Emerging mechanisms of ecosystem functioning in a warmer and drier world

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Many regions on Earth experience more extreme weather, including heatwaves and drought events …

Impact of the extreme heatwave and drought of summer 2018, as compared to summer 2017, on fields around the town of Slagelse in Zealand, Denmark. Photo: European Space Agency (CC BY-SA 3.0 IGO). The west and central European summer 2018 serves as an example of an extreme hot and dry event that led to soil drought and reduced plant cover.

… which have already exerted, mostly negative, impacts on ecosystems during recent decades, e.g. leading to widespread tree mortality, damage to crop production, decreases in terrestrial carbon assimilation, and loss of biodiversity and ecosystem services

Danish maize field in July 2018. The west and central European summer 2018 serves as an example of an extreme hot and dry event that led to soil drought and reduced plant cover. Photo: Janne Hansen (CC BY-NC 4.0; https://dca.au.dk/en/current-news/news/show/artikel/climate-changes-require-better-adaptation-to-drought/).

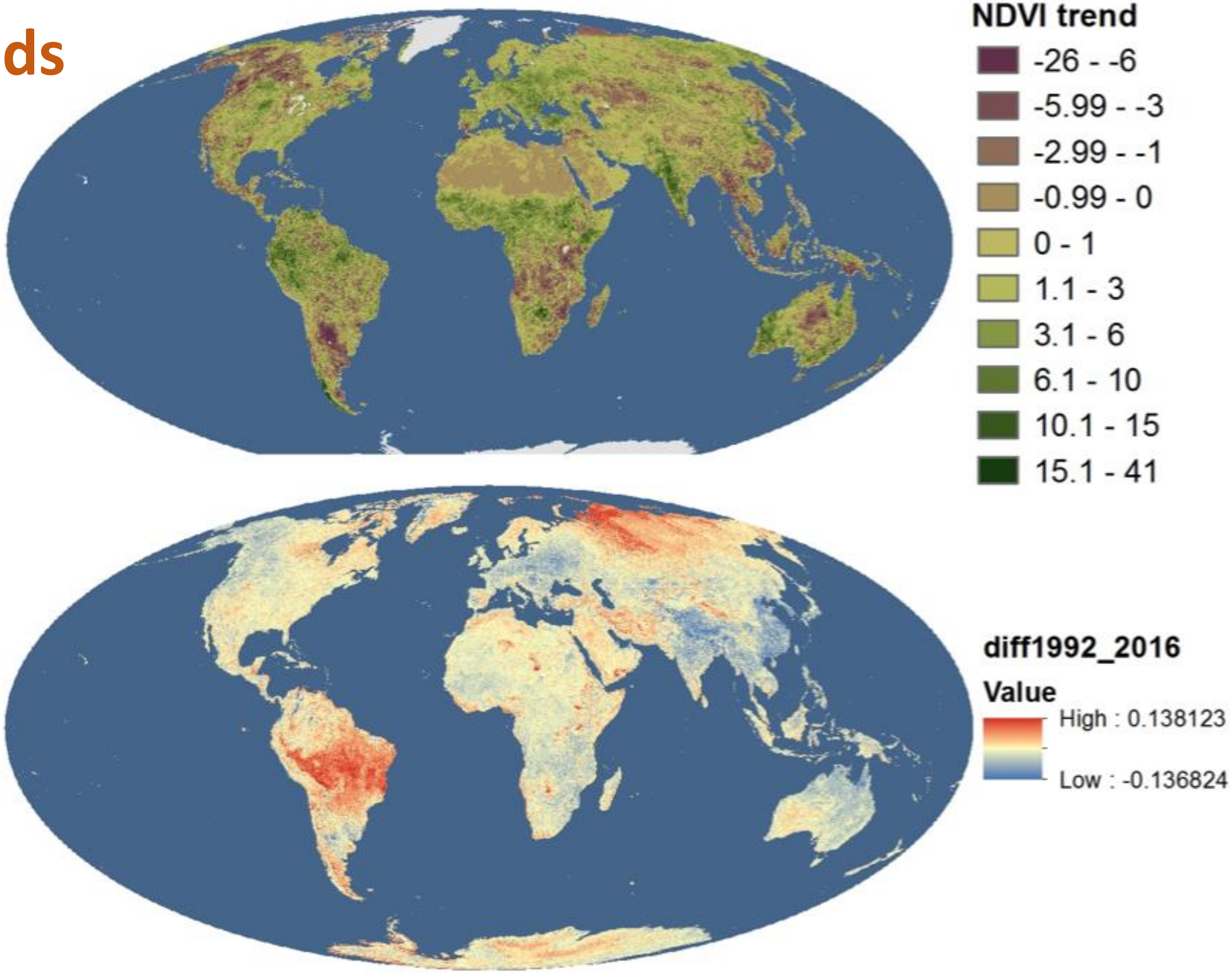
Climate change studies setting out to unravel responses of vegetation and ecosystems to warming and drying have been performed in mesic, humid and cold biomes, and have focused on the known dominant mechanisms of ecosystem functioning and their drivers.

However, the structure and functioning of these systems may change when climatic regime shifts occur.

Major mechanisms typical of drylands ('dryland mechanisms' of ecosystem functioning) may become important in mesic, humid and cold ecosystems when critical thresholds get crossed in a warmer and drier climate.

Browning and drying trends

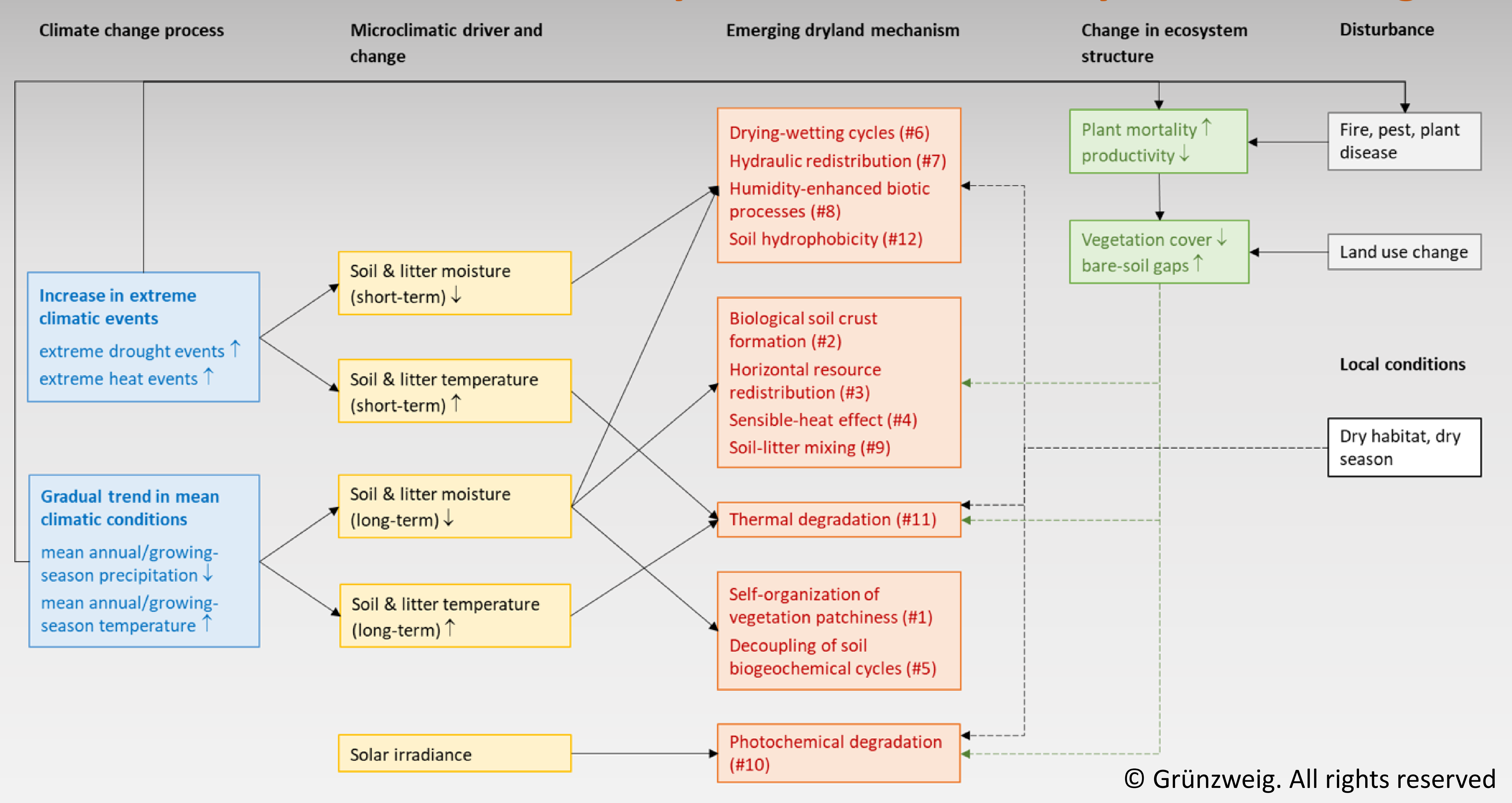
Many mesic, humid and cold regions experience lower vegetation cover and drier soils in recent decades



Top: Trends in greening and browning (NDVI trend based on AVHRR GIMMS data between 1982 and 2008; reproduced from De Jong et al. 2012 Glob Change Biol 18, 642-655). Bottom: Soil moisture difference (m^3 m^{-3}) between 1992 and 2016 (data from: https://www.earth-syst-sci-data-discuss.net/essd-2019-191/).

Dryland mechanism (#)	Drivers	Immediate consequences	Affected processes
Self-organization of vegetation patchiness (#1)	Soil drought	Vegetation patchiness, gaps of bare soil	Production, water and nutrient budgets
Biological soil crust formation (#2)	Soil drought	Cover of bare soil	Production, water flow, carbon and nutrient cycling, energy budget
Horizontal resource redistribution (#3)	Water, wind, animals	Concentration of resources	Water, carbon and nutrient budgets, vegetation development
Sensible-heat effect (#4)	Aridity, sparse vegetation cover	Decrease in surface temperature	Energy budget, productivity, boundary layer dynamics
Decoupling of soil biogeochemical cycles (#5)	Aridity, sparse vegetation cover	Reduction in soil OM and N, increase in P	Plant production, respiration, OM decay
Drying-wetting cycles (#6)	Drought, rain pulses	Soil/plant desiccation and rehydration	Plant production, respiration, OM decay, nutrient cycling
Hydraulic redistribution (#7)	Soil drought, water potential gradient	Transient soil rehydration	Plant nutrient uptake, OM decay, C cycle
Humidity-enhanced biotic processes (#8)	Fog, dew, water vapor (non-rainfall water)	Increased soil, litter and plant moisture	Plant activity, microbial OM degradation
Soil-litter mixing (#9)	Soil deposition, litter transport	Increased litter moisture	Microbial OM degradation
Photochemical processes (#10)	Solar radiation	Increased energy uptake by OM	OM decay, trace gas emission
Thermal processes (#11)	Heat	Increased energy uptake by OM	OM decay, trace gas emission
Soil hydrophobicity (#12)	Drought, heat	Low soil moisture	Plant production, root water access, OM decay

Potential enhancement of dryland mechanisms by climate change



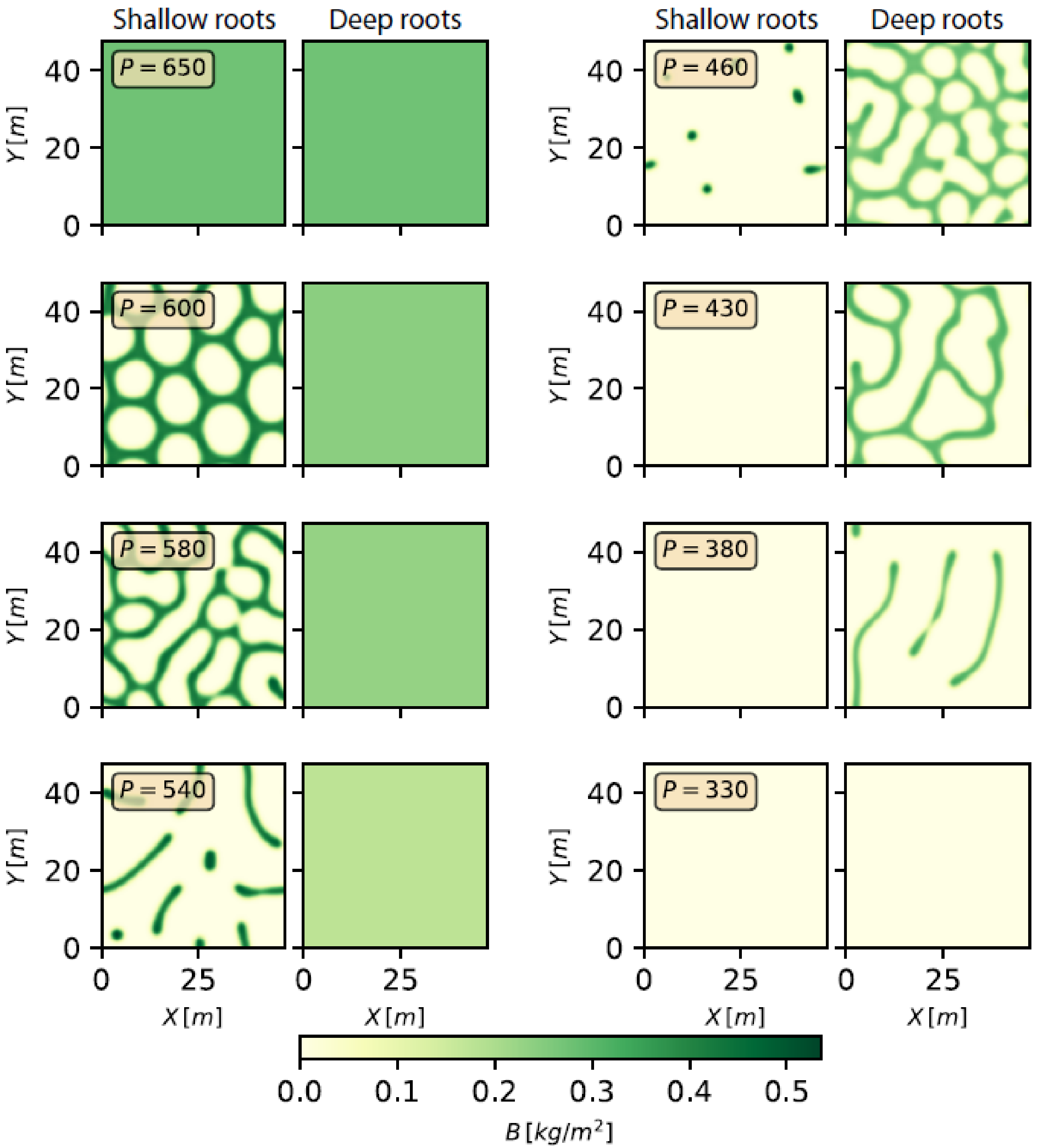
Self-organization of vegetation patchiness at low precipitation (#1)

Spatially uniform vegetation forms patches of vegetation interspersed by bare soil when precipitation (*P*) decreases and passes a threshold

This threshold is much higher for plants with shallow roots not adapted to drought than for drought-adapted plants with deep roots.

Shown are spatial biomass distributions (*B*) of each plant type at decreasing long-term annual precipitation rates (mm/yr) on square domains of $47\ m \times\ 47\ m$.

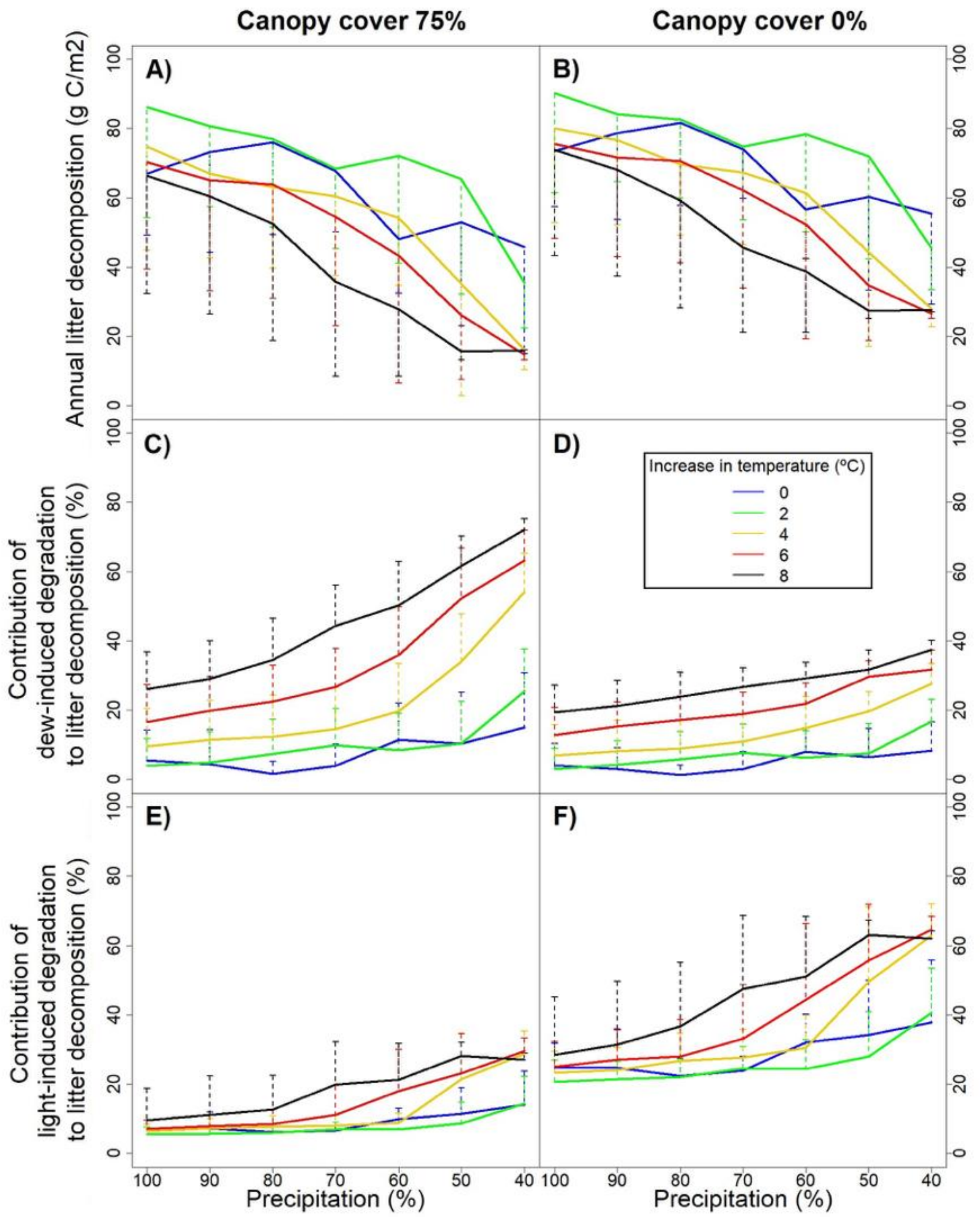
Continuum vegetation model for flat terrains that consists of nonlinear partial differential equations for three state variables (Getzin et al. 2016 PNAS).



Relative importance of dryland litter decay mechanisms (#8, 10) at low precipitation and high temperature

Simulations of extreme drought and warming in a temperate forest:

- **decline in litter decomposition**
- **increased contribution of microbial degradation induced by dew, particularly under high canopy cover**
- **rise in light-induced photodegradation, especially in forest gaps (0% cover)**



Global change scenarios using KEYLINK , a mechanistic process-based soil model simulating the carbon cycle in soils, and its responses to climate, soil structure, ecohydrology and soil food web processes (https://github.com/Plant-Root-Soil-Interactions-Modelling/KEYLINK).

Emerging mechanisms: strength of evidence

Dryland mechanism (#)	Likelihood	Potential importance
Self-organization of vegetation patchiness (#1)	●●	●●●
Biological soil crust formation (#2)	●●	●●
Horizontal resource redistribution (#3)	●●	●●●
Sensible-heat effect (#4)	○	●●●
Decoupling of soil biogeochemical cycles (#5)	○	●●●
Drying-wetting cycles (#6)	●●●	●●

Dryland mechanism (#)	Likelihood	Potential importance
Hydraulic redistribution (#7)	●●●	●●
Humidity-enhanced biotic processes (#8)	●●●	●●
Soil-litter mixing (#9)	●●	●
Photochemical processes (#10)	●●●	●●
Thermal processes (#11)	●●●	●
Soil hydrophobicity (#12)	●●●	●●●

○ unknown, ● little, ●● moderate, ●●● strong

Integrating hypotheses for the emergence of dryland mechanisms in mesic, humid and cold regions

Long-term rise in mean temperatures and decrease in soil water availability, and the increase in the frequency and duration of extreme drought and heat events in many regions globally may force volumetric soil water content below ~25-35% and soil temperature above ~25-50°C, thresholds beyond which the emergence of various dryland mechanisms is expected.

Conclusions

With a globally increasing area exposed to gradually rising temperatures, decline in soil moisture, and increasing frequency, duration and intensity of extreme heat and drought events, we envision that dryland mechanisms will increasingly control ecosystem functioning in many regions of the world.