Exploring the effects of rainfall variability on banded vegetation

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Motivation

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Runoff loss in hillslopes is modulated by rainfall intensity, i.e., increasing rainfall intensity is likely to favour runoff over infiltration, and therefore affect the banded vegetation formation.

Different inter-storm dry periods prompt different responses from the vegetation. Semi-arid climates exhibit highly variable rainfall, with a few intense events and a larger number of very mild events.

Dryland ecosystems are in a quasi-permanent transient condition, exhibiting non-linear and far-from equilibrium responses to boundary conditions and forcings.

The mismatch between the default modelling approach for vegetation-self organisation and the properties of rainfall in such systems calls for further complexity in the models and in the forcing, in particular regarding sloping terrain and vegetation bands.

Here we present a first exploration (and very preliminary results) to evaluate sensitivity and influence of variability

Goals and approach

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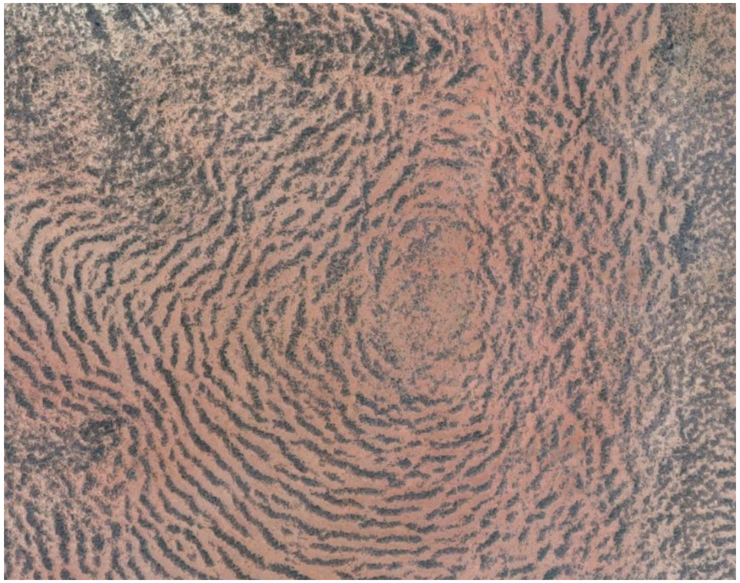
In the context of banded vegetation on hillslopes, we aim to explore how rainfall variability, through spatiotemporal water redistribution, can influence the vegetation self-organisation (VSO) process



What do we do?

1- use Rietkerk's model for VSO

2- upgrade the surface water equation with a physically-based zero-inertia shallow-water approximation → account for multiscale hydrodynamics

3- compute a simple hillslope, allowing a runoff loss at the foot

4- compare VSO evolution with randomised (yet idealised) rainfall signals against periodic (yet not-continuous) rainfall

Mathematical model

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Reaction-diffusion PDE system proposed by HilleRisLambers et al. (2001)

$$\frac{\partial b(\mathbf{x},t)}{\partial t} = D_b \nabla^2 b + c_b \mathcal{U}(b,W) - d_b b$$

Biomass evolution

$$\frac{\partial W(\mathbf{x},t)}{\partial t} = D_w \nabla^2 W + i(b) - \mathcal{U}(b,W) - pW$$

Subsurface water evolution

Infiltration

$$i(b,h) = \alpha h \frac{b + kW_0}{b + k}$$

Uptake

$$\mathcal{U}(b,W) = g_b b \frac{W}{W + k_b}$$

Surface water depth (h) evolution

Zero-inertia (diffusive-wave) approximation of the shallow water eqs.

$$\frac{\partial h(\mathbf{x},t)}{\partial t} = D_h \nabla^2 h + r - i(b)$$

Surface flow

$$\frac{\partial h(\mathbf{x},t)}{\partial t} = \nabla \left[h^{\frac{5}{2}} \left(\frac{8g}{f} \right)^{\frac{1}{2}} \frac{\mathbf{Z}}{||\mathbf{Z}||} \right] + r(t) - i(b)$$

Rain

Infiltration

$$\mathbf{Z} = \nabla (h + z)$$

Water surface gradient

HilleRisLambers, R.; Rietkerk, M.; van den Bosch, F.; Prins, H. H. T. & de Kroon, H. *Vegetation pattern formation in semi-arid grazing systems.* Ecology, 2001, 82, 50-61

Numerical experiment

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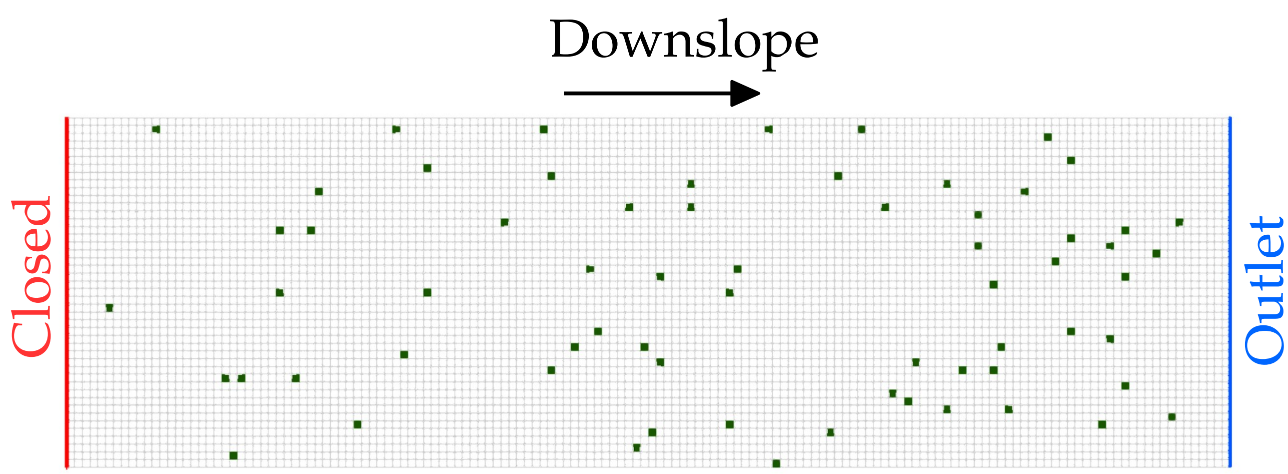
Computational domain: sloping plane, 300x90 m



Random initial biomass distribution

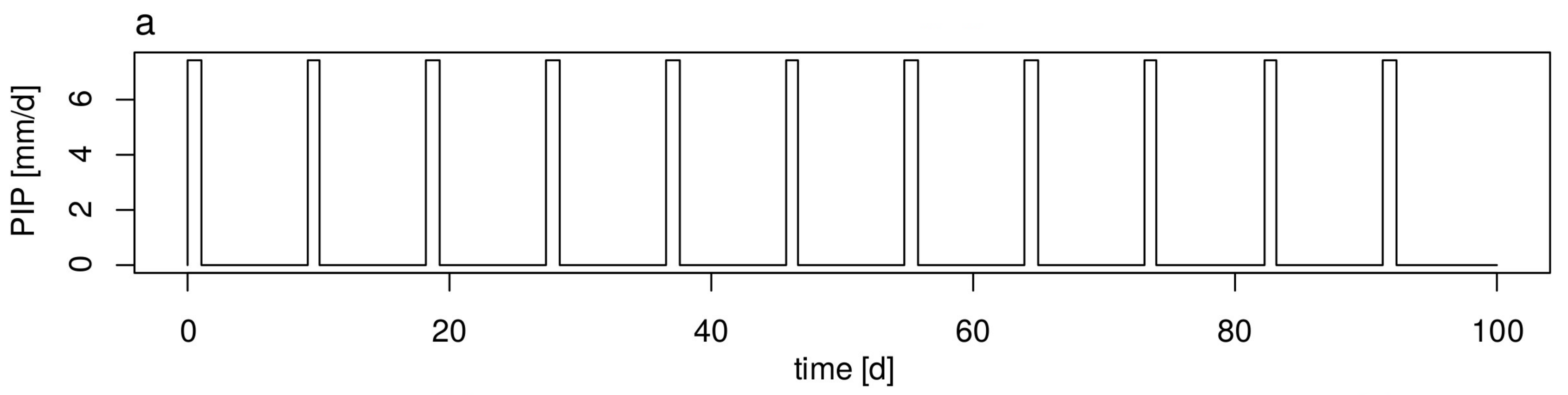
Spatial resolution 2m.

Variable temporal resolution, high resolution during runoff (seconds) following stability of hydrodynamics (seconds). Lower resolution during dry periods (minutes – hours).

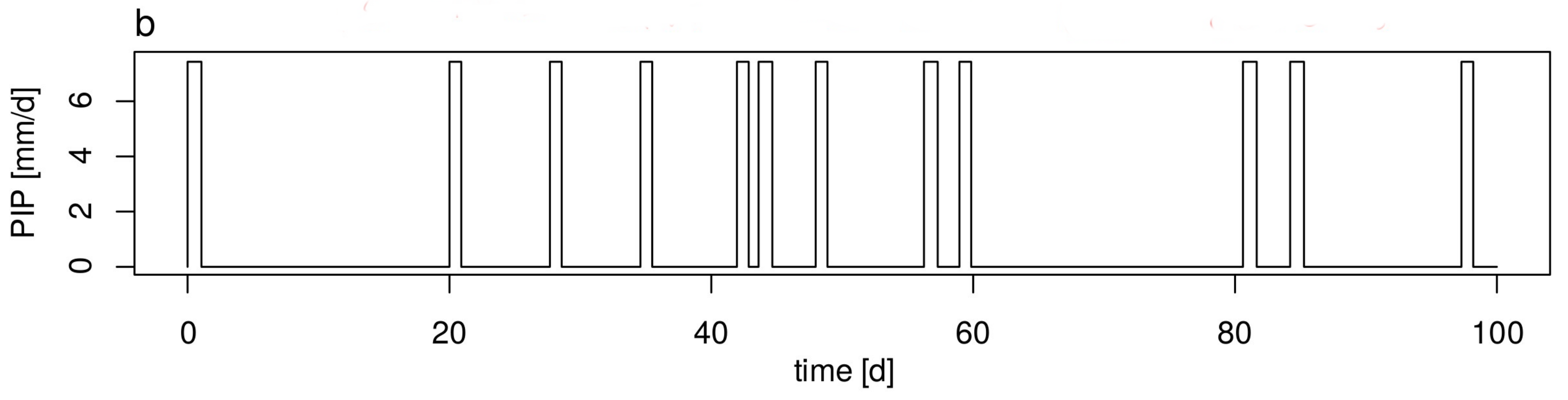
Simulations run for 30 years.

Numerical experiment

Reference case: periodic rainfall signal, single day of constant rainfall intensity, followed by a dryspell



Randomisation: keep a single day of rain of constant intensity, randomise the dryspell duration, keep annual rainfall constant



Preliminary results

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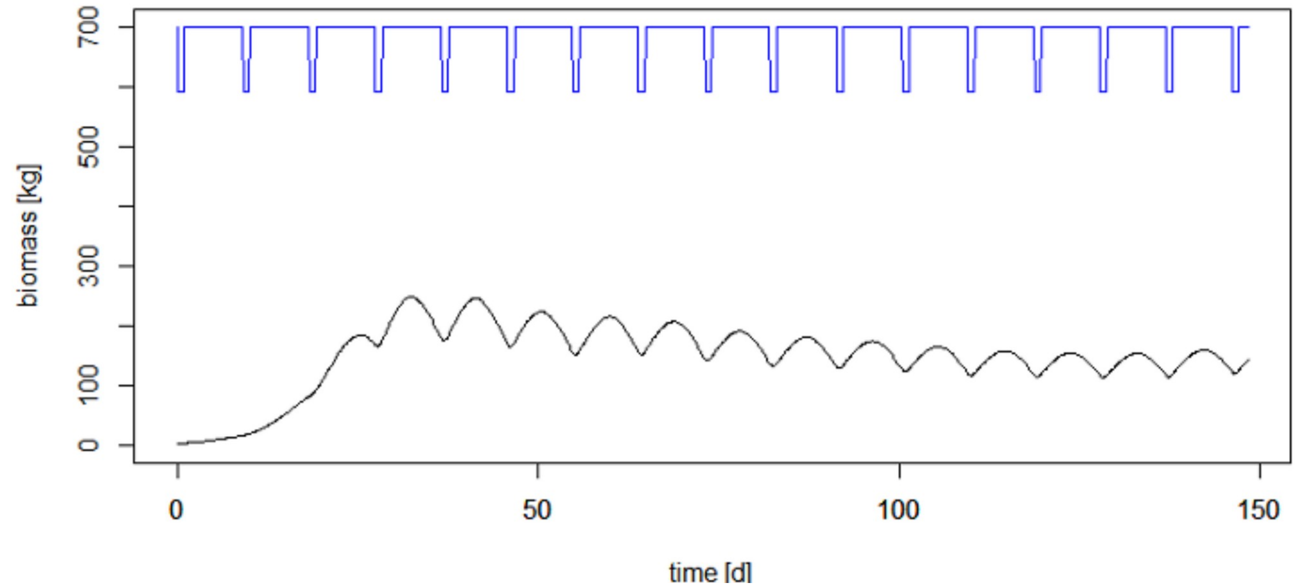
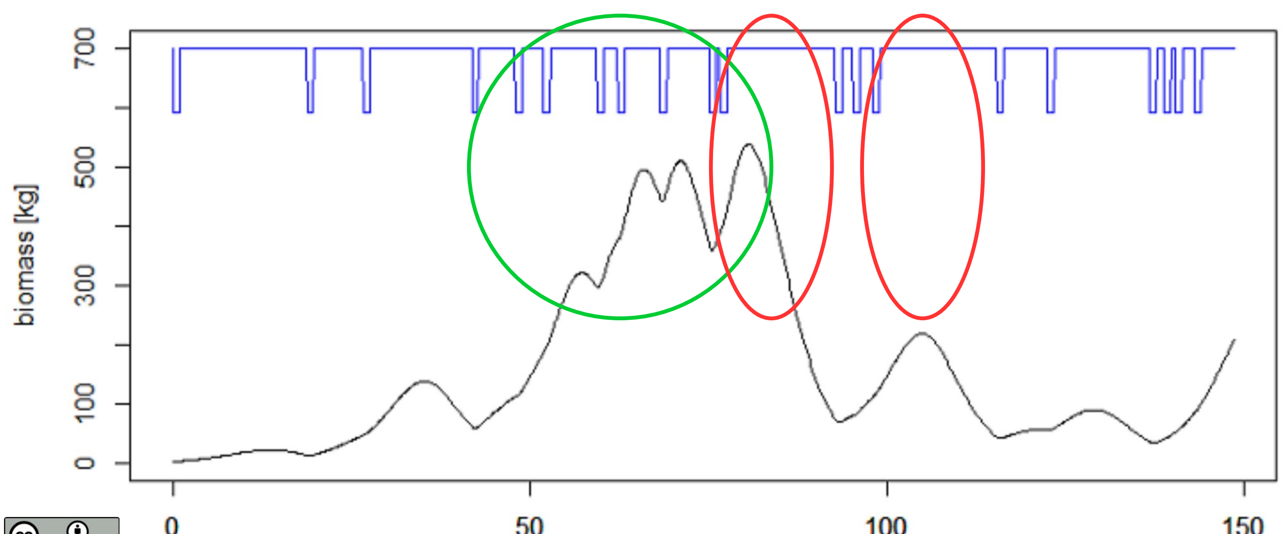
The reference biomass yield signal produces a rather stable, periodic biomass yield, with some long-term pseudo-steady trend



Wet period → growth   Dry period → decay



Randomised rainfall shows that the particular sequence of events can play a very strong role (too strong?!)

Preliminary results

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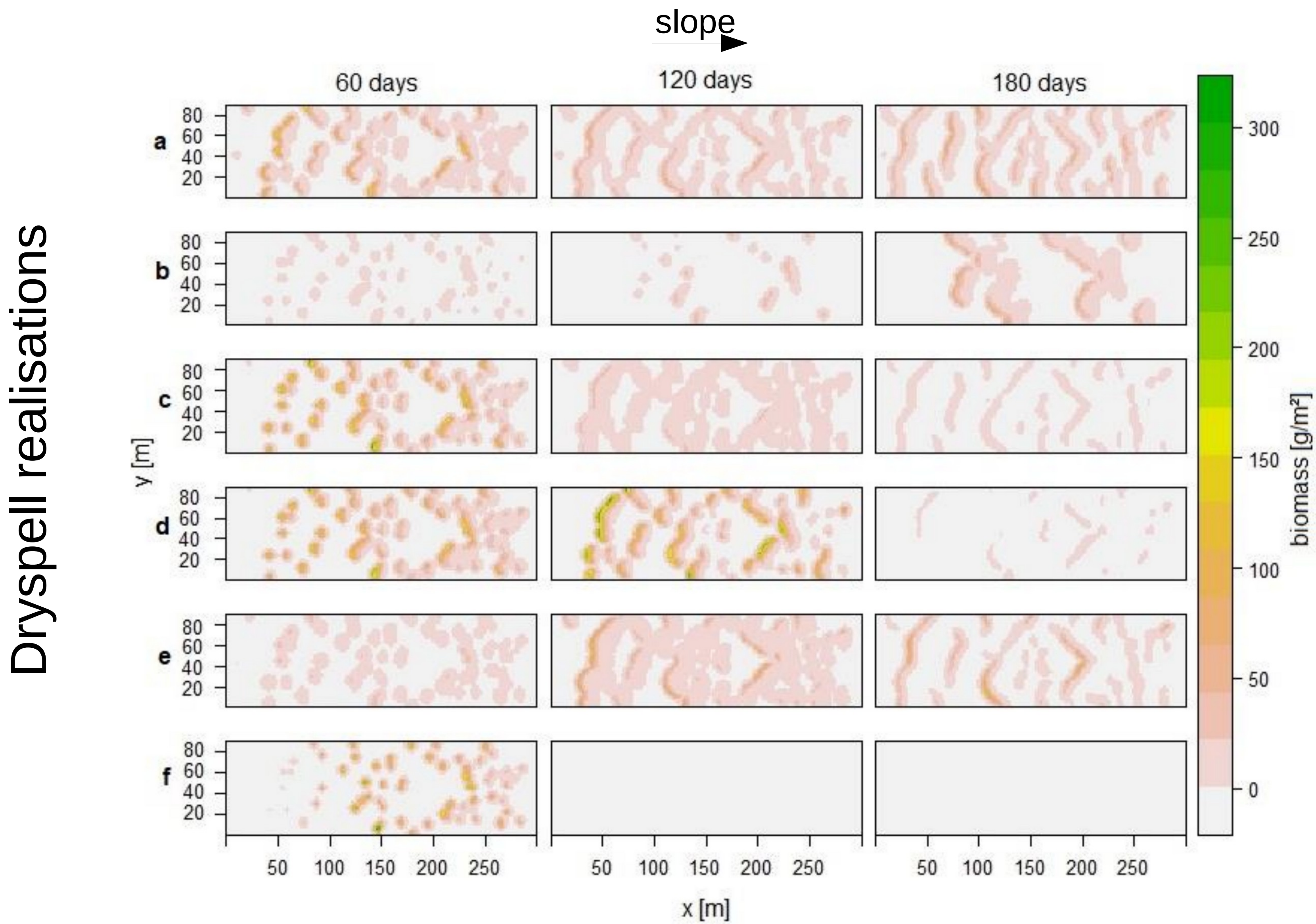
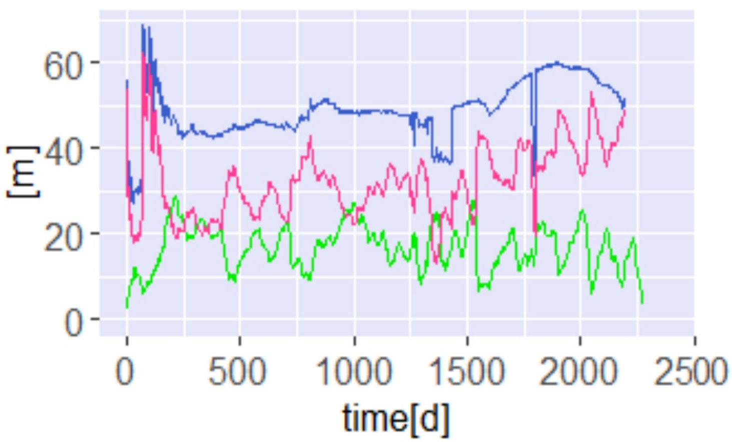
The simulated banded vegetation has a strong response to rainfall variability.

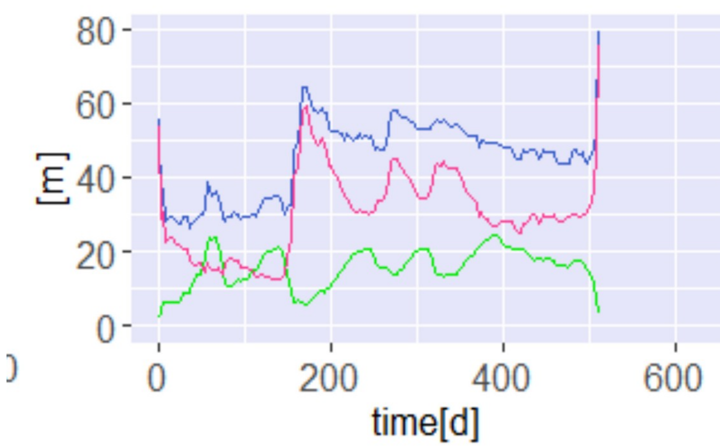


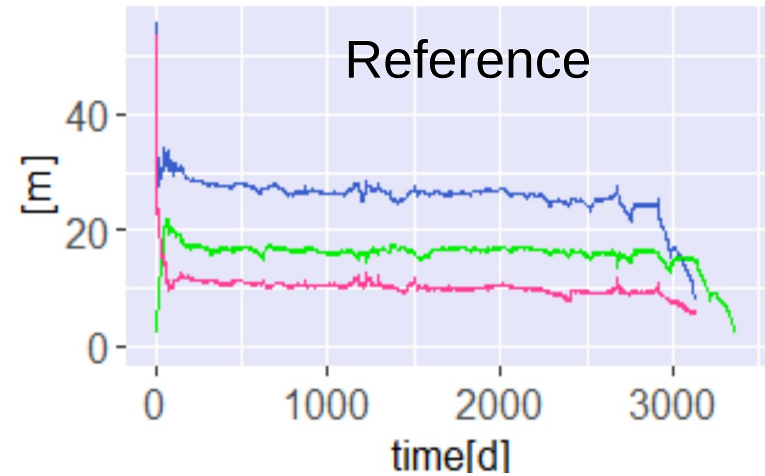
Preliminary results

Pattern properties are affected

Random dryspell realisations (examples)







Mean band wavelength
Mean bandwidth
Mean interband width

Different magnitudes:
- wavelength goes from around 30m (reference) to around 50m (realisations)
- temporal signals are noisier and highly variable, but all different

Preliminary results

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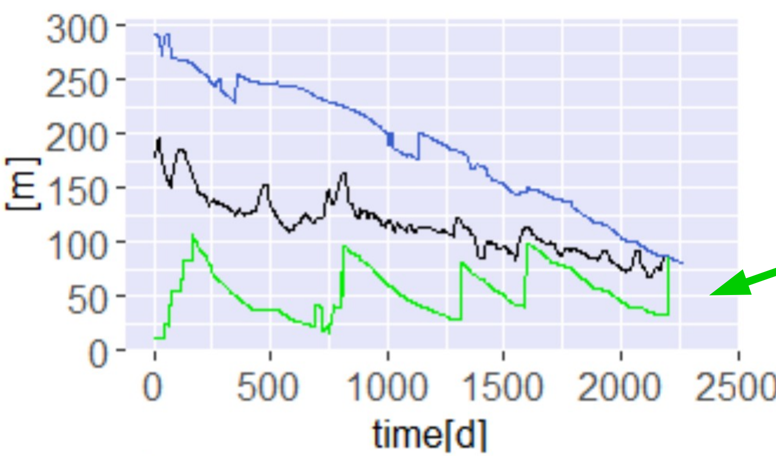
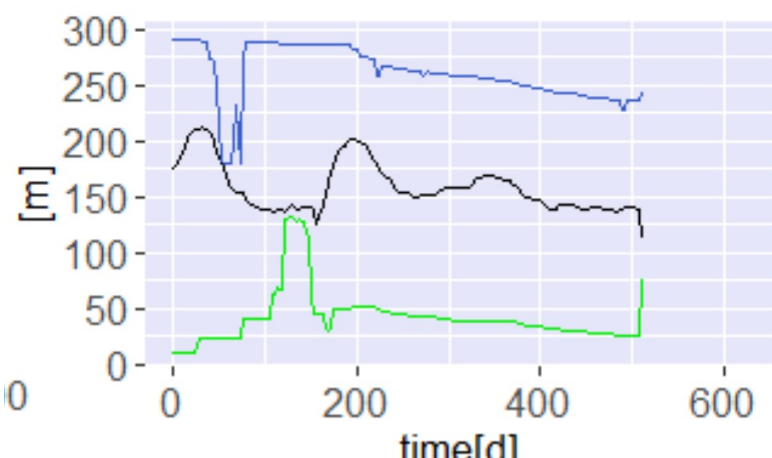
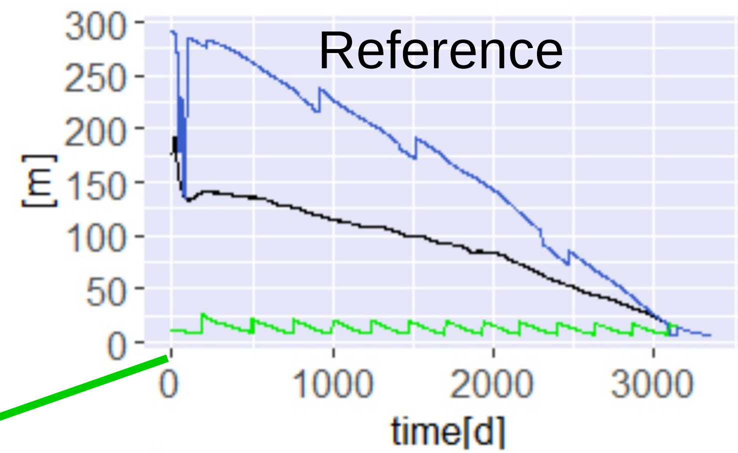
Band migration speed is affected

Random dryspell realisations (examples)







Mean migration speed
Lead band migration speed
Last band migration speed

The leading band is strongly affected, other bands seem less affected.

Summary and outlook

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- Results show qualitatively and quantitatively that the simulated banded vegetation has a strong response to rainfall variability.
- Results also suggest that the sequence of events / dryspells can play a different role if they occur early (far from equilibrium) or late (closer to equilibrium).
- Proper statistical analysis and a large number of realisations needs to be done to assess meaningful trends, this is underway.
- We are also extending of randomising other properties of the idealised rainfall signal, one at a time (duration of rain, intensity of pulse, etc).
- Preliminary results suggest that the model reacts to strongly to variability → address standing problems with rates and time-scales associated to (most likely) parametrisation of the model.