Analysis of shifts in the spatial distribution of vegetation due to climate change

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Motivation

- The similarities embedded in the enormous diversity existing in river basins makes one wonder about the possible **existence of basic organizing principles** controlling the fundamental themes that nature plays to bring about such richness of forms
- Fundamental to the possible existence of such organizing principles is the **role of energy** in the formation and maintenance of theses systems
- **Thermodynamics** is the study of the properties of energy and its transformations. It will play a key role in the search of the aforementioned principles.

Motivation

$$H(s) \approx \sum_i Q_i^{\gamma} L_i \quad \gamma = 0.5$$

$$\rightarrow \sum_i Q_i^{0.5}$$

$$\rightarrow \sum_i A_i^{0.5}$$

Motivation

Is there a similar principle controlling the spatial organization of vegetation?

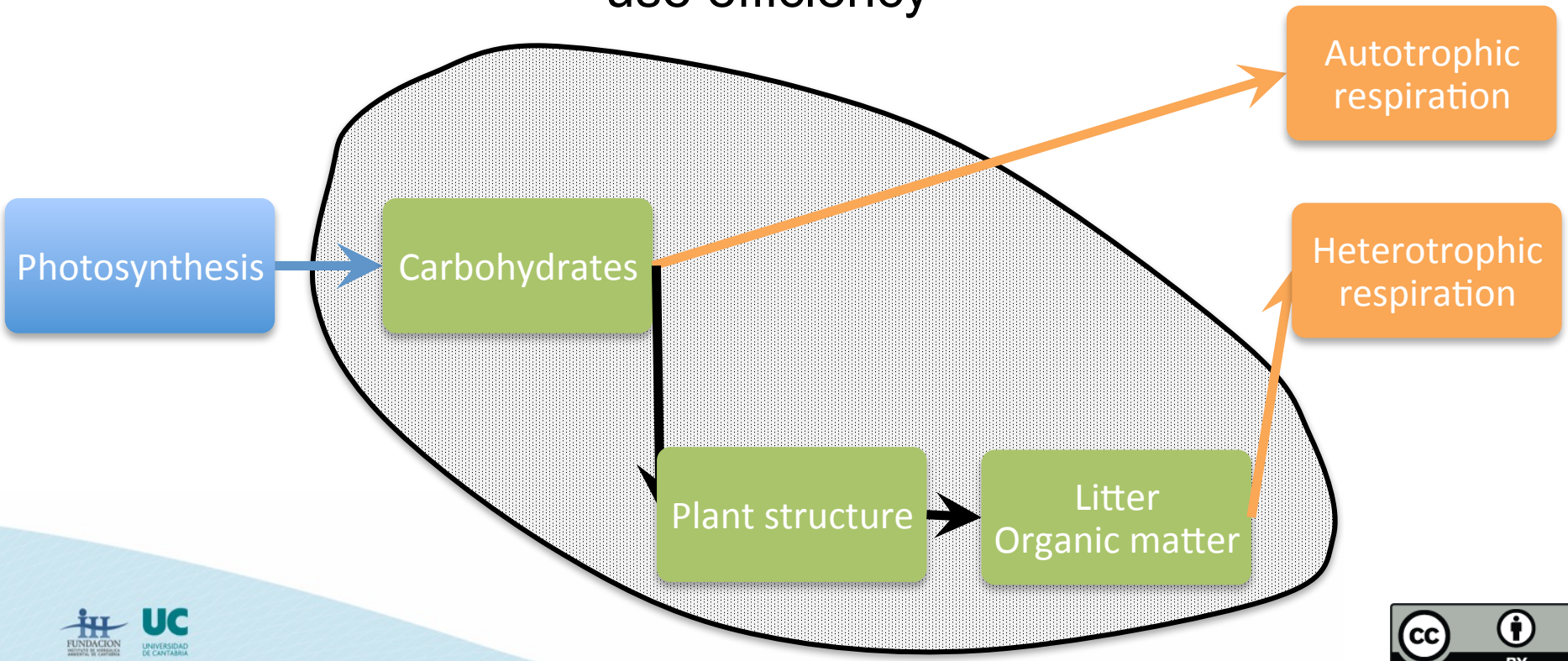
- Vegetation constitutes a **far from equilibrium thermodynamic systems**, maintained by the flux of energy that arrives from the sun
- **Entropy** cannot be defined as it is not a state function anymore but it is produced at a given rate
- There is is need to make use of a different framework

Maximum entropy production

- **Maximum Entropy Production (MEP; Kleidon 2010, Dewar 2010)** serves as a general thermodynamic limit toward which complex, far from equilibrium systems evolve.
- MEP postulates that these systems are driven toward MEP states, which are preferably selected among all attainable states because they can exist within a greater number of environments.
- We use MEP to study the organization of vegetation at the ecosystem scale on a river basin.

Maximum entropy production

Maximum entropy production is equivalent to the maximization of atmospheric CO_2 assimilation, which can be approximated as the product of plant transpiration and water use efficiency



Maximum entropy production

$$\sigma_{system} = \frac{1}{T}(P\ \mu_P - R_A\ \mu_R - R_B\ \mu_R)$$

$$\sigma_{system} = \frac{1}{T}(P\ \mu_P - (R_A + R_B)\ \mu_R)$$

$$\sigma_{system} = \frac{1}{T}(P\ (\mu_P - \mu_R))$$

$$\sigma_{system} \propto P$$

Dewar 2010, Kleidon 2010

Objective

Analyze the shift of the spatial distribution of vegetation in a semi-arid watershed due to climate change

Study site

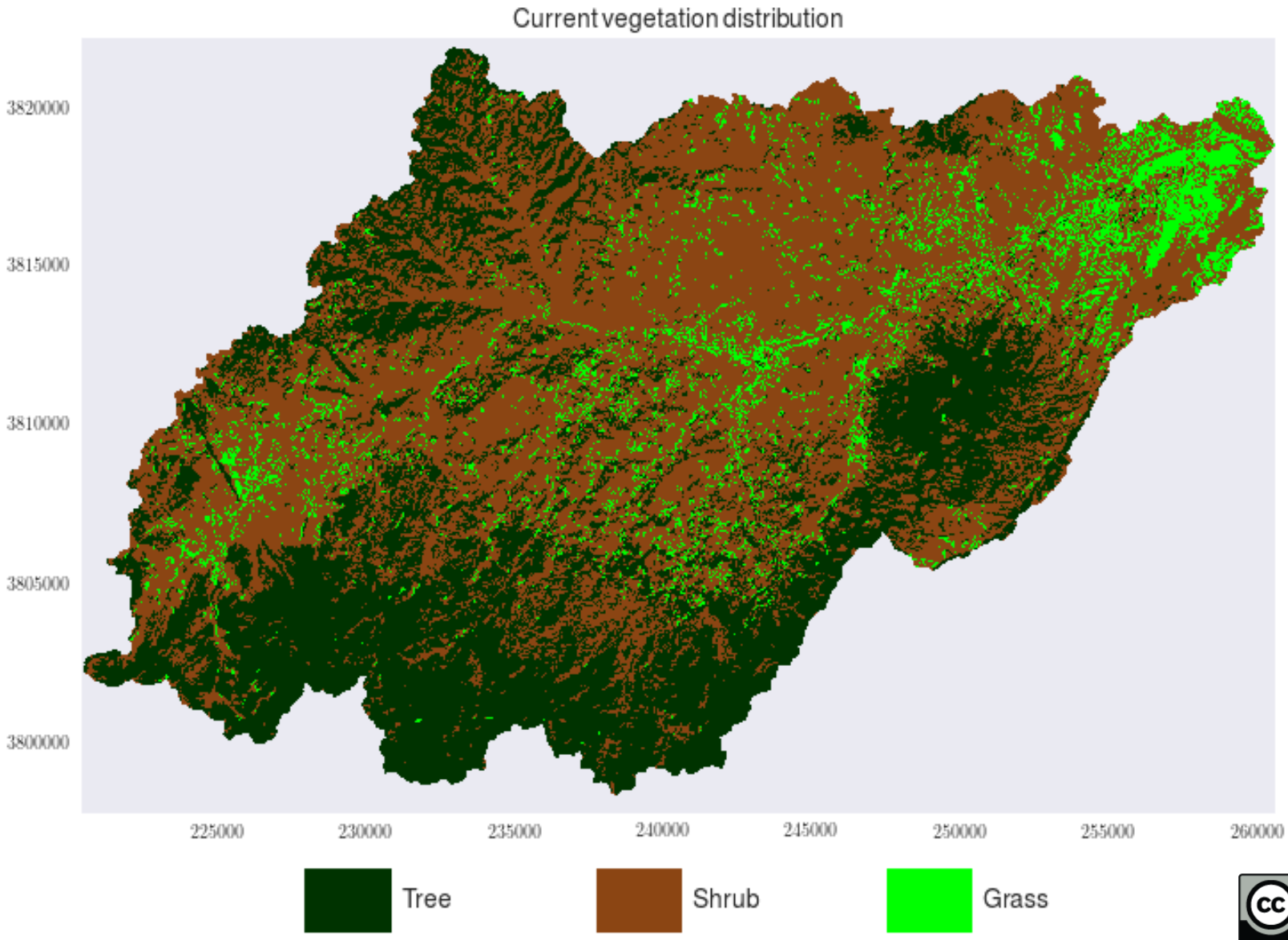
Upper Rio Salado

- Located near Sevilleta LTER, New Mexico and the Cibola National Forest
- 464 Km²
- Strong precipitation gradient (220 mm/year at 1600 m to 325 mm/year at 2500 m)
- Average temperature during growing season (May to September) around 20ºC
- Snow accumulation during winter

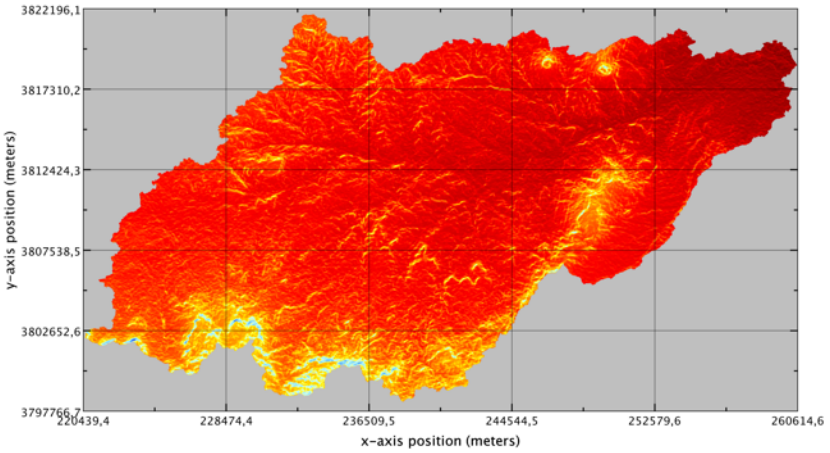
Data

- **DEM:** ASTER Global DEM
- **Meteorological information:** Sevilleta LTER and GHCN daily (NOAA)
- **Soil Texture:** U.S. General Soil Map (STATSGO2) by State, U.S. Department of Agriculture (USDA)
- **Land Cover:** 2011 National Land Cover Data Set (NLCD), U.S. Geological Survey
- **Climate change:** Ensemble of CMIP5 models.

Data


Current vegetation distribution
3820000
3815000
3810000
3805000
3800000
225000
230000
235000
240000
245000
250000
255000
260000
Tree
Shrub
Grass

Daily mean temperature during during Growing Season

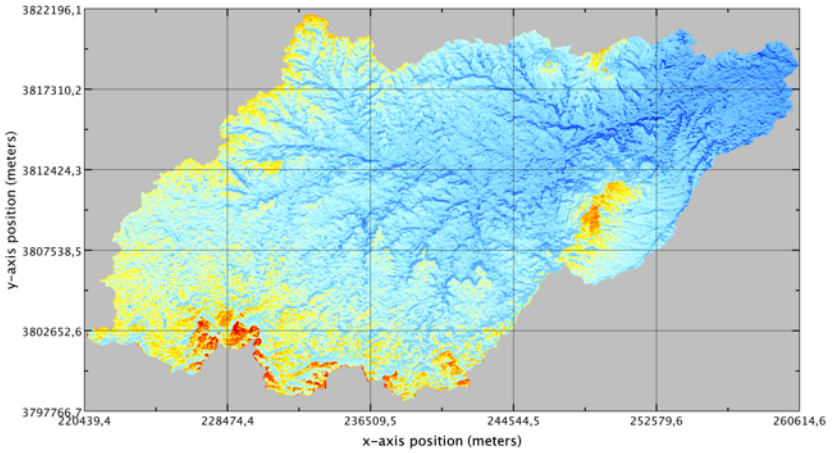


Daily mean temperature during during Growing Season (Celsius Degrees)

10,2 | 12,6 | 14,9 | 17,2 | 19,5 | 21,8

Data Min = 10,2, Max = 21,8

Daily mean rainfall intensity during Growing Season

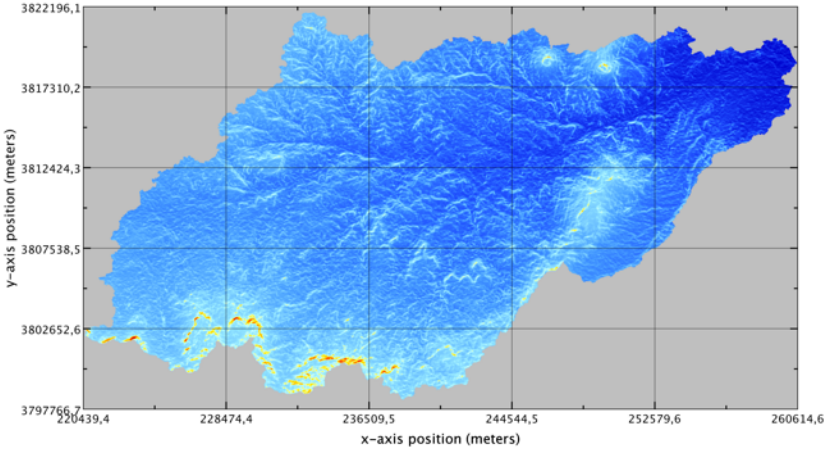


Daily mean rainfall intensity during Growing Season (mm/day)

5,1 | 6,1 | 7,1 | 8,1 | 9,2 | 10,2

Data Min = 5,1, Max = 10,2

Daily mean reñative humidity during Growing Season

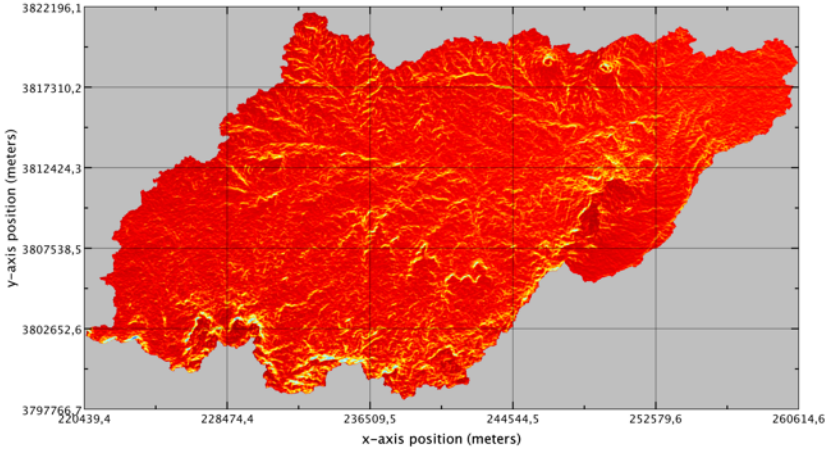


Daily mean reñative humidity during Growing Season (%)

36,9 | 40,0 | 43,1 | 46,1 | 49,2 | 52,3

Data Min = 36,9, Max = 52,3

hourly mean Incoming Shortwave Radiantion during Growing Season



hourly mean Incoming Shortwave Radiantion during Growing Season (W/m2)

199,2 | 250,9 | 302,6 | 354,2 | 405,9 | 457,5

Data Min = 199,2, Max = 457,5

Hydrological model

Stochastic water balance (Laio et al. 2001)

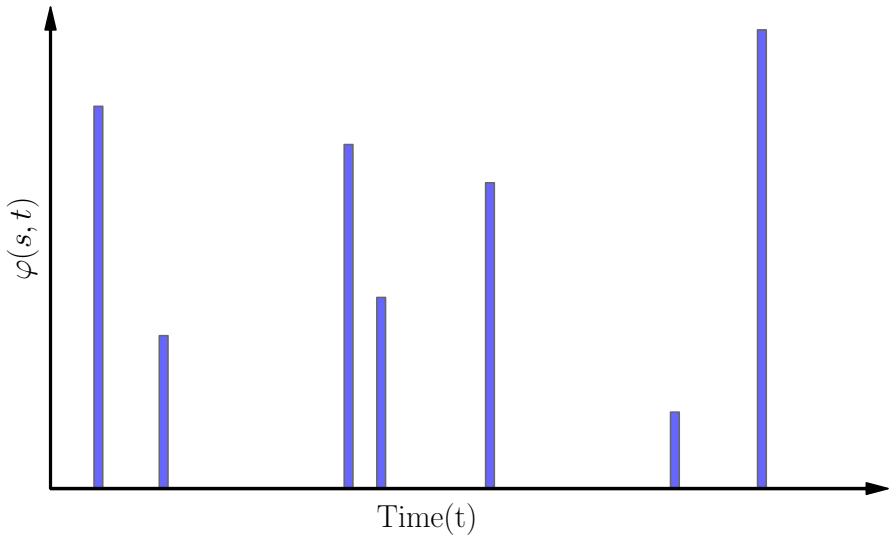
- Provides a **steady state solution** for soil moisture that takes into account the characteristics of soil and vegetation
- Initial transient conditions may be included using **means first passage times** where initial conditions may be important
- Analytically solving the soil moisture expression allows us to solve all the different fluxes completely, and thus, also **transpiration**.

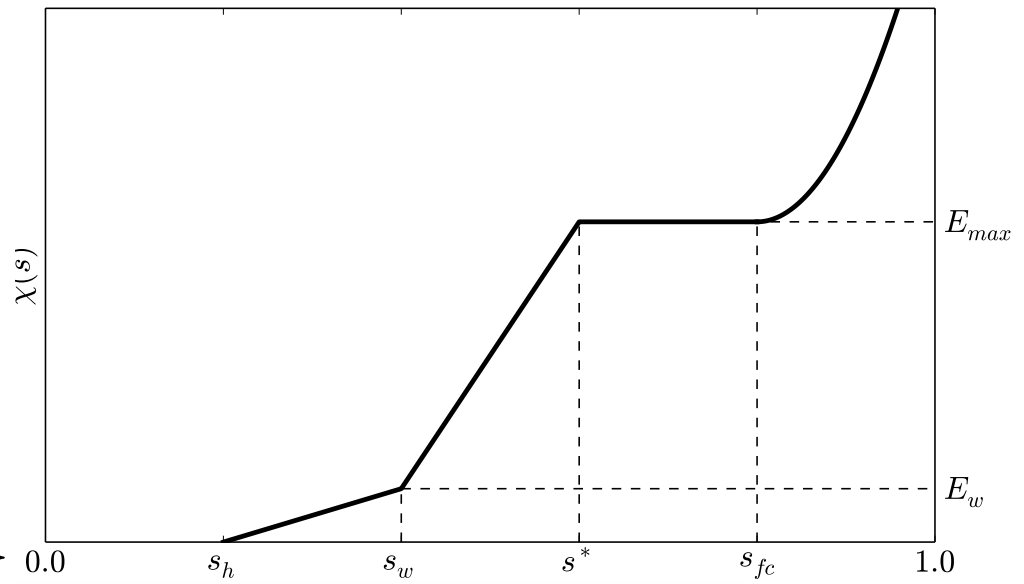
Hydrological model

$$nZ_r \frac{ds}{dt} = \varphi(s,t) - \chi(s)$$

$$\varphi(s,t) = R(t) - I(t) - Q(s,t)$$

$$\chi(s) = E(s) + L(s)$$





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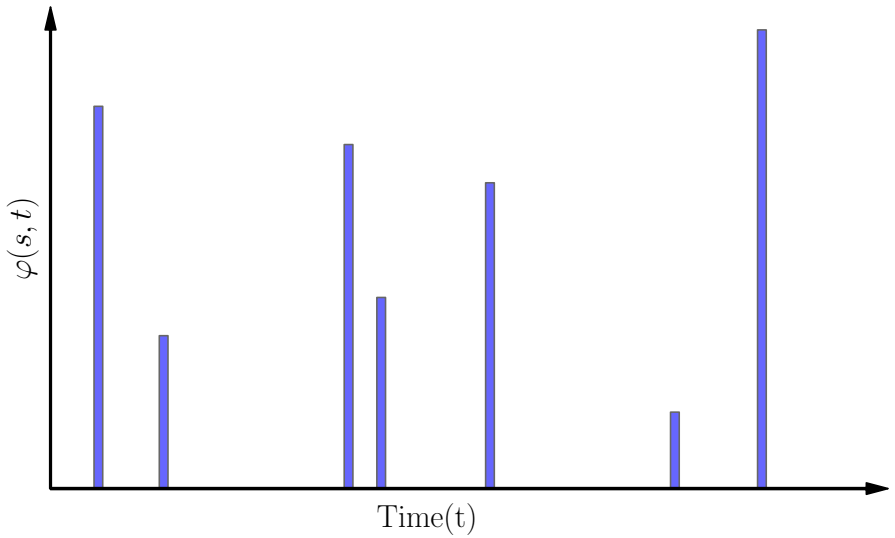
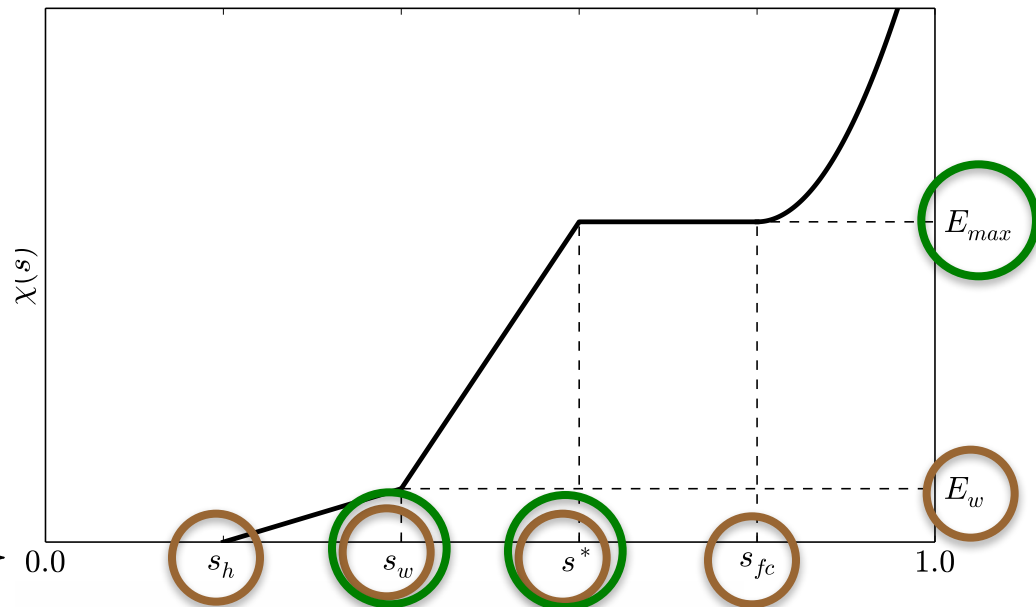
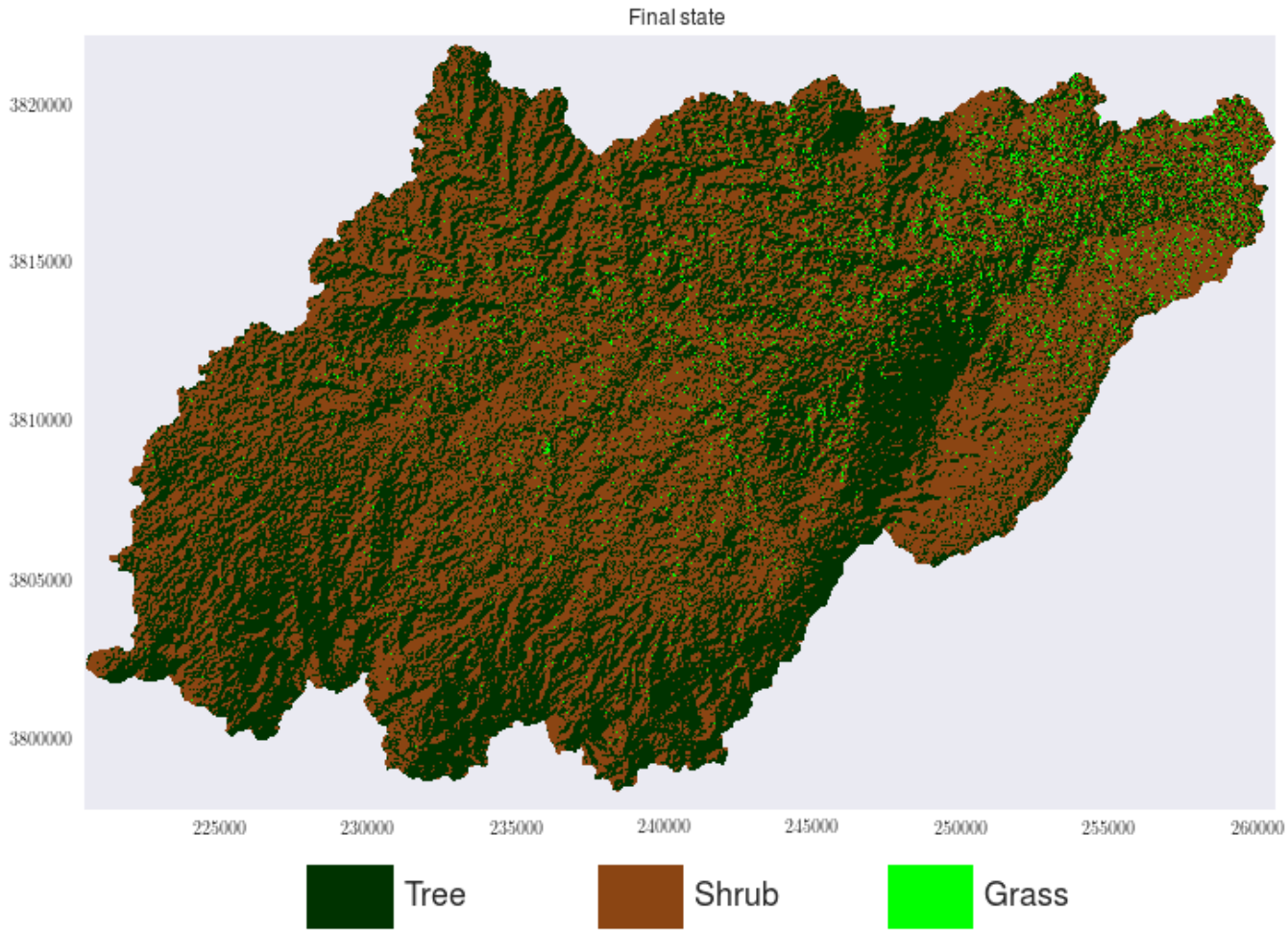




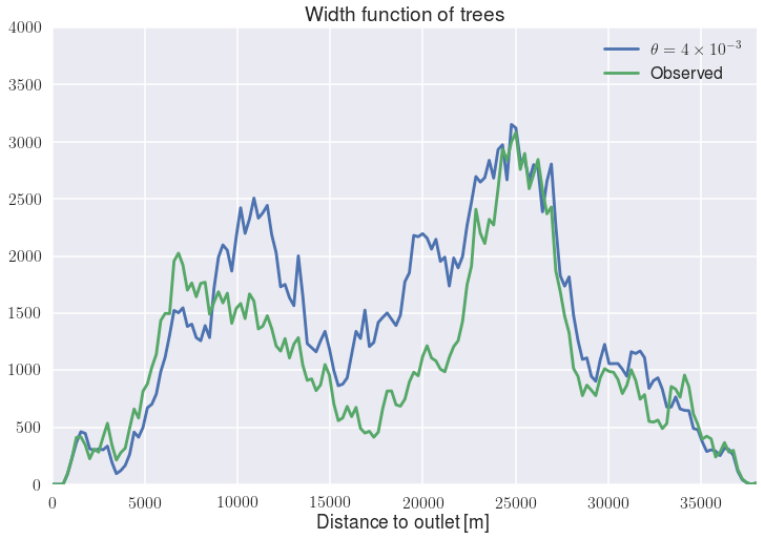
Results

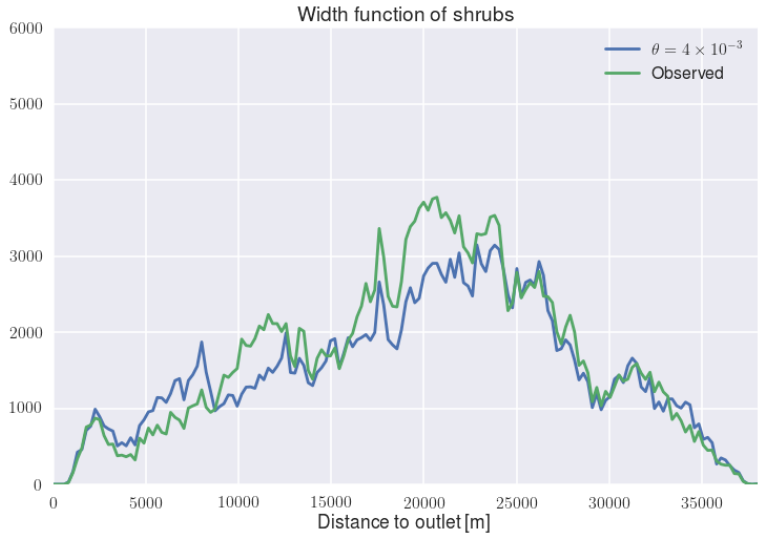
Current situation

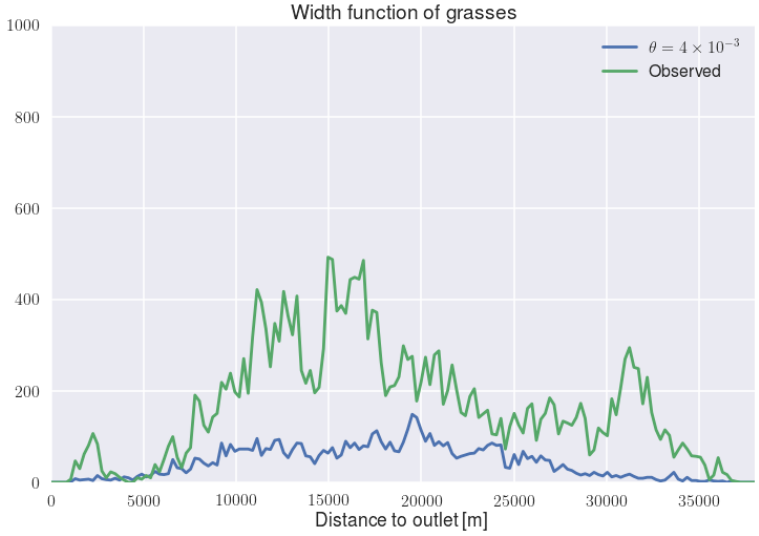


Results

Current situation

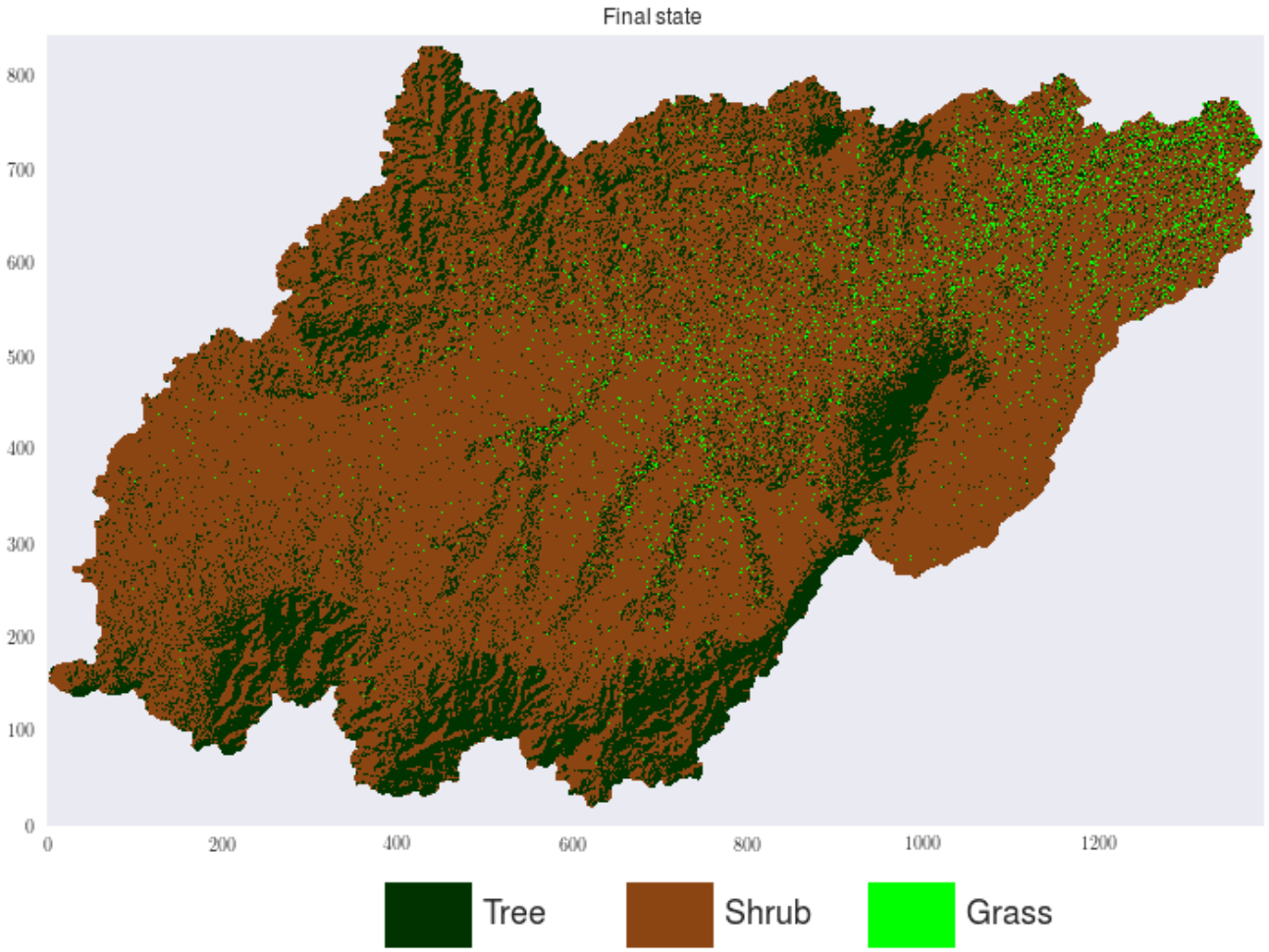






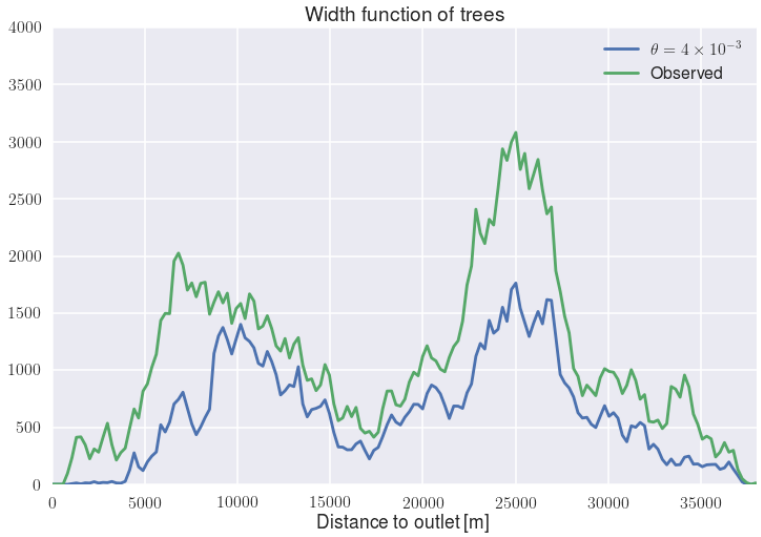
Results

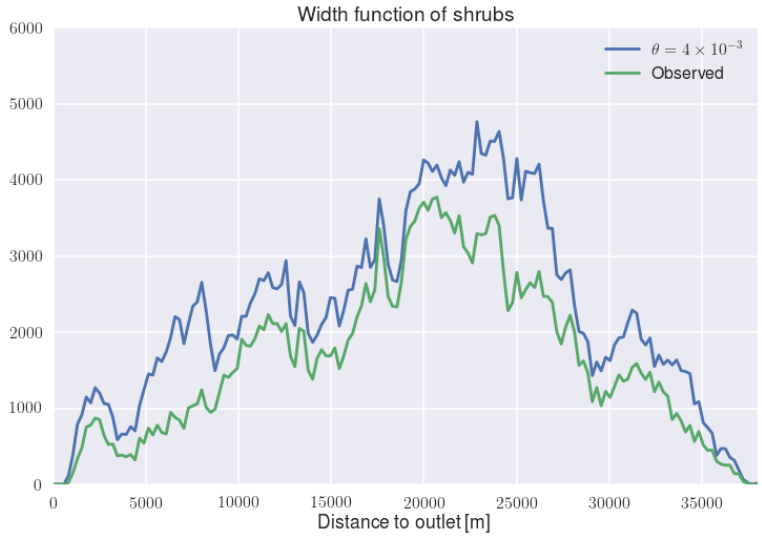
RCP 4.5 – 2016-2035

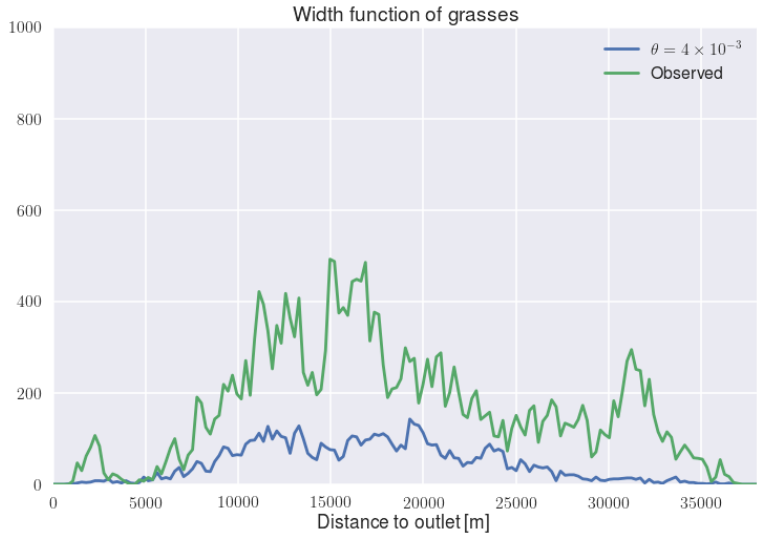


RCP 4.5 – 2016-2035

Results

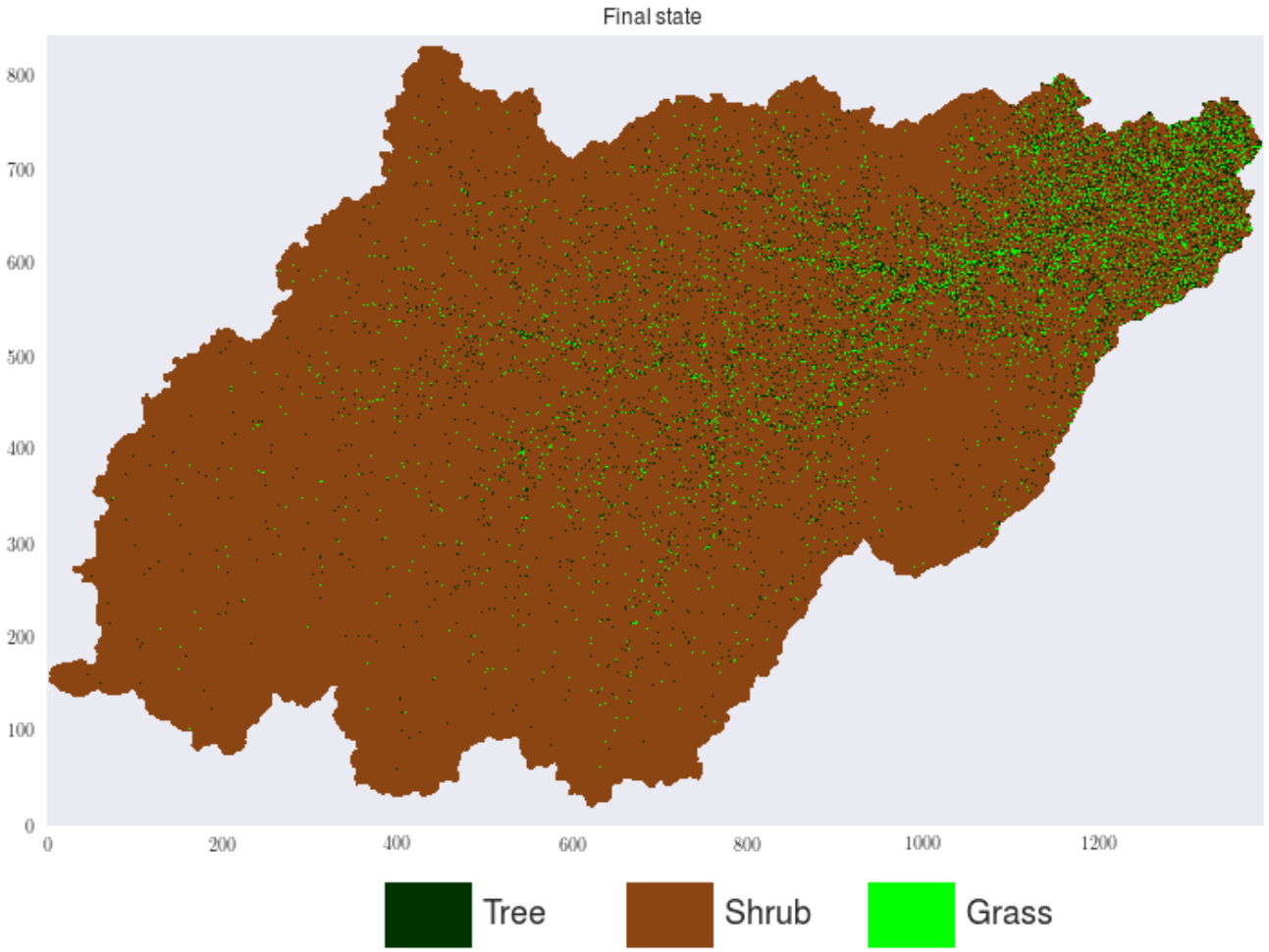






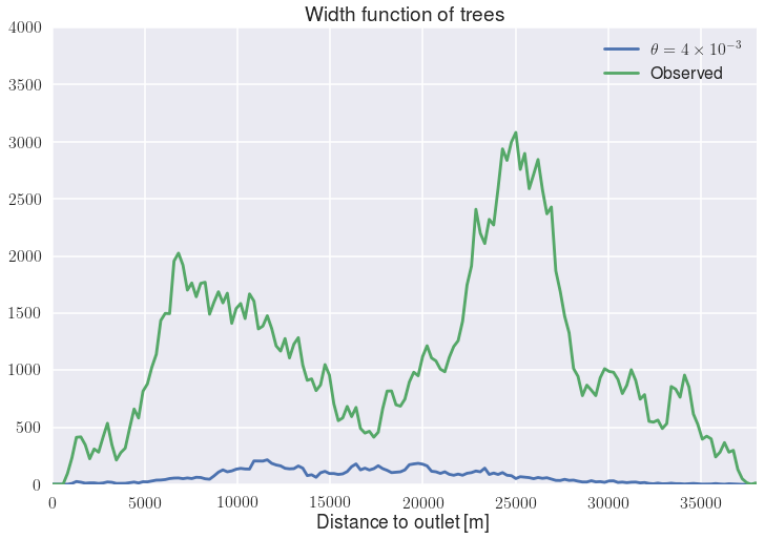
Results

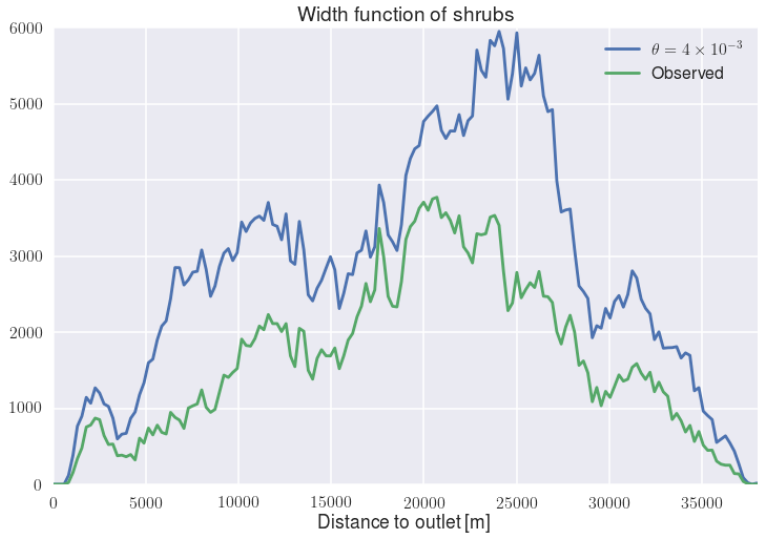
RCP 8.5 – 2065-2100

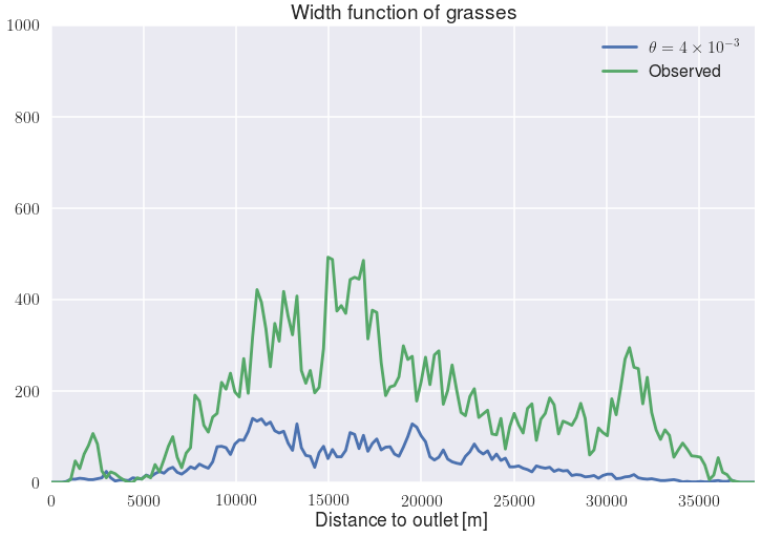


Results

RCP 8.5 – 2065-2100







Conclusions

- There seems to be an underlying organizing principle for vegetation in watersheds, and MEP is a promising candidate for the position
- In spite of not capturing the finest details, the model provides a simple tool to generate plausible spatial distributions of vegetation for different uses
- Climate change seems to be reinforcing the shrub encroachment in the Upper Rio Salado river basin and reducing the ecosystem capability of fixing atmospheric CO_2 (about 20% for the end of the century)

Acknowledgements

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