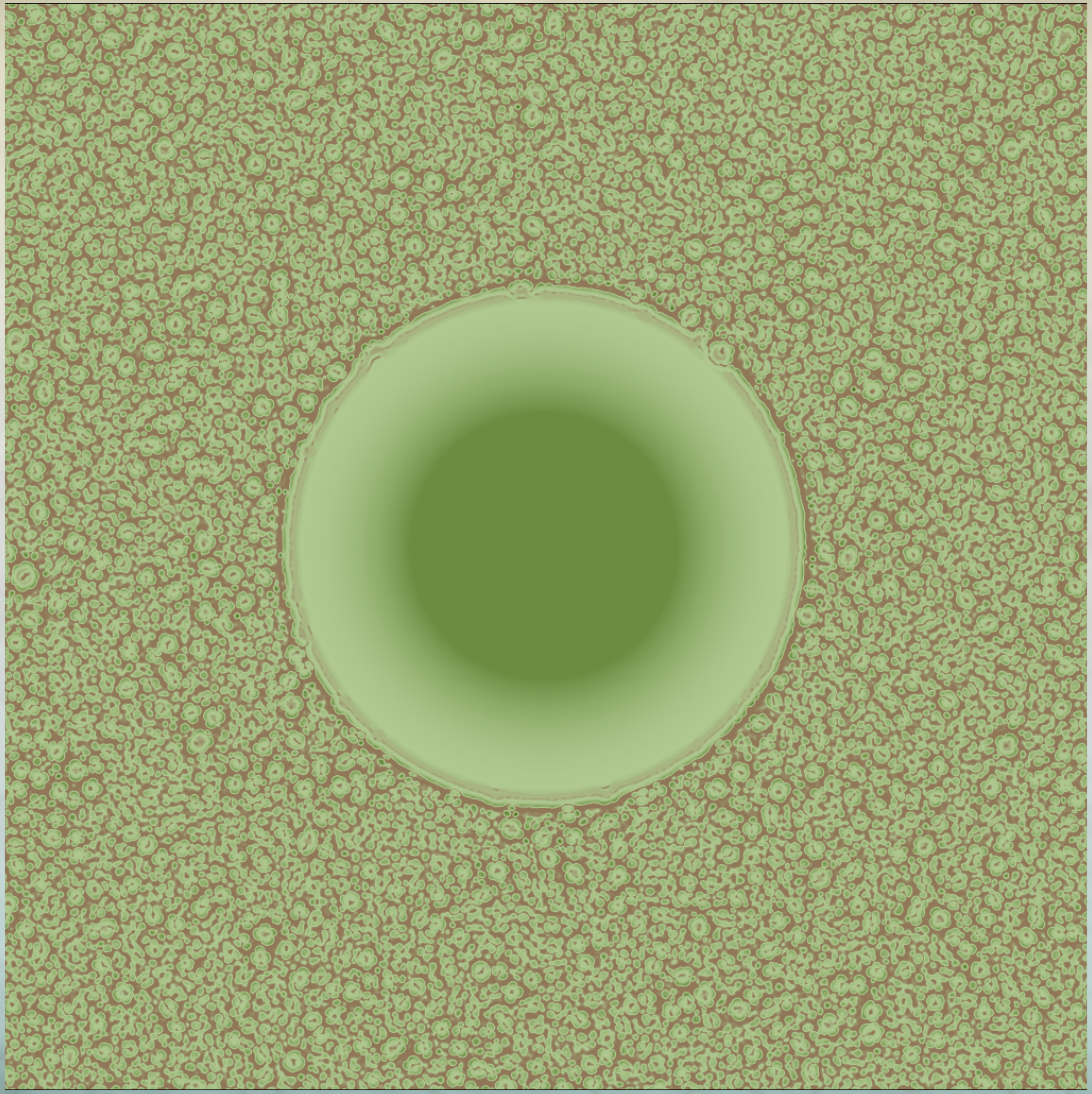
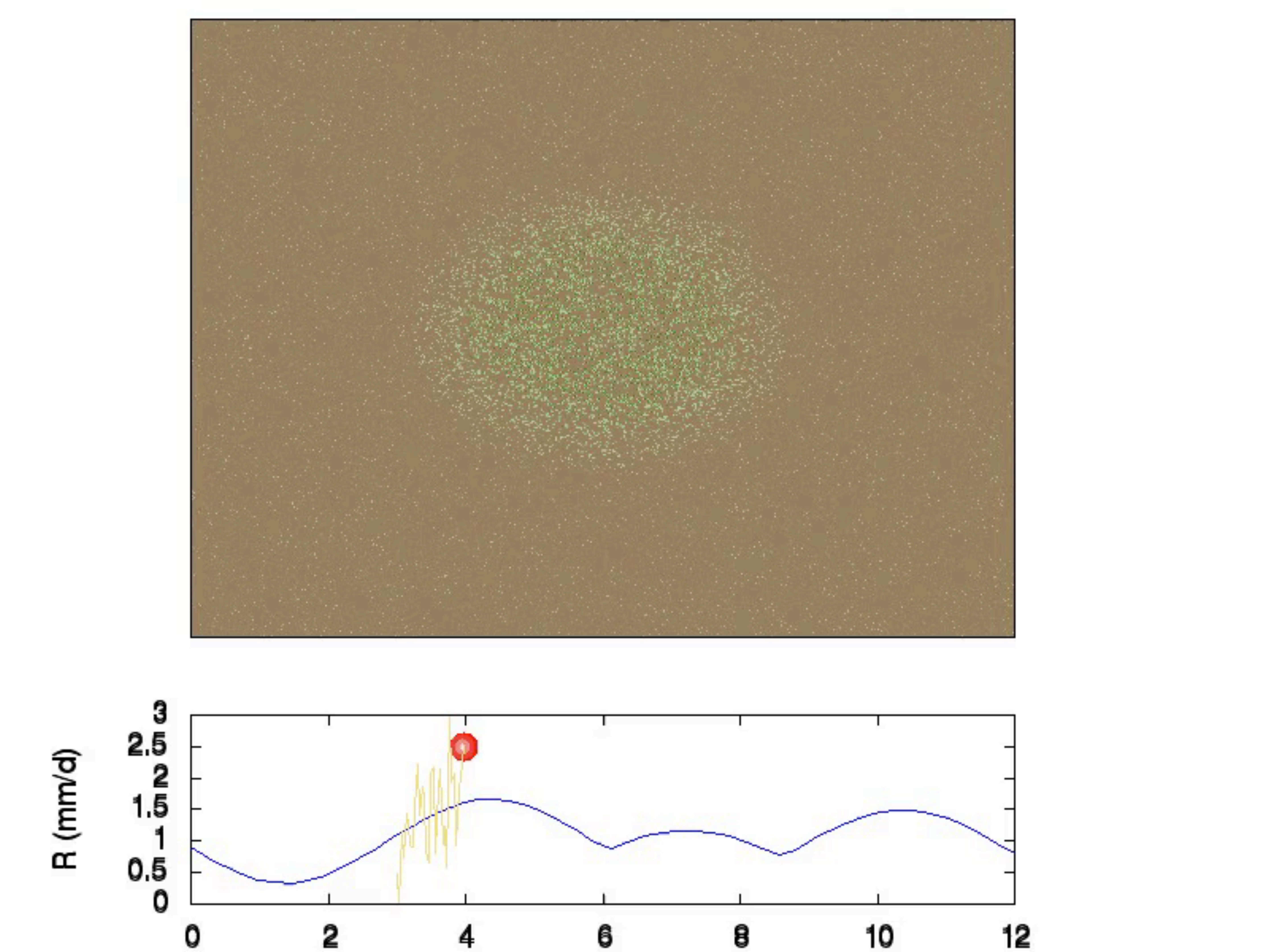
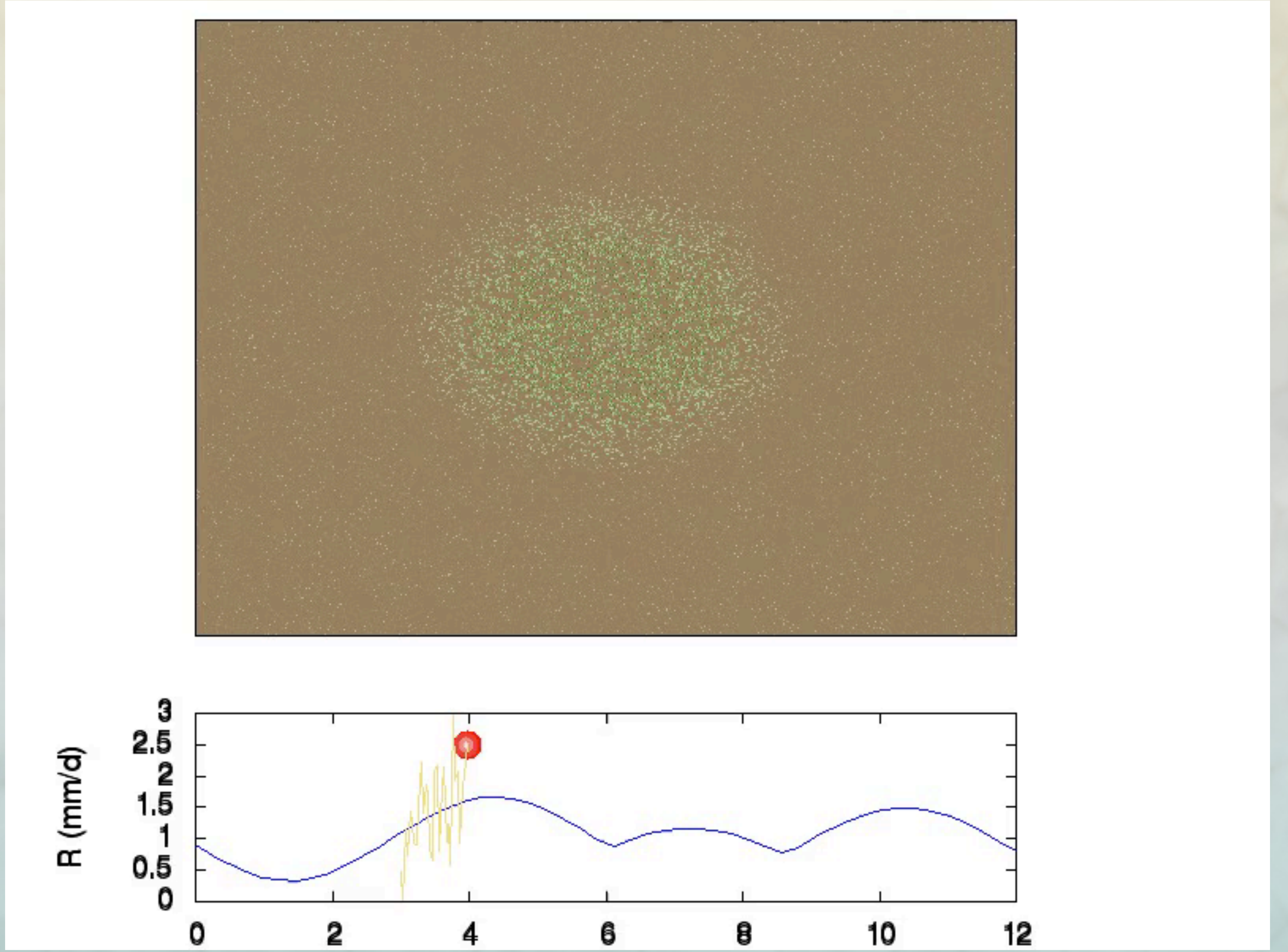
- R = precipitation







Bonachela et al (2015), *Science*



Bonachela et al (2015), *Science*


N
Northwestern Tanzania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Northwestern Tanzania


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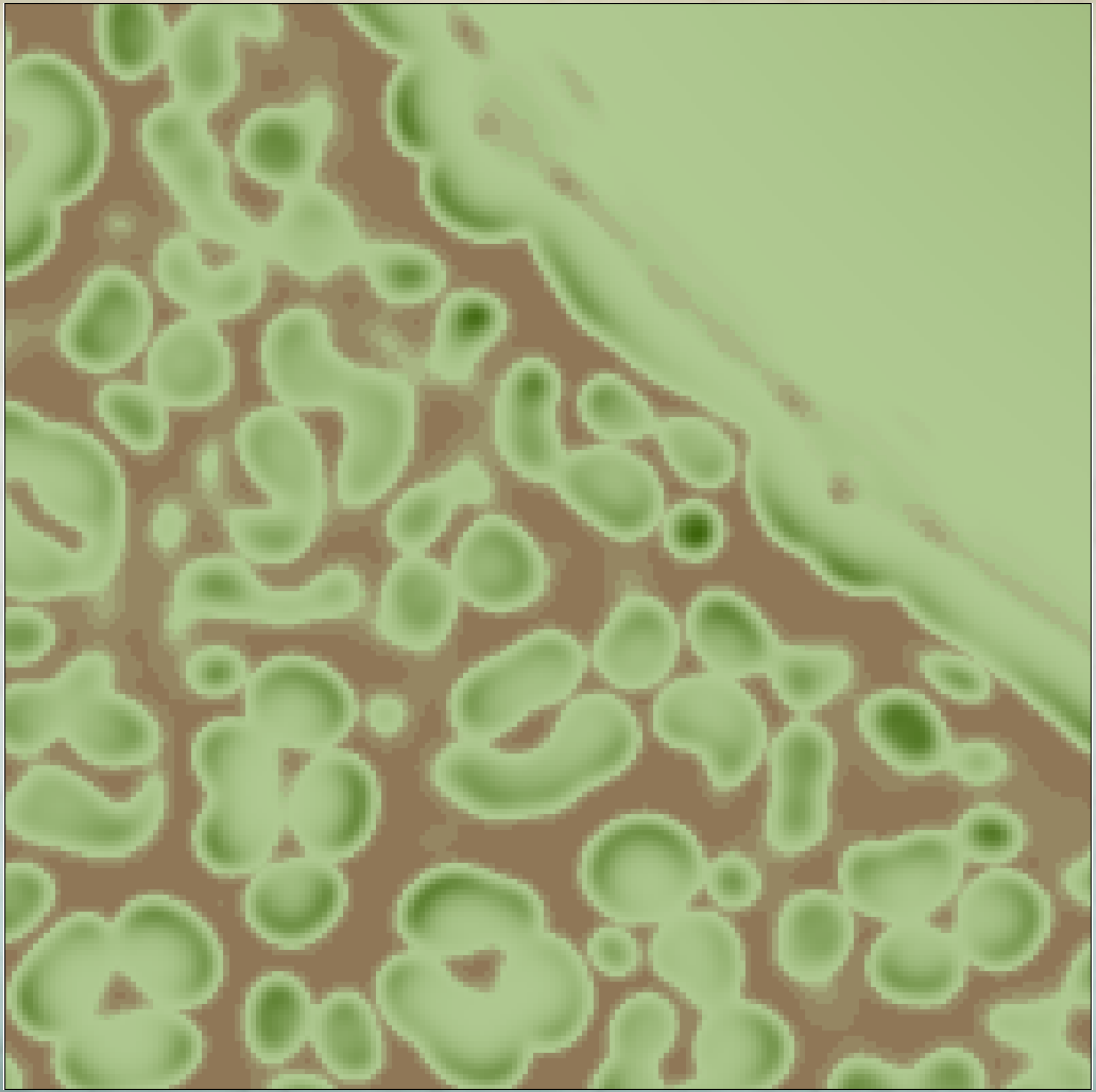


Prediction: we should see smaller scale vegetation patterns in between the mounds. But where were they?

In Between the Termite Mounds Vegetation Is Patterned

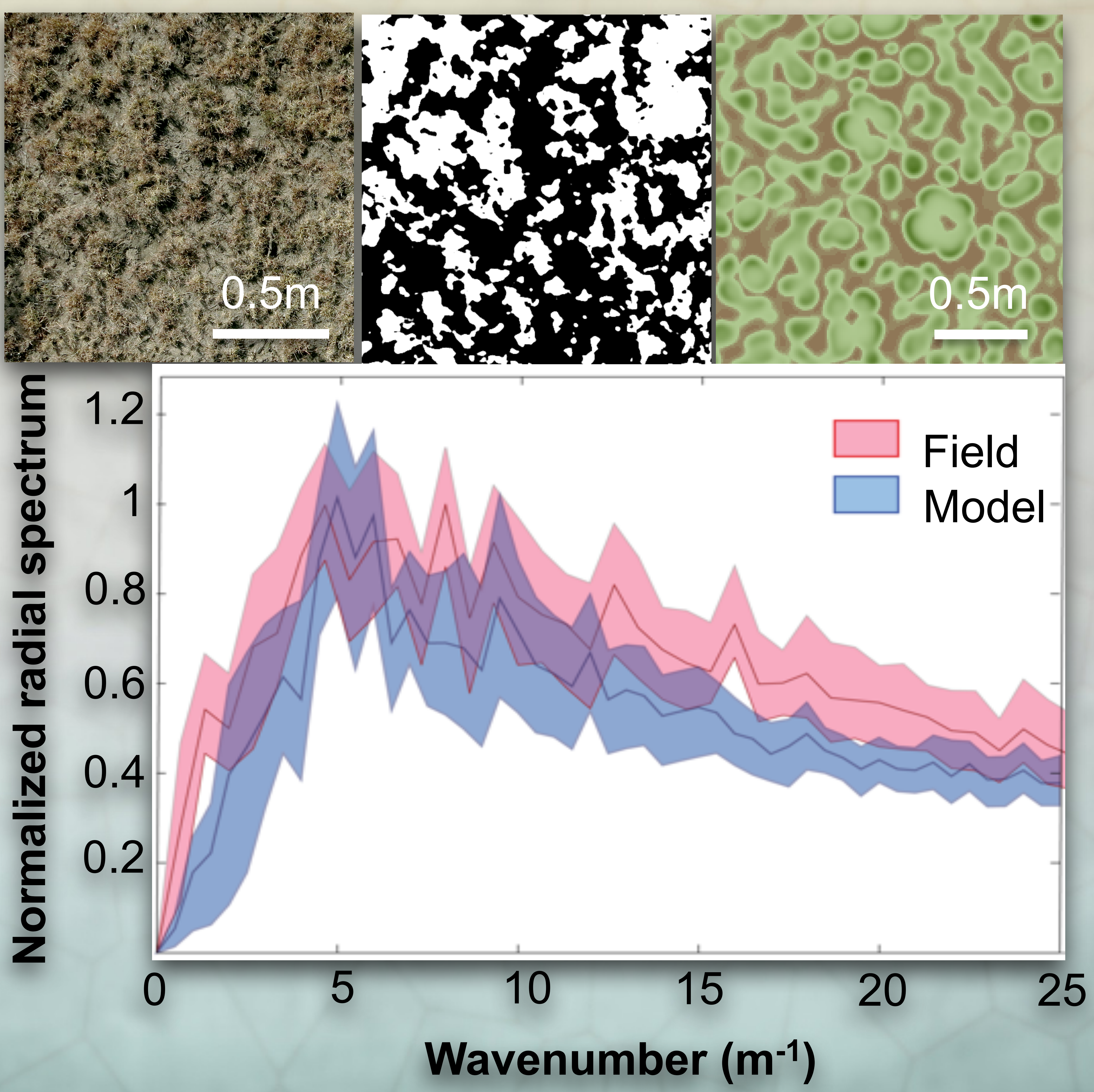
Tyler Coverdale

Jen Guyton

Model predictions match field observations

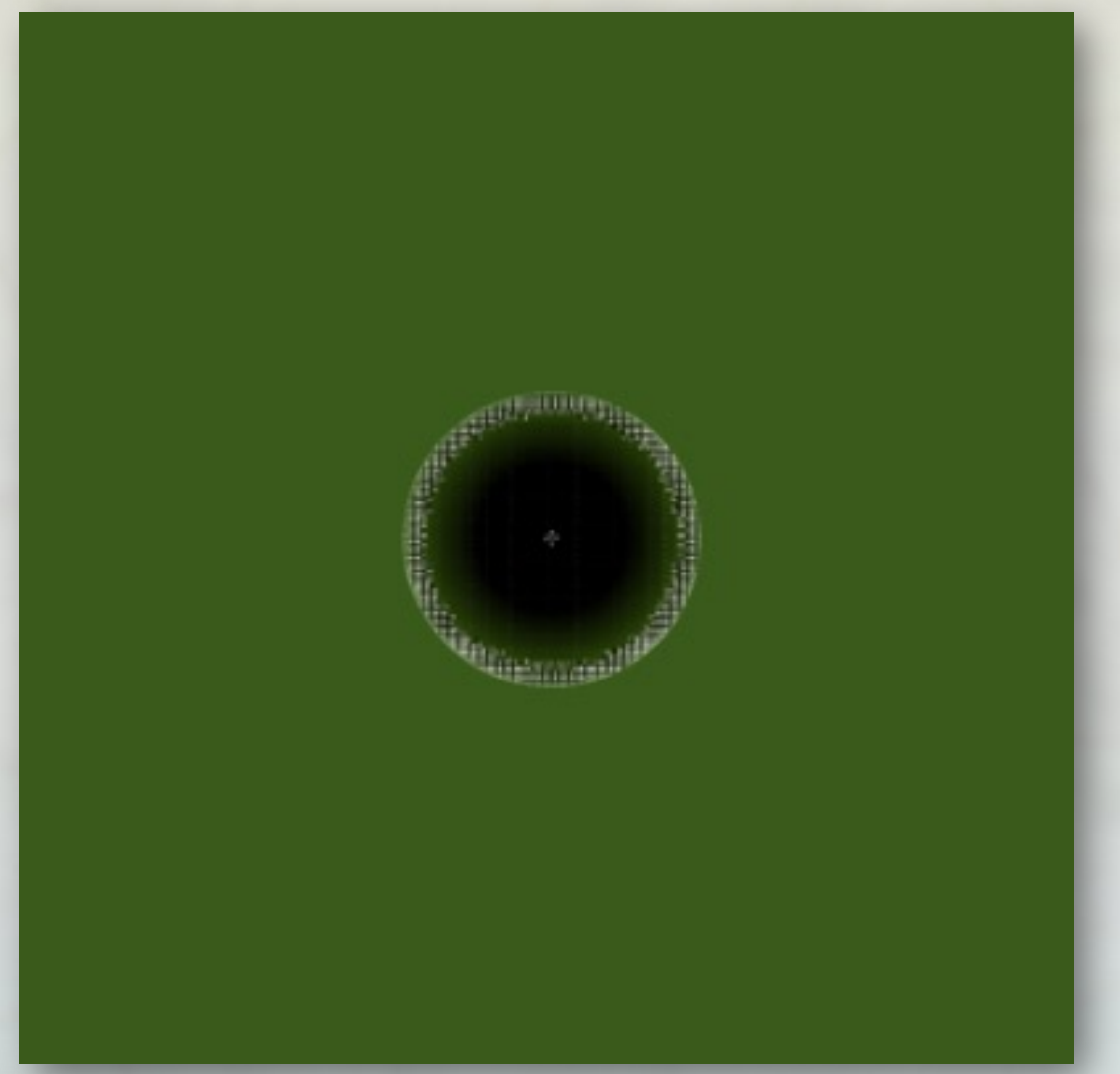
Fourier Transform analysis and comparison of field images and simulations

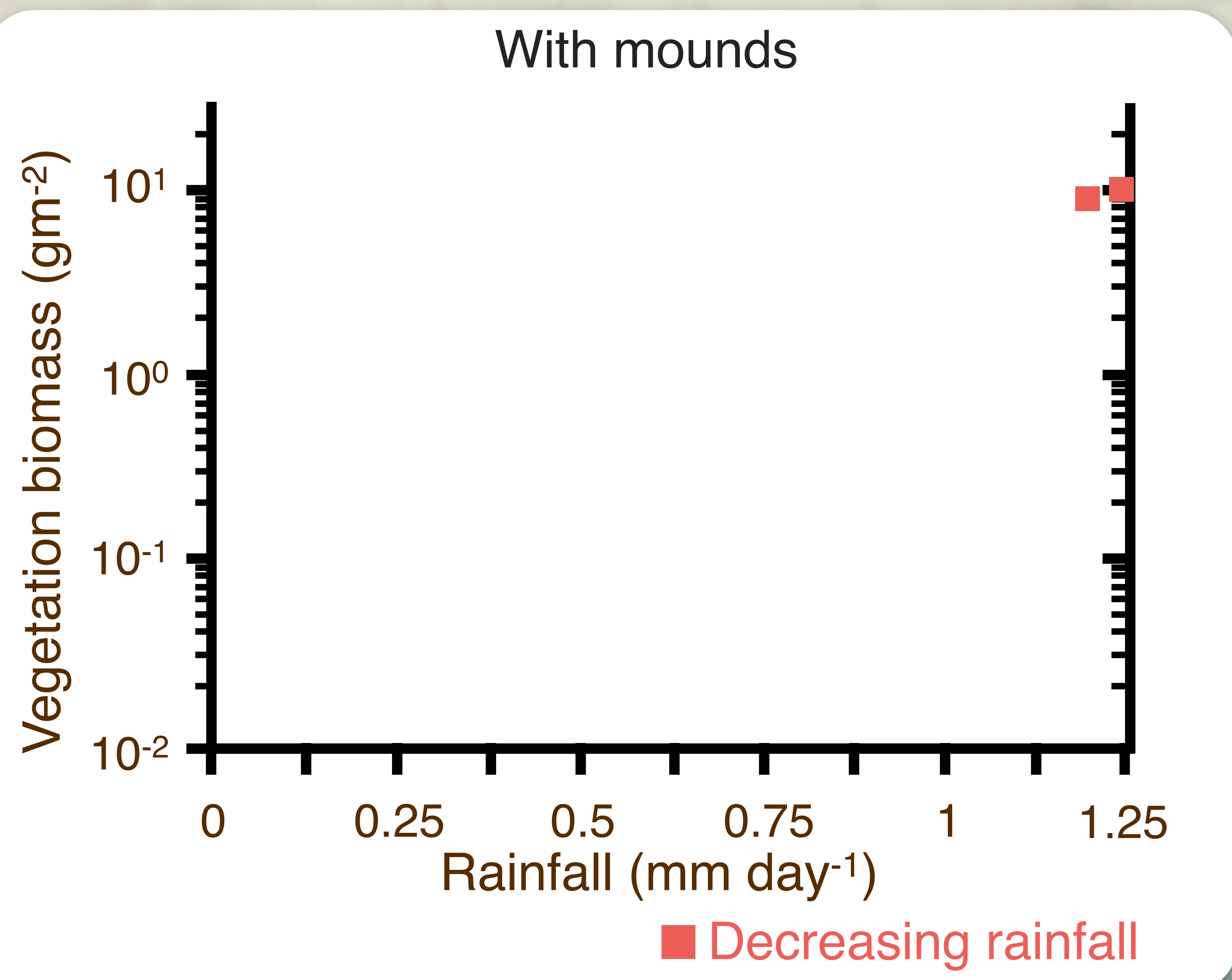
Efrat Sheffer



So Is This Ecosystem in Danger of Collapse?

Mounds Increase Drought Resistance





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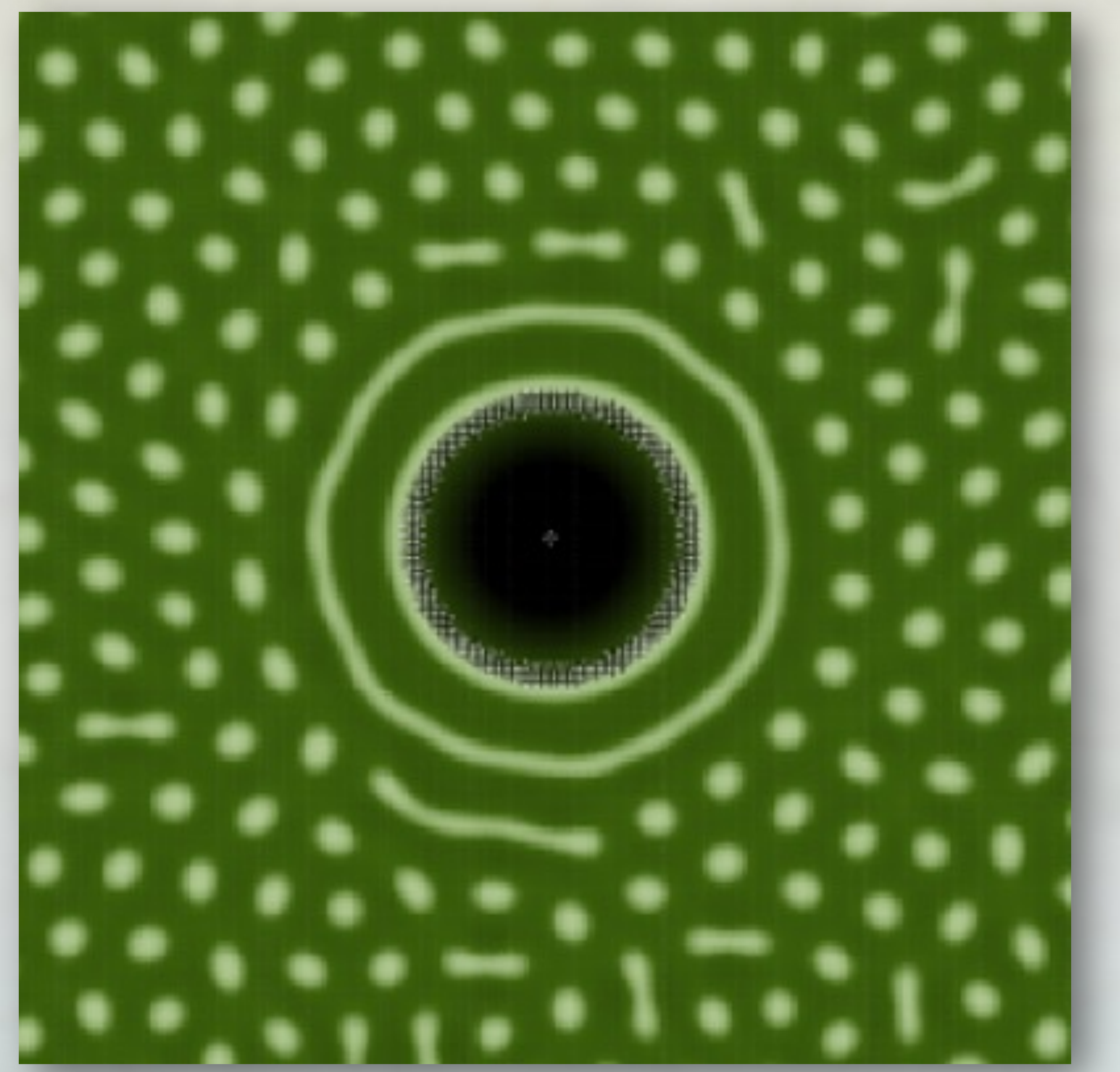

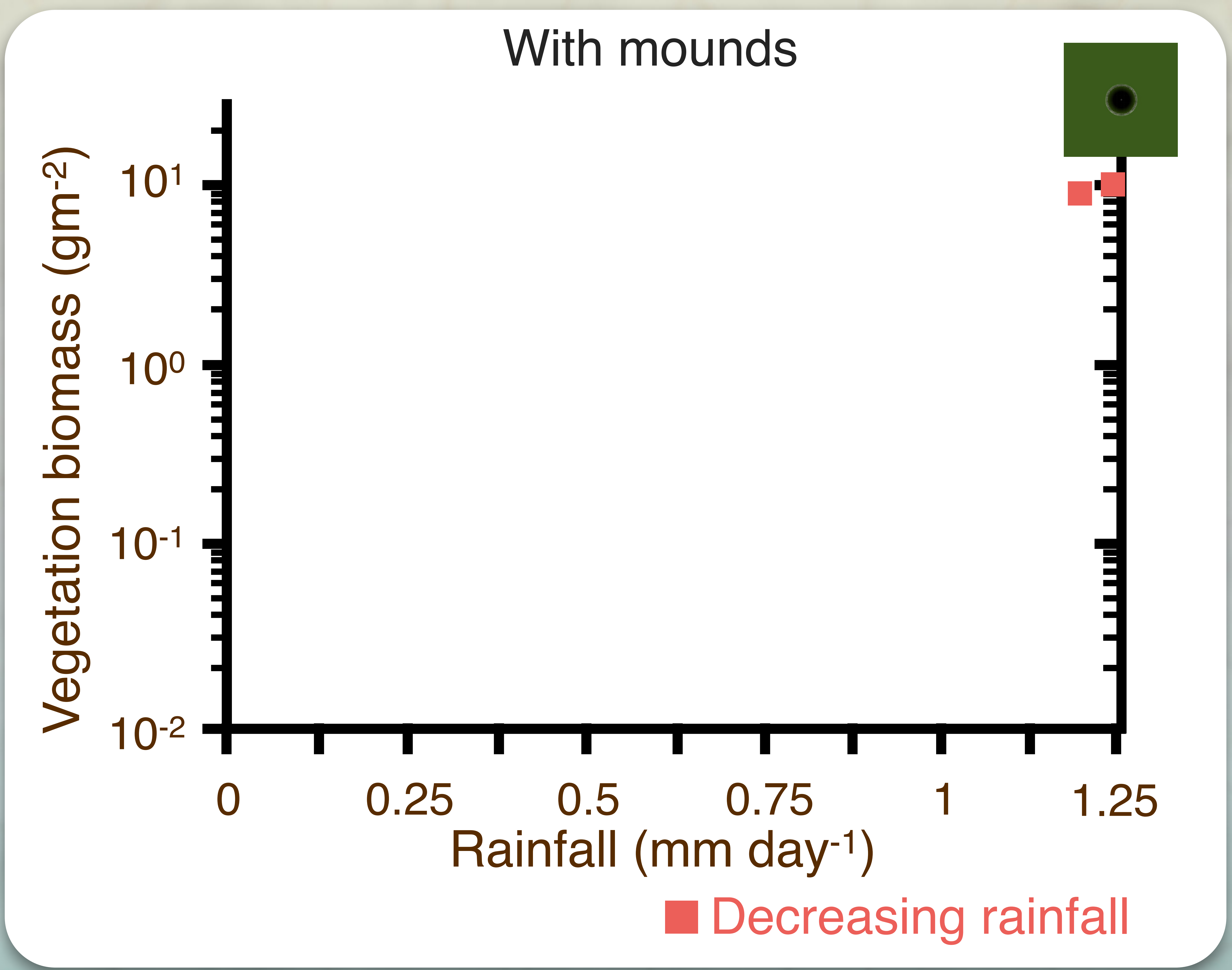

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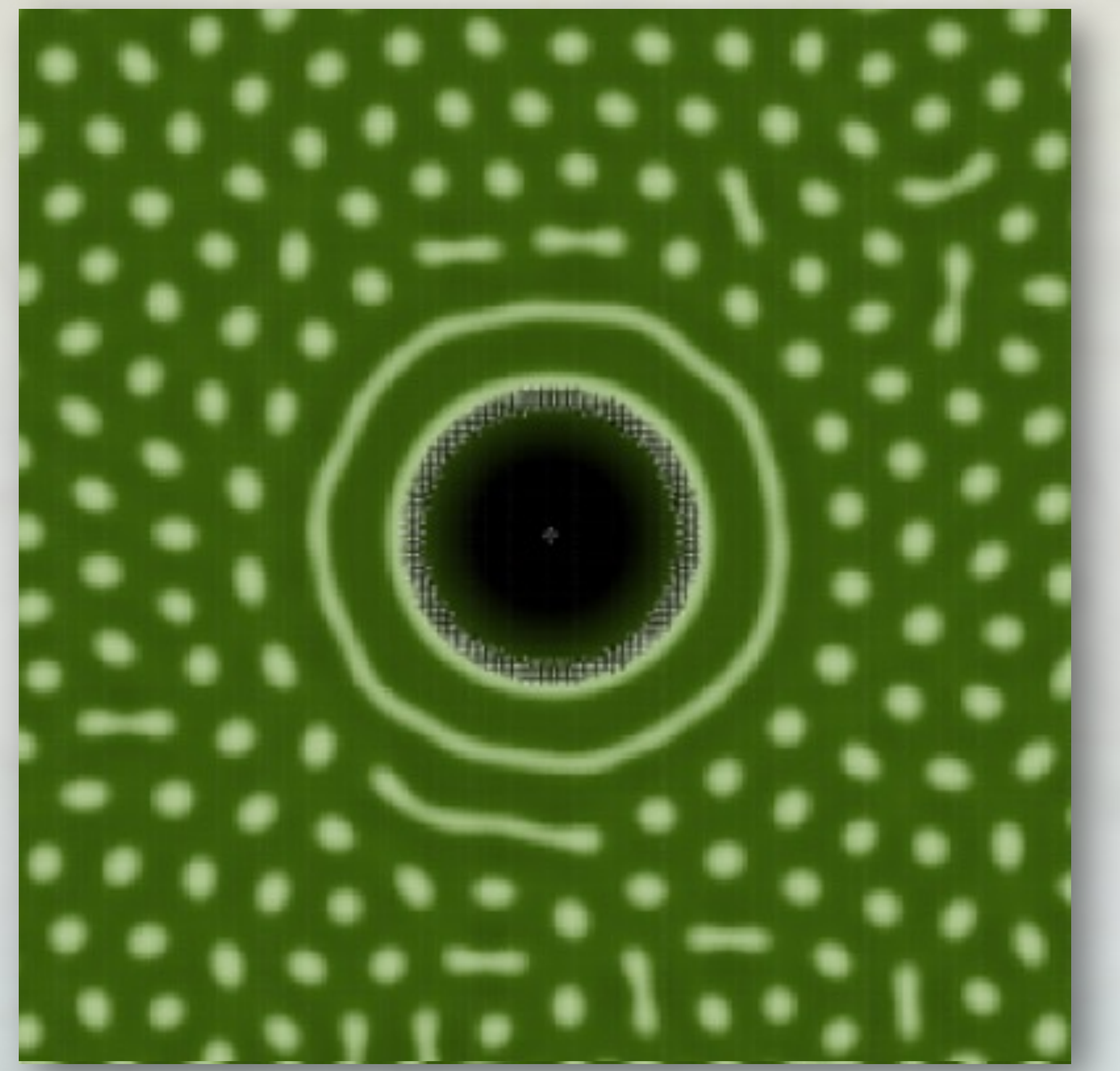

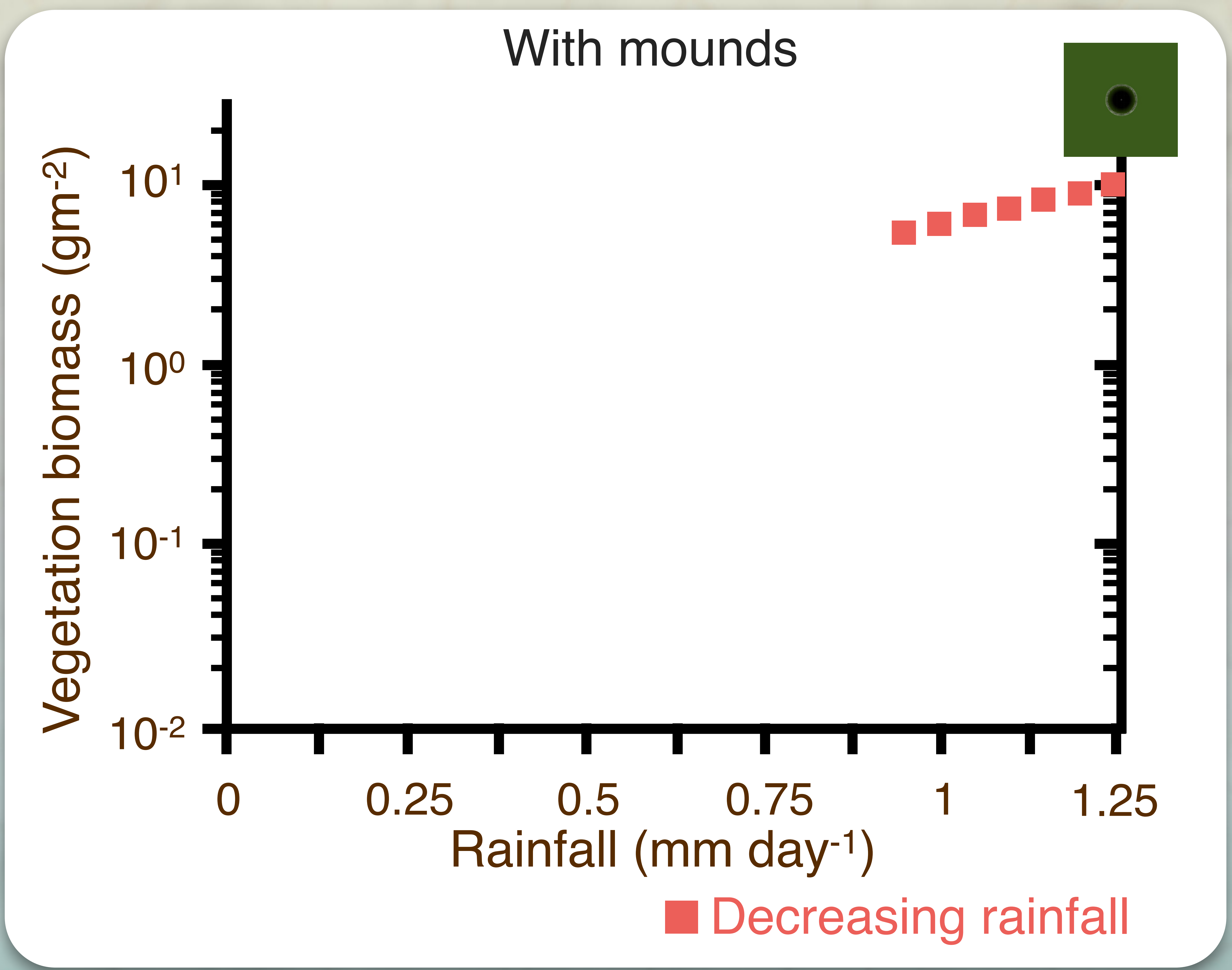

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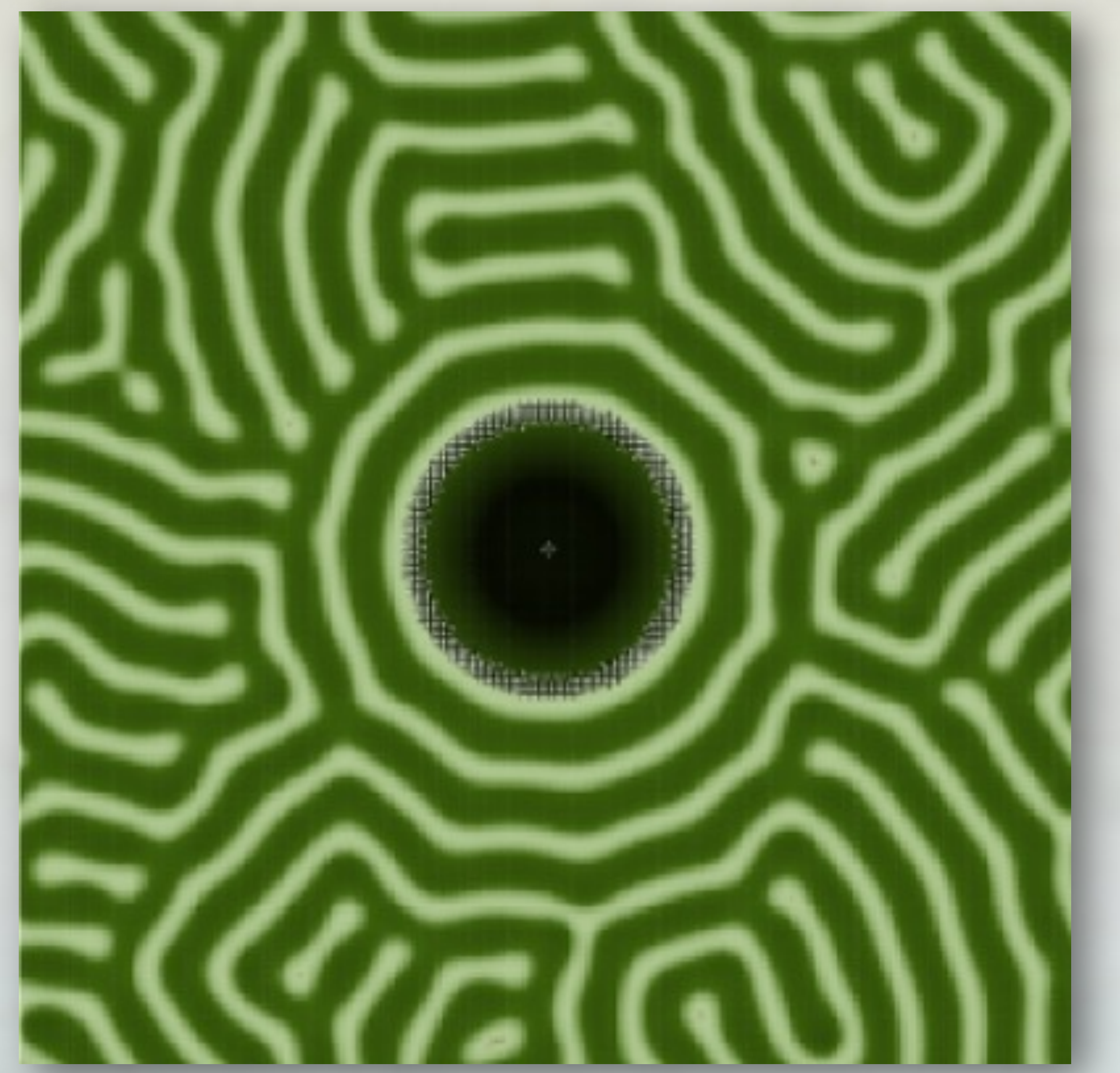

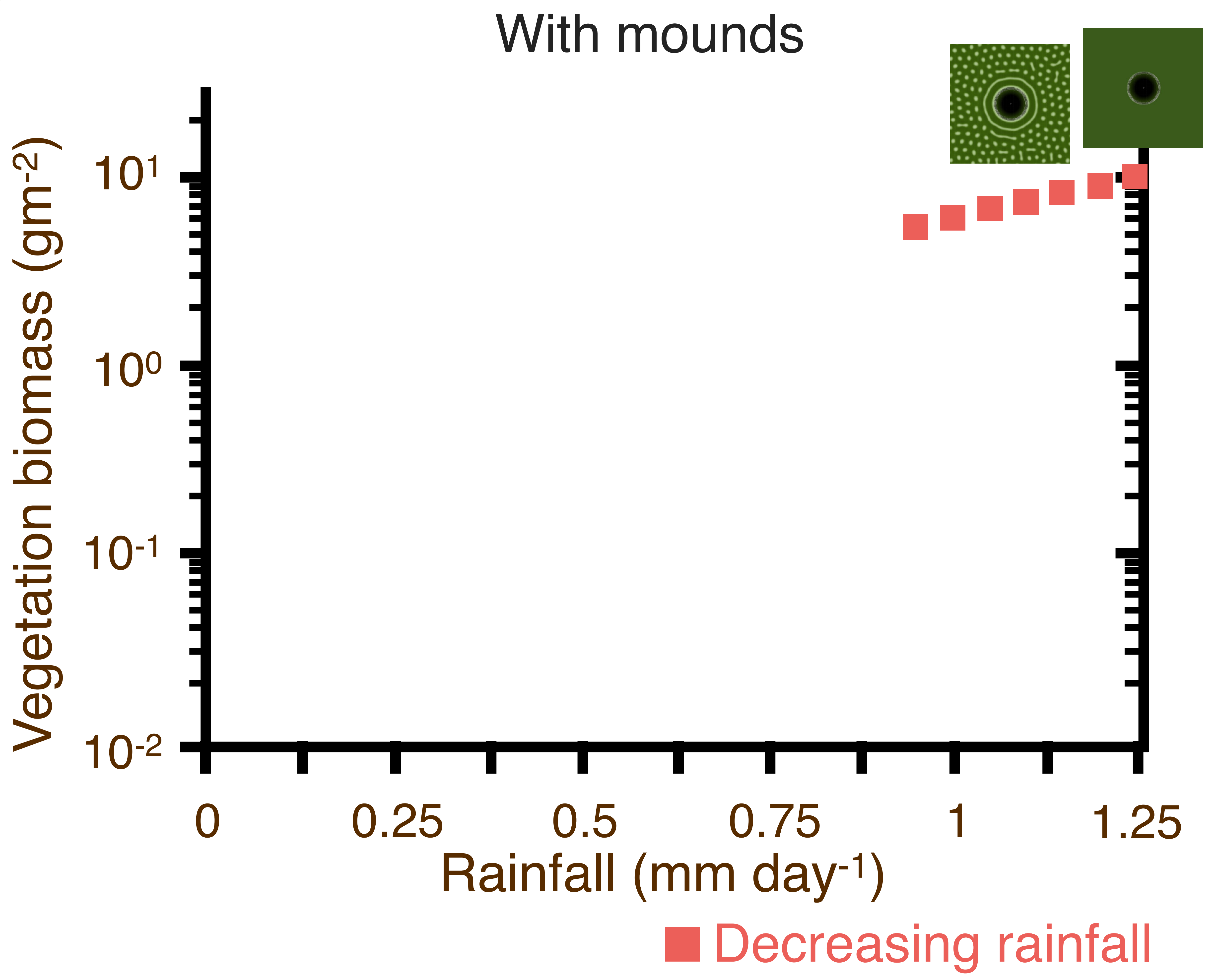

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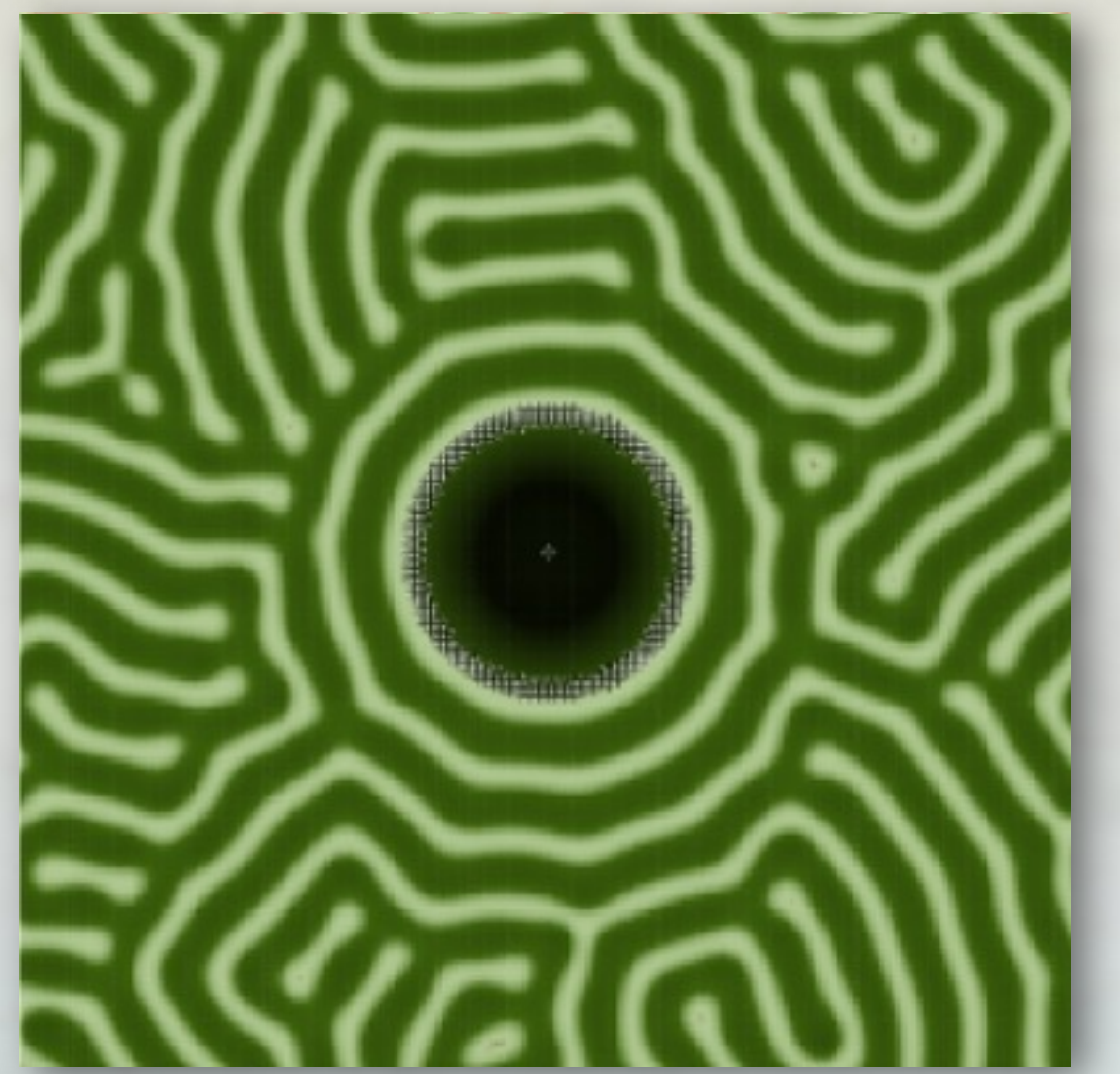

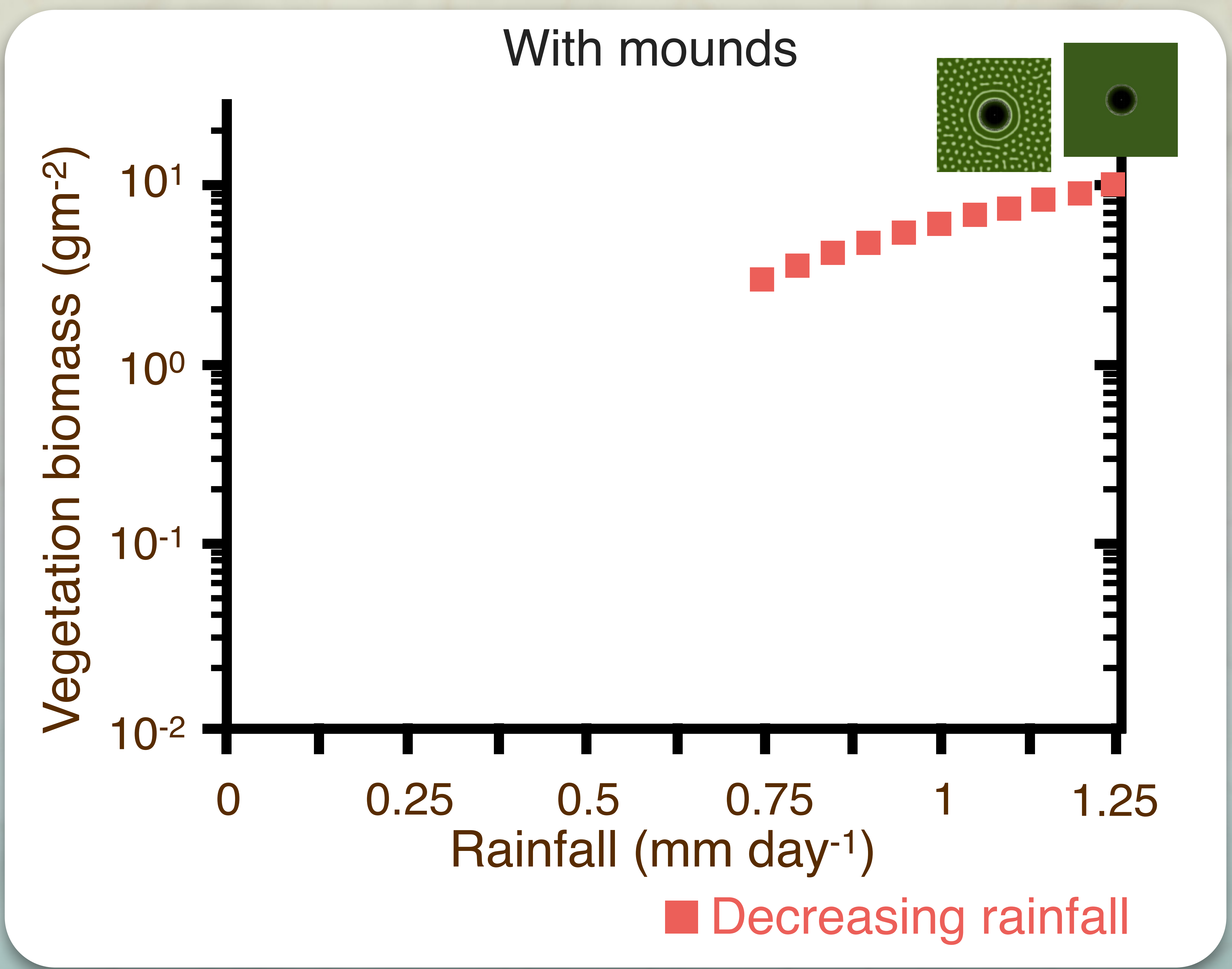

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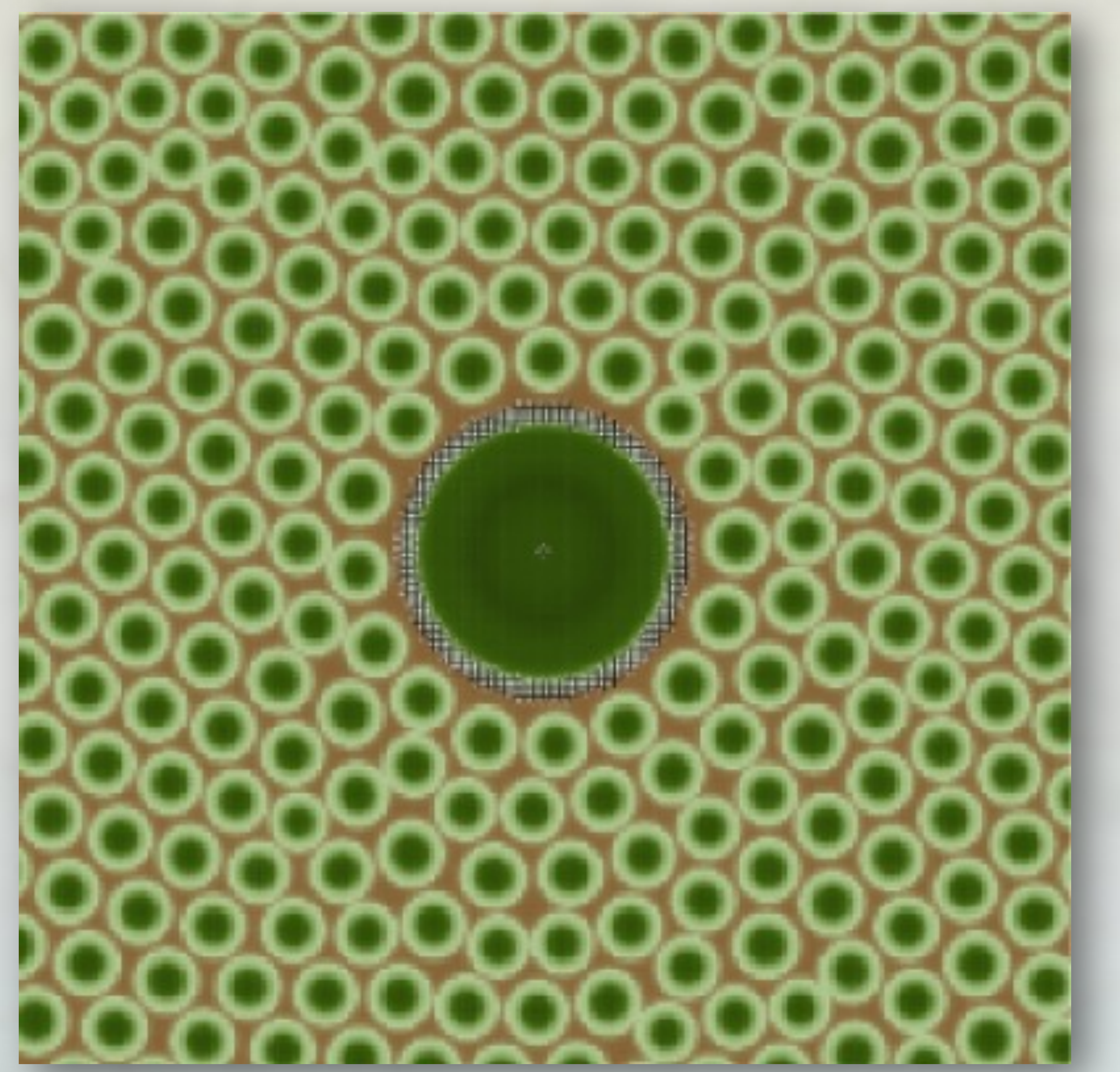

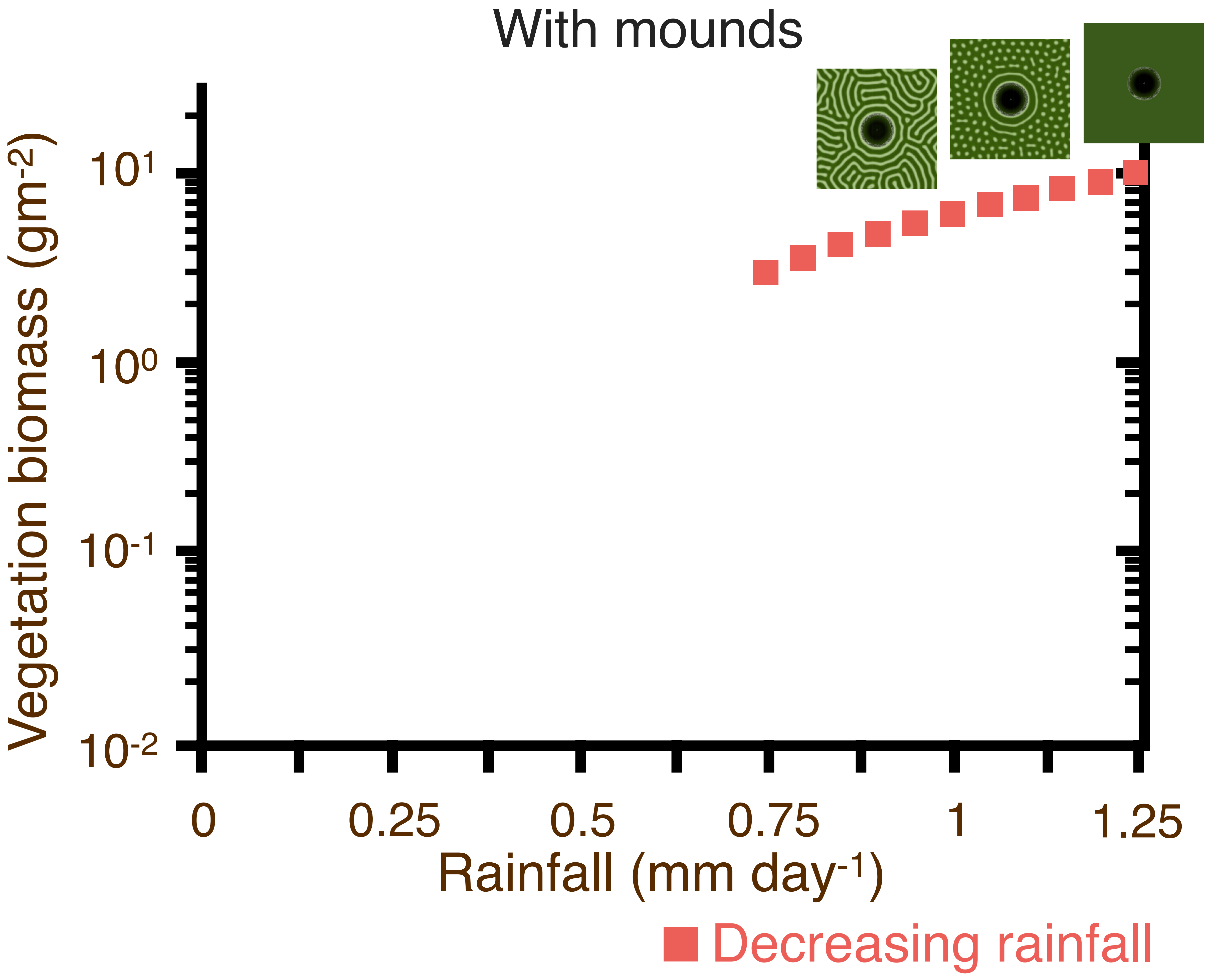

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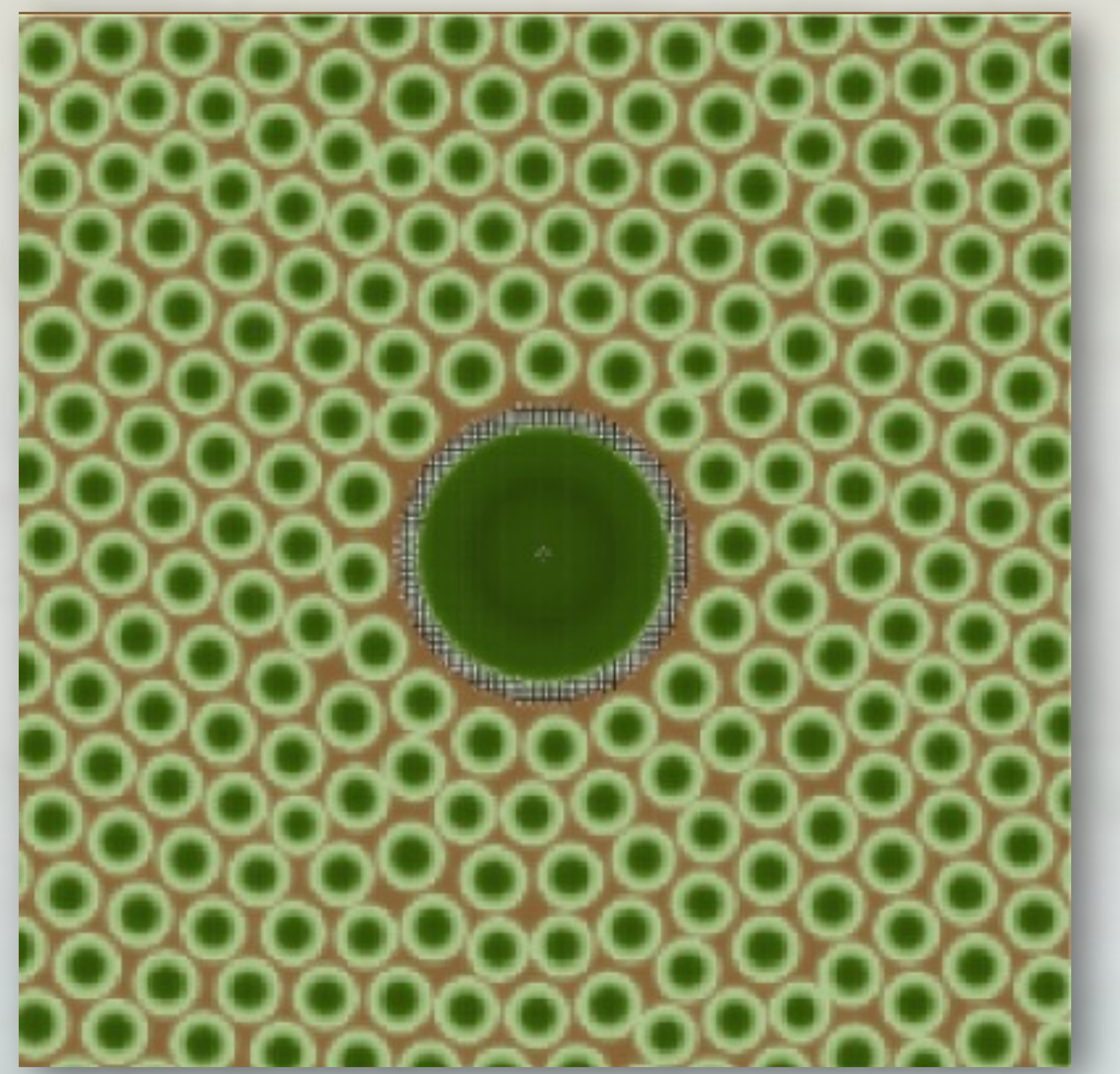

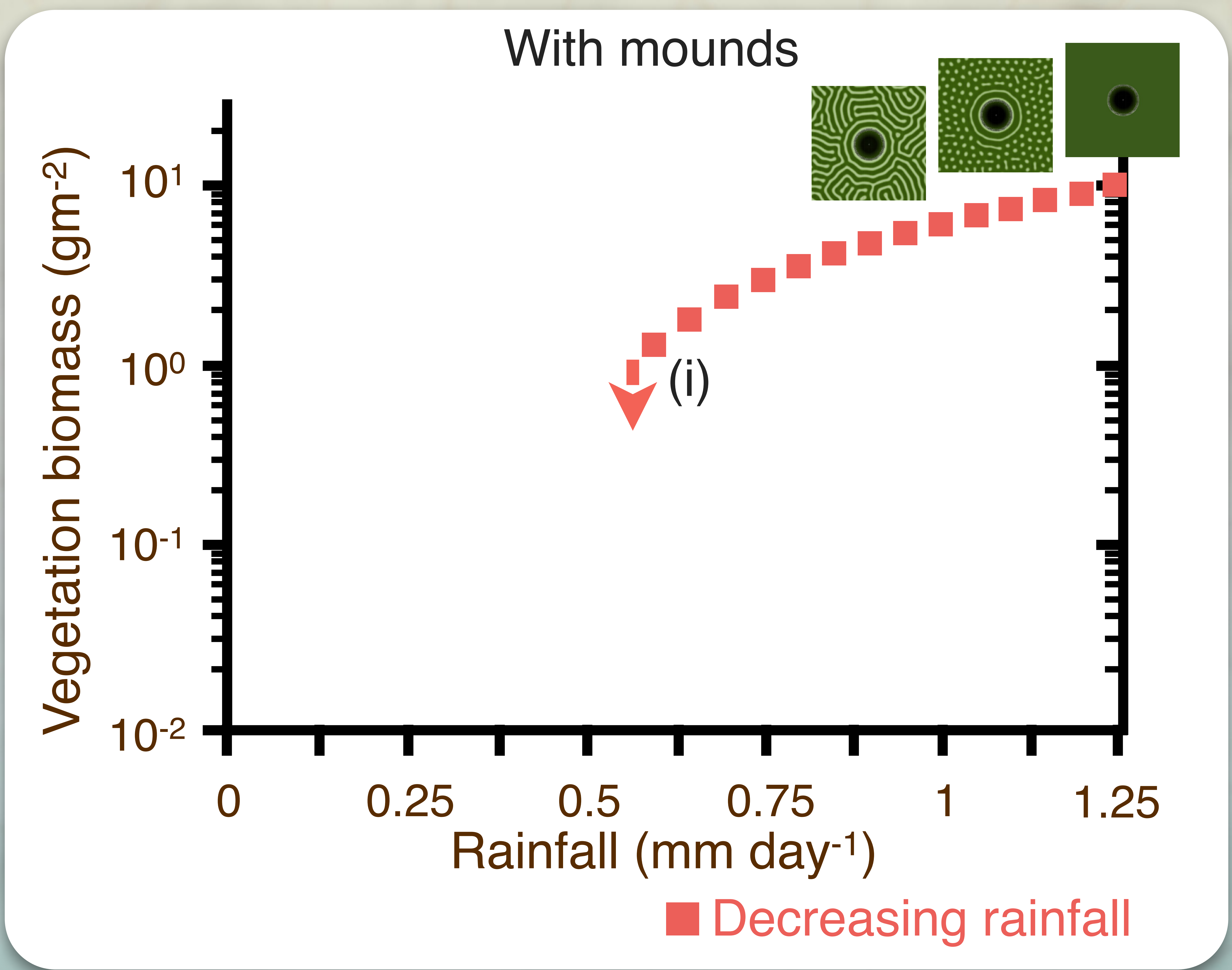

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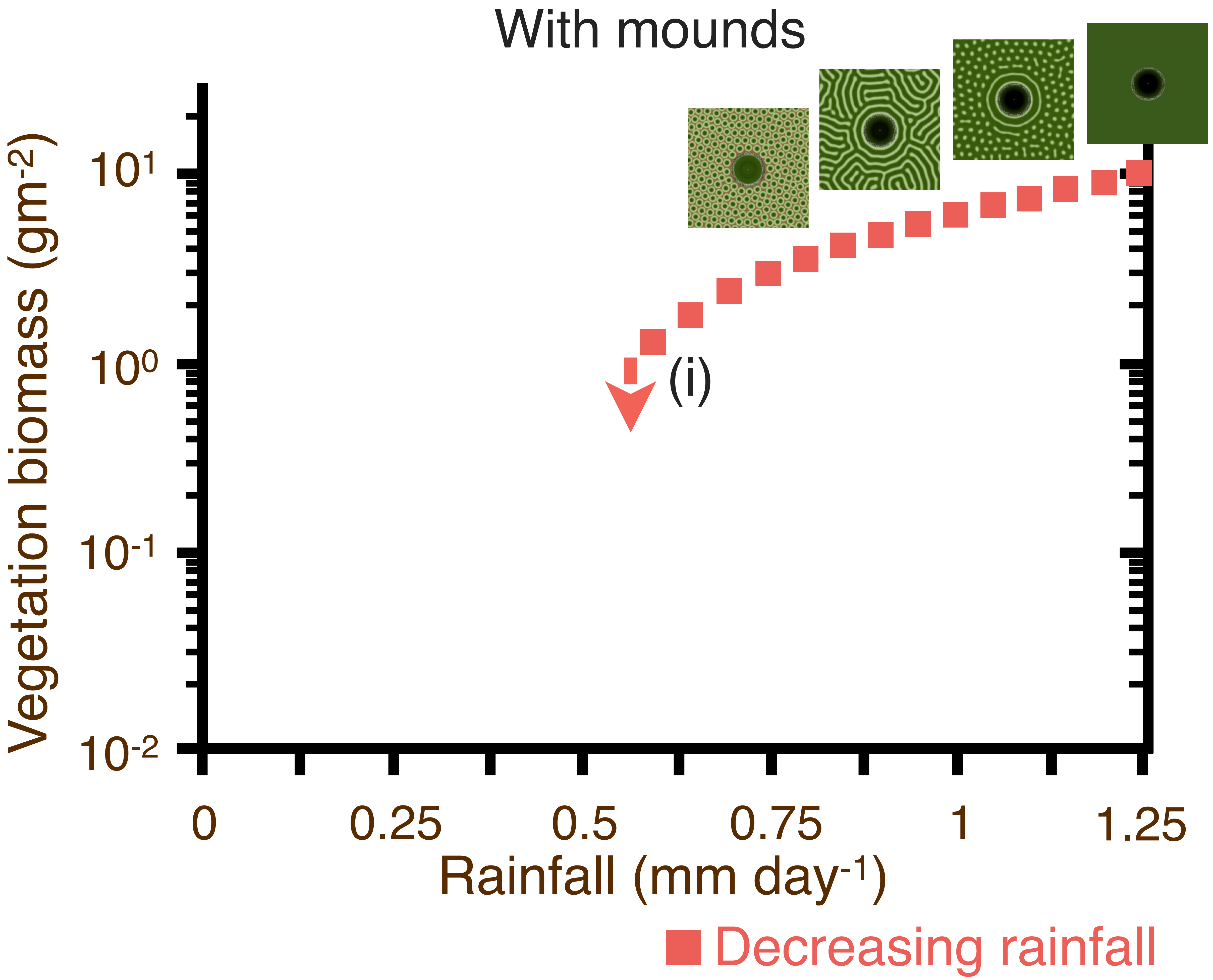

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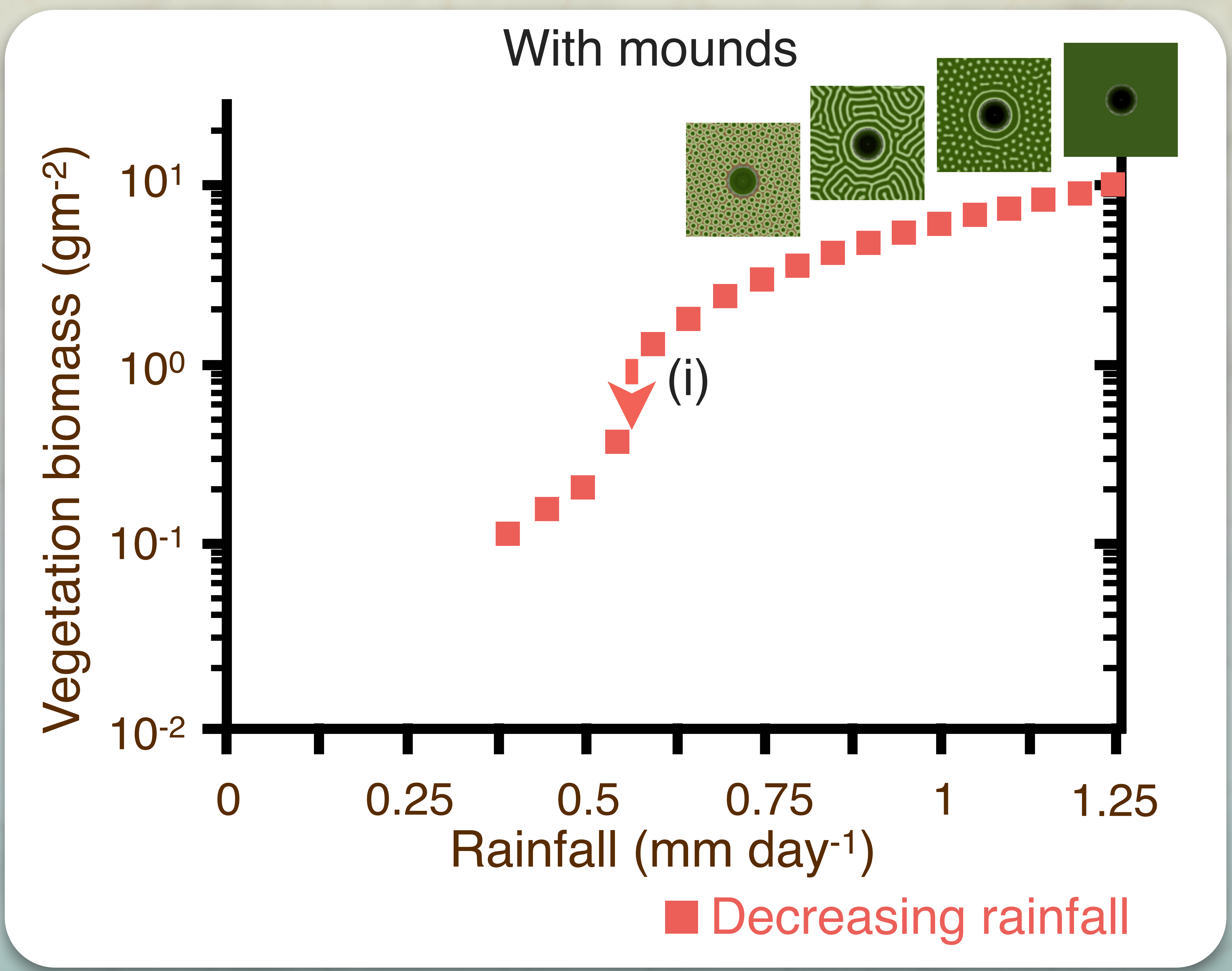

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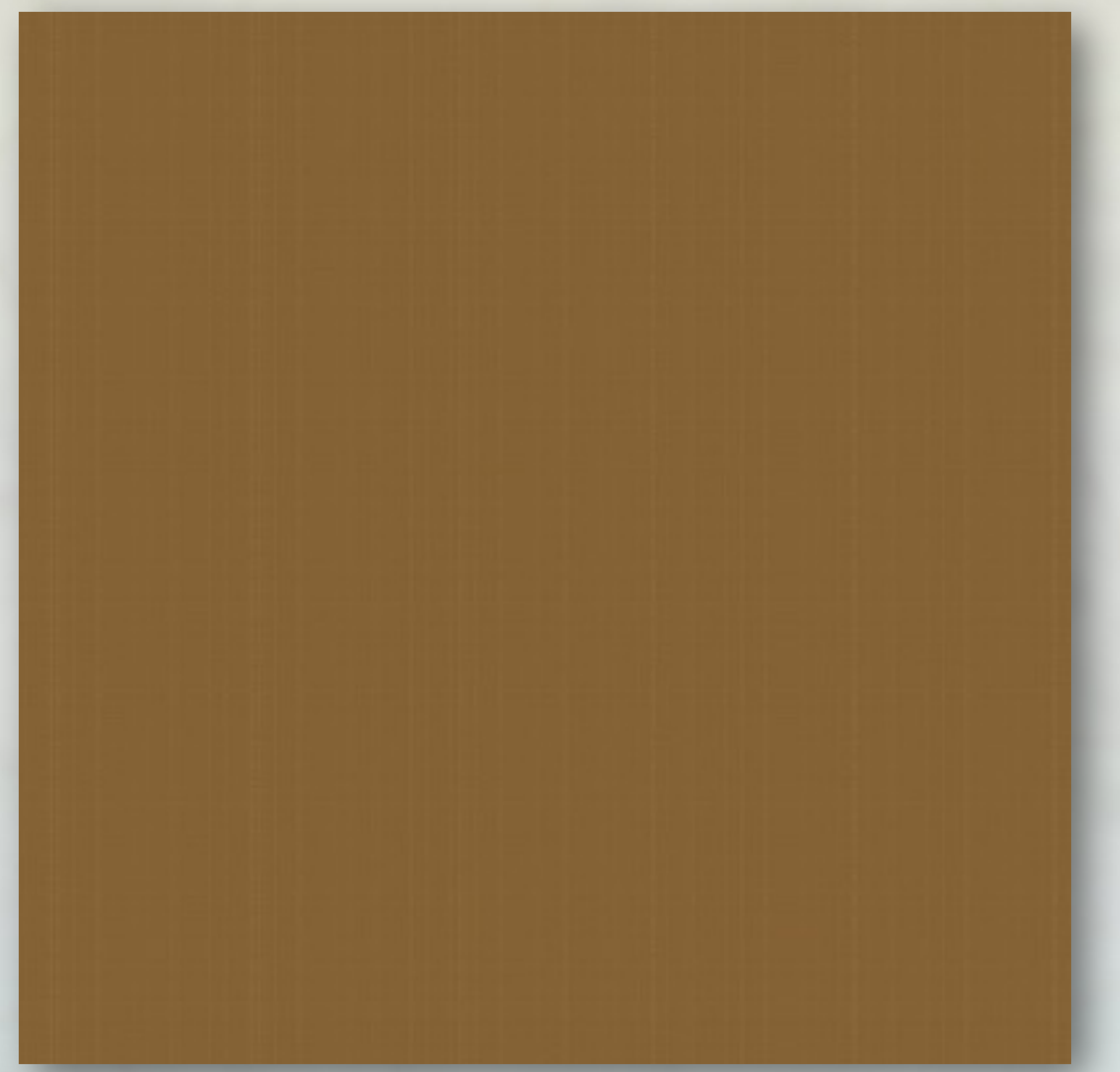

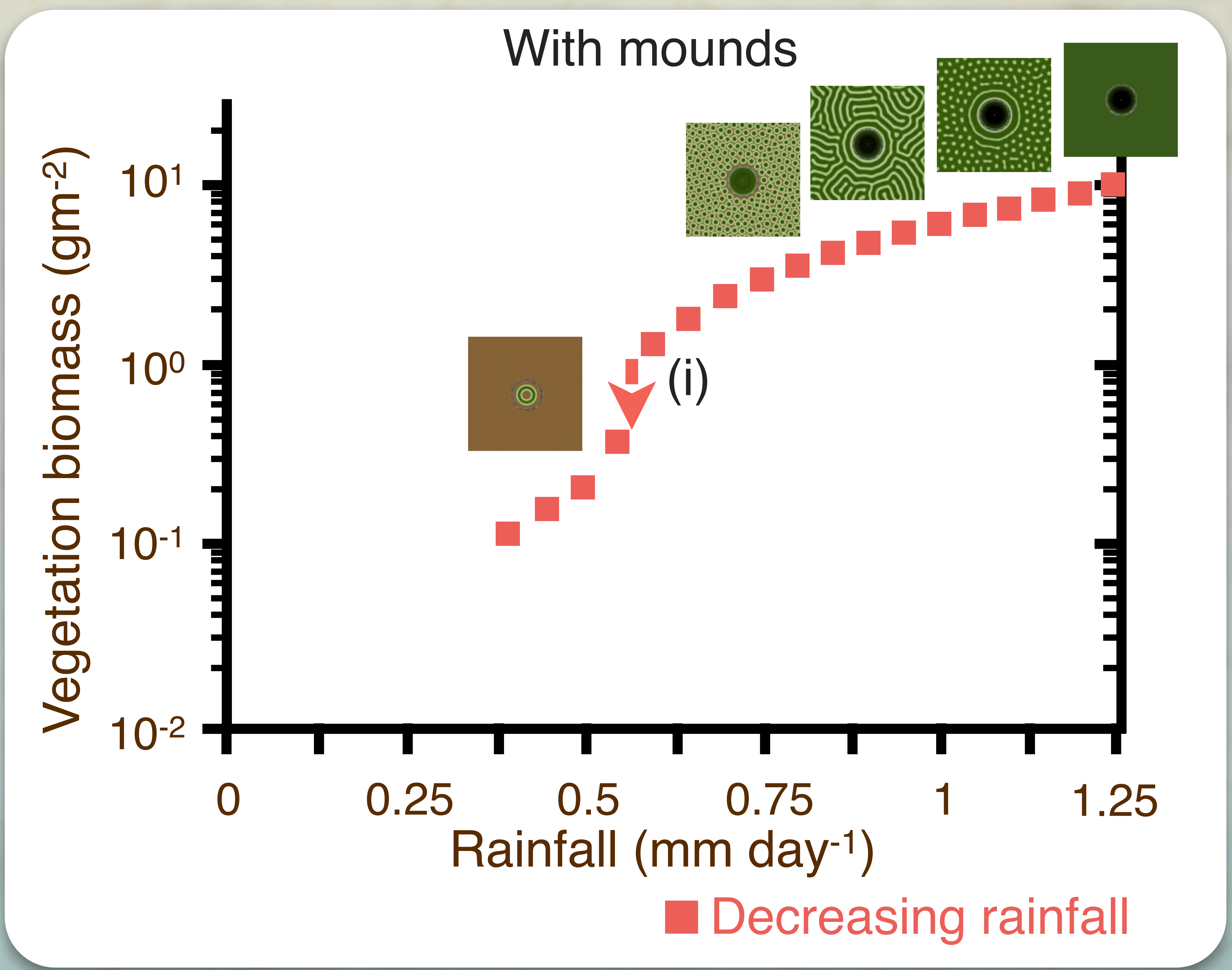

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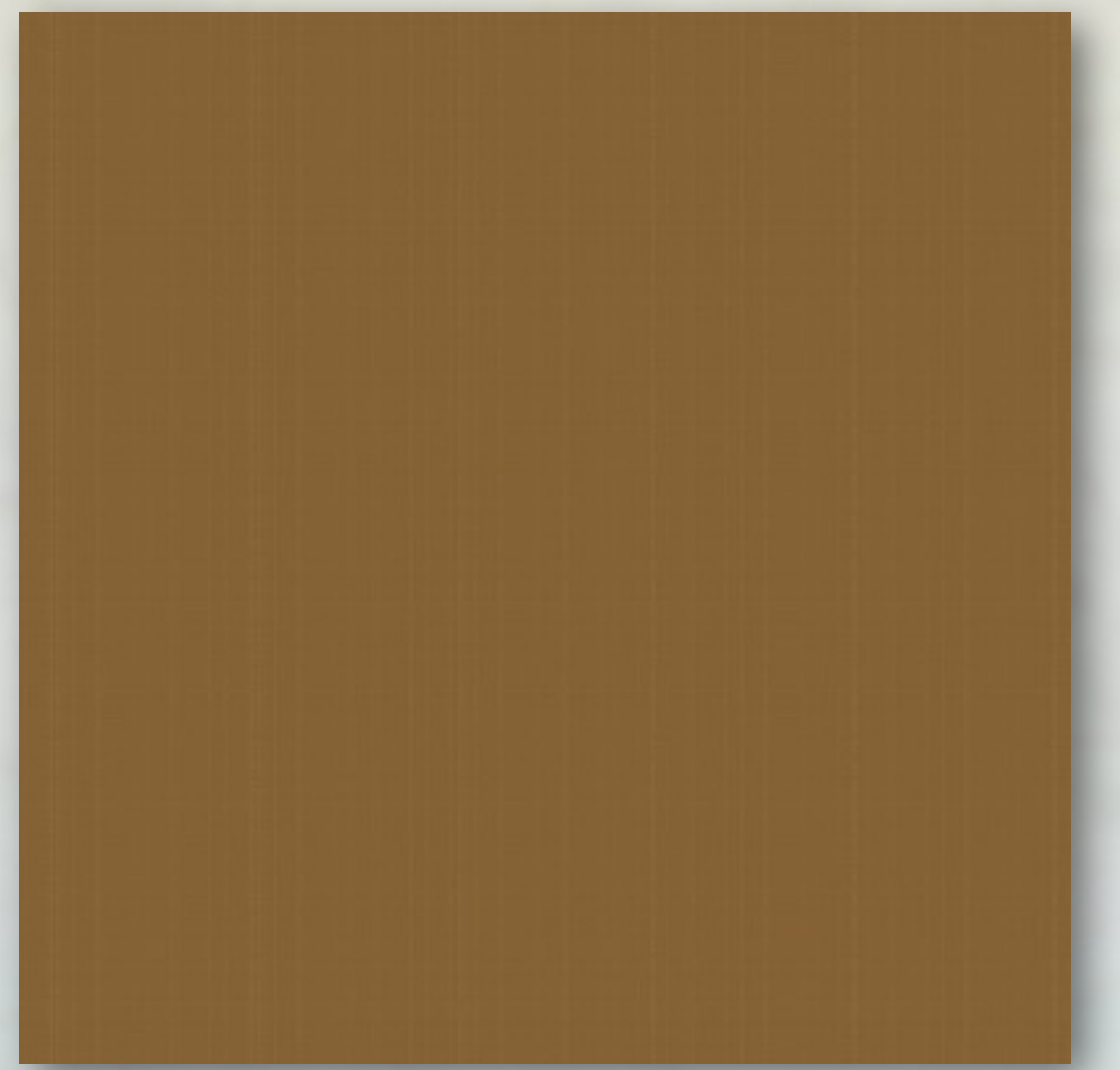

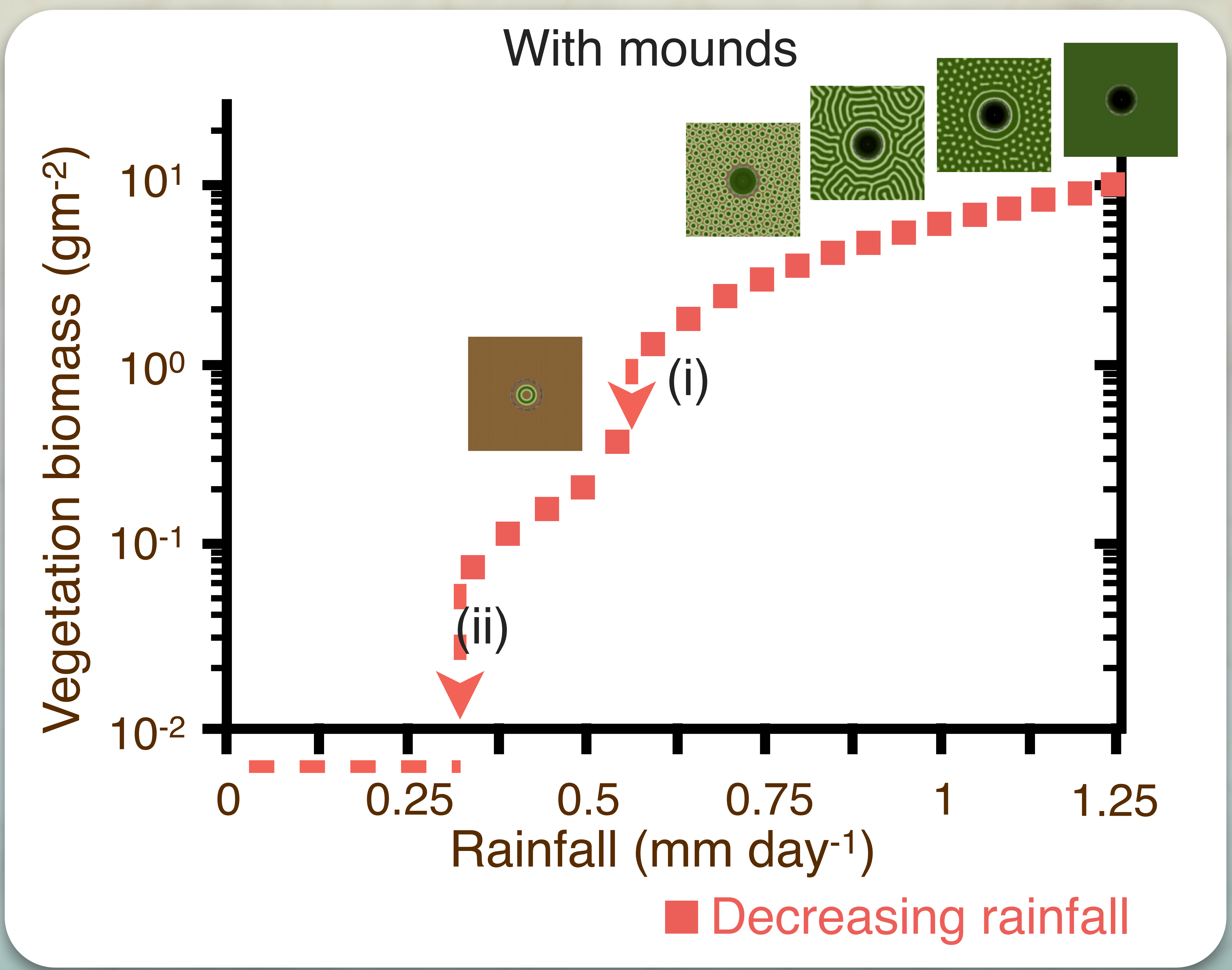

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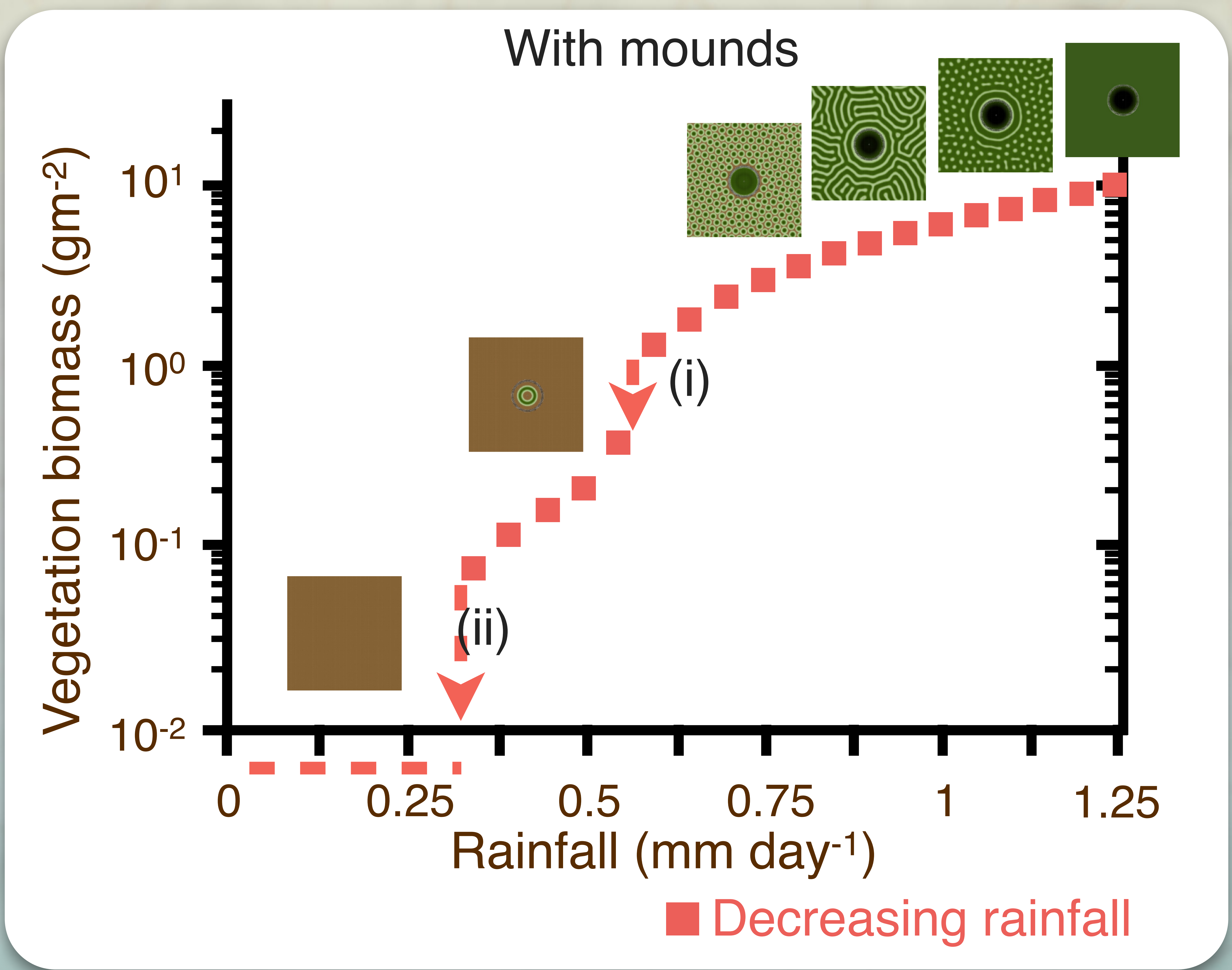

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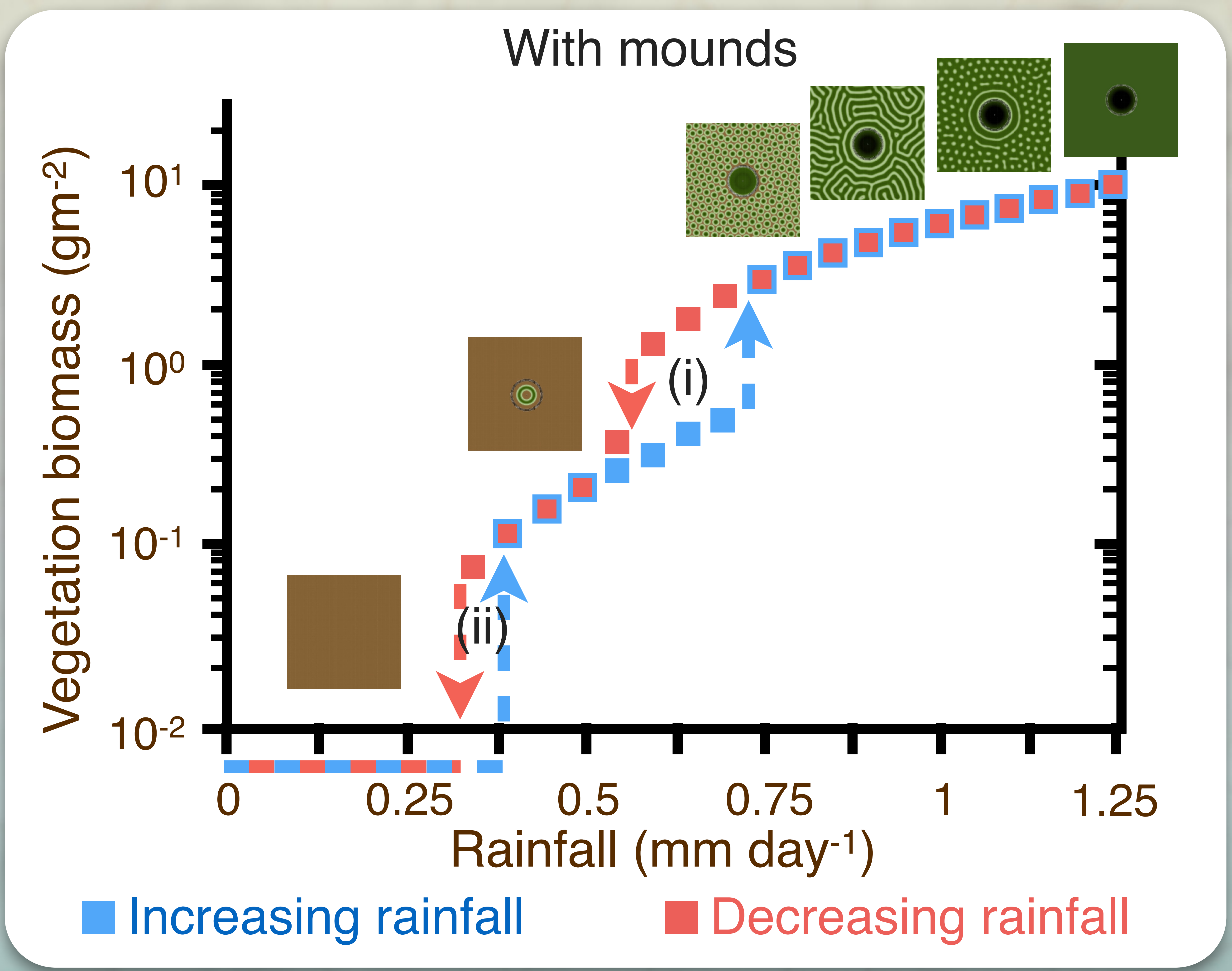
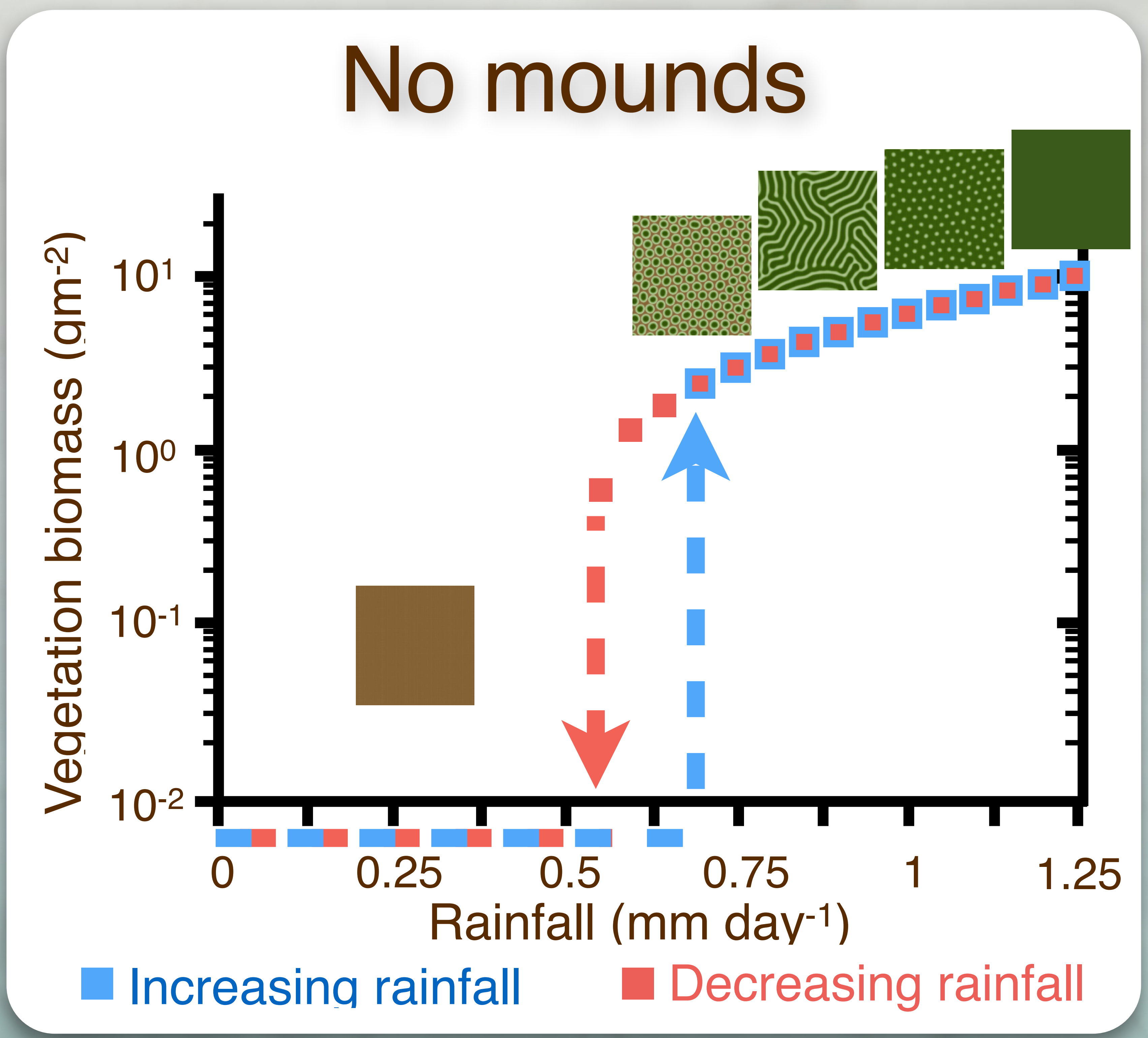
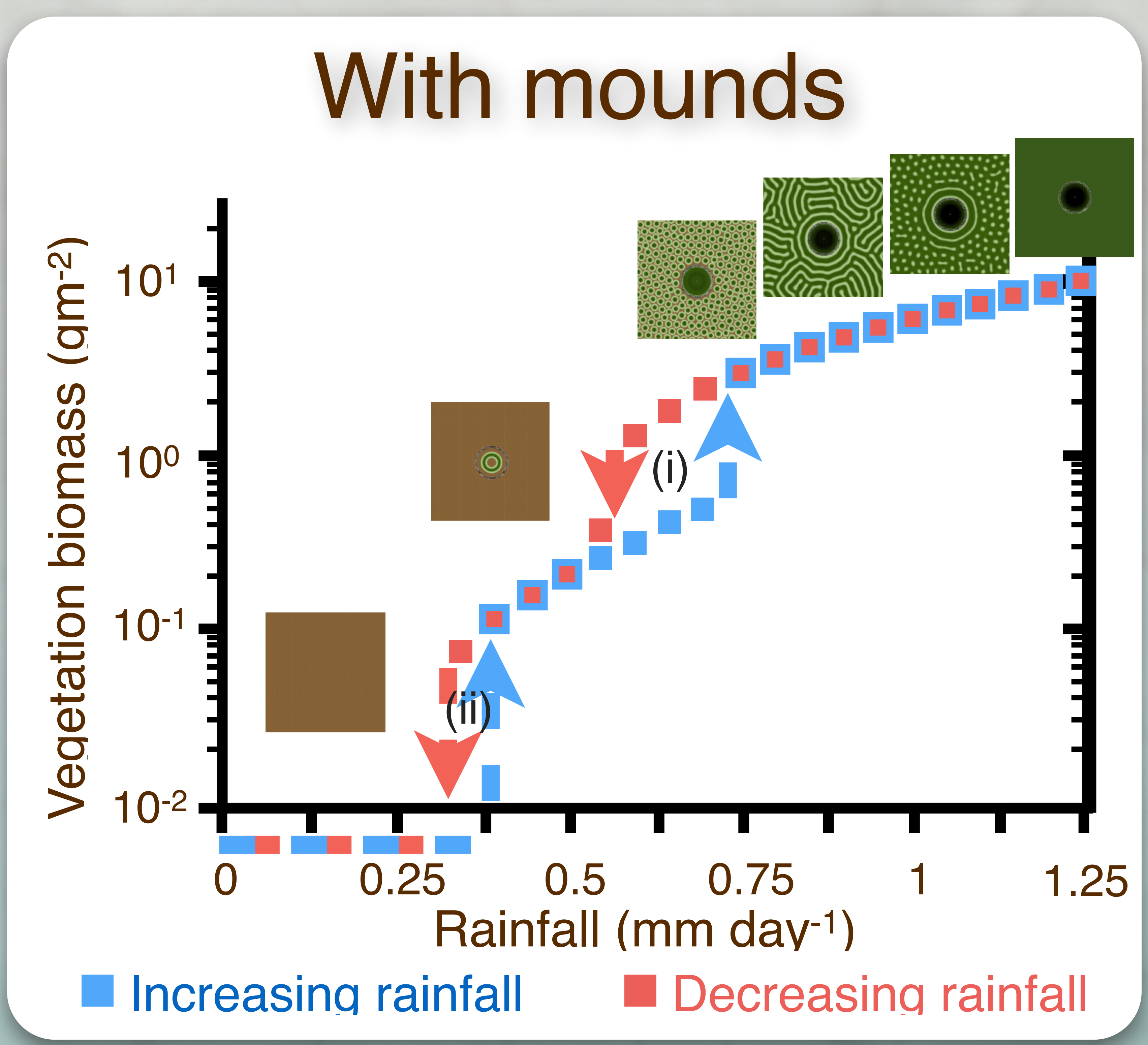


ECOLOGICAL FEEDBACKS

Termite mounds can increase the robustness of dryland ecosystems to climatic change

Juan A. Bonachela,[1*] Robert M. Pringle,[1,2] Efrat Sheffer,[1] Tyler C. Coverdale,[1] Jennifer A. Guyton,[1] Kelly K. Caylor,[2,3] Simon A. Levin,[1] Corina E. Tarnita[1,2]†





nature COMMUNICATIONS

ARTICLE

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Pattern formation at multiple spatial scales drives the resilience of mussel bed ecosystems

Quan-Xing Liu[1,2], Peter M.J. Herman[1], Wolf M. Mooij[3,4], Jef Huisman[2], Marten Scheffer[4], Han Olff[5] & Johan van de Koppel[1,5]

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Physics of Life Reviews

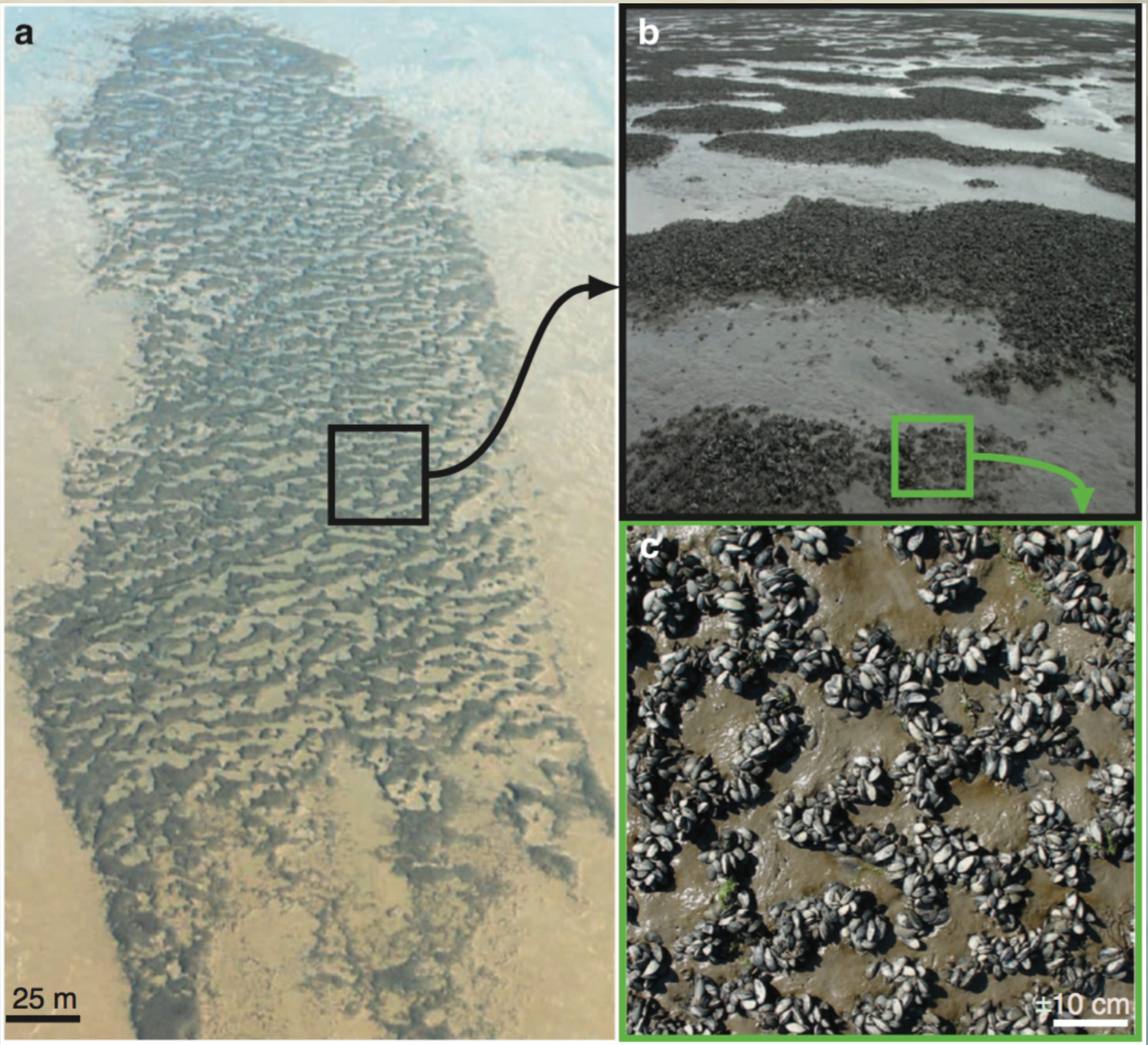
Available online 16 July 2016

In Press, Corrected Proof — Note to users

Review

Phase separation driven by density-dependent movement: A novel mechanism for ecological patterns

Quan-Xing Liu[a, b, h], Max Rietkerk[c], Peter M.J. Herman[b], Theunis Piersma[d, e], John M. Fryxell[f], Johan van de Koppel[b, g]



Conclusions

Patterns are **common** in nature and are created by abiotic and biotic processes.

Patterns **matter**: Understanding patterns can help us explain ecosystem functioning and stability. But also **engineer** solutions.

Mechanisms matter: Similar patterns can arise from different processes and have different effects on the ecosystem.

Multiple mechanisms can coexist and interact, possibly at different scales.

Thank you!

Rob Pringle
Juan Bonachela
Efrat Sheffer
Kelly Caylor
Simon Levin
Jen Guyton
Tyler Coverdale
Ryan Long
Jess Castillo-Vardaro

NSF National Science Foundation

Alfred P. Sloan Foundation

PEI Princeton Environmental Institute

Grand Challenges