Experimental evidence for drought induced alternative stable states of soil moisture

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Background

Fig. 1: *C. vulgaris* dominated experimental field site showing an automated rain exclusion setup.

Ecological stable states of ecosystems and the transition between states in response to environmental change has been suggested[1]; though experimental evidence is scarce for state shifts that do not result in ecosystem collapse (e.g. dying of coral reefs, desertification, etc.). However, environmental change has been shown to affect ecosystem processes such as plant photosynthesis[2], soil respiration[3] and soil carbon storage capacity[4]. Especially changes in precipitation patterns as forecast are likely to affect ecosystem processes[5] and may result in invisible ecological state shifts. Recent research has shown that drought can induce soil carbon loss[6] and changes in soil hydraulic properties were suggested to be the main driver. Here we test if repeated summer drought reduces the soil moisture retention leading to permanent alternative states of soil moisture[7].

Methods

Drought is manipulated *in-situ* in an UK Atlantic upland heath dominated by the dwarf shrub *Calluna vulgaris* since 1999. About 22 % of annual precipitation was removed from experimental plots during the plants growing season. The experiment consists of 3 drought removal and 3 untreated control plots. The site has podzolic organo-mineral soils with ~10 cm organic horizon overlying a ~ 28 cm thick mineral soil layer over weathered fractured mudstone[6,7].

Soil moisture

- 1998-2008 with a ThetaProbe
- After 2008 with embedded TDR sensors

Hydraulic measurements

- Soil water release curves on 250 cm^3 cores (0-5 cm) under *C. vulgaris* with a Hyprop
- Field hydraulic conductivity measured with mini-disk infiltrometer

Soil moisture model

- Numerical model Hydrus 1-D to simulate soil moisture

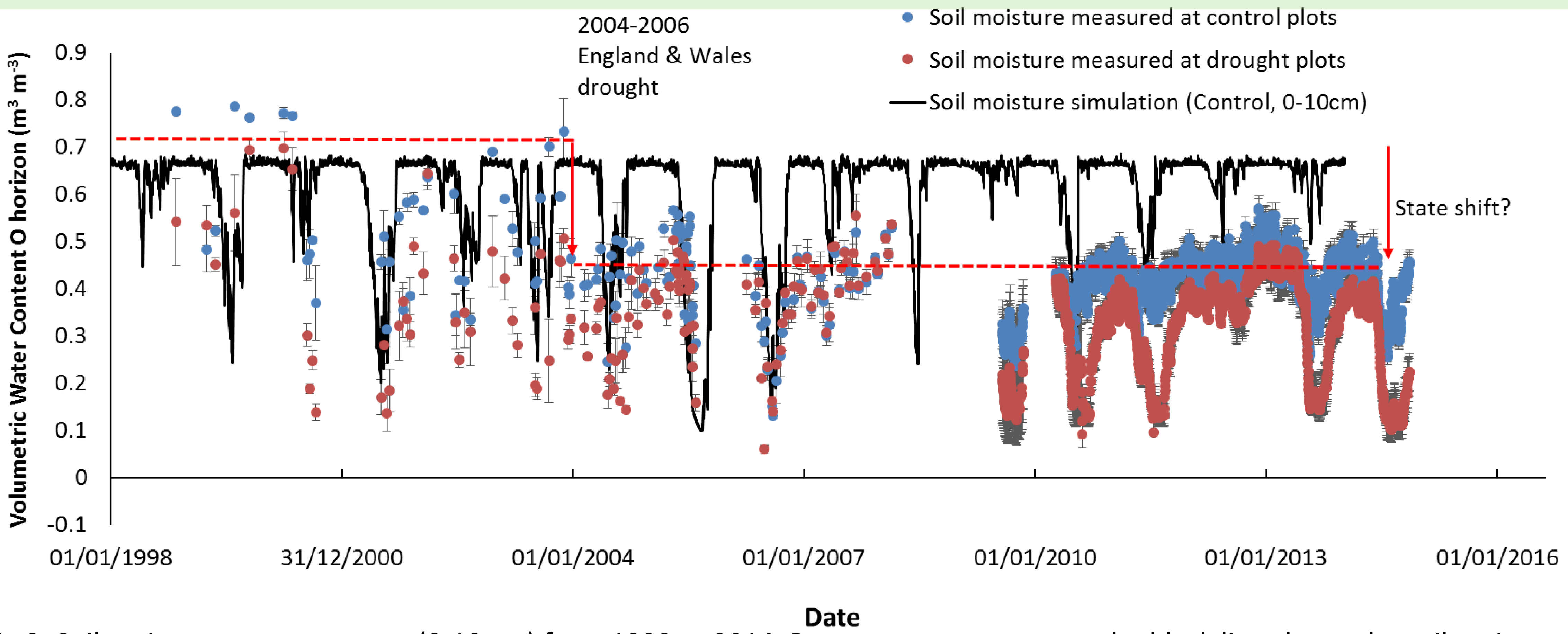

Fig.2: Soil moisture measurements (0-10 cm) from 1998 to 2014. Dots are measurements, the black line shows the soil moisture simulation using Hydrus 1-D passed on soil hydraulic parameters determined from the control plots.

Results

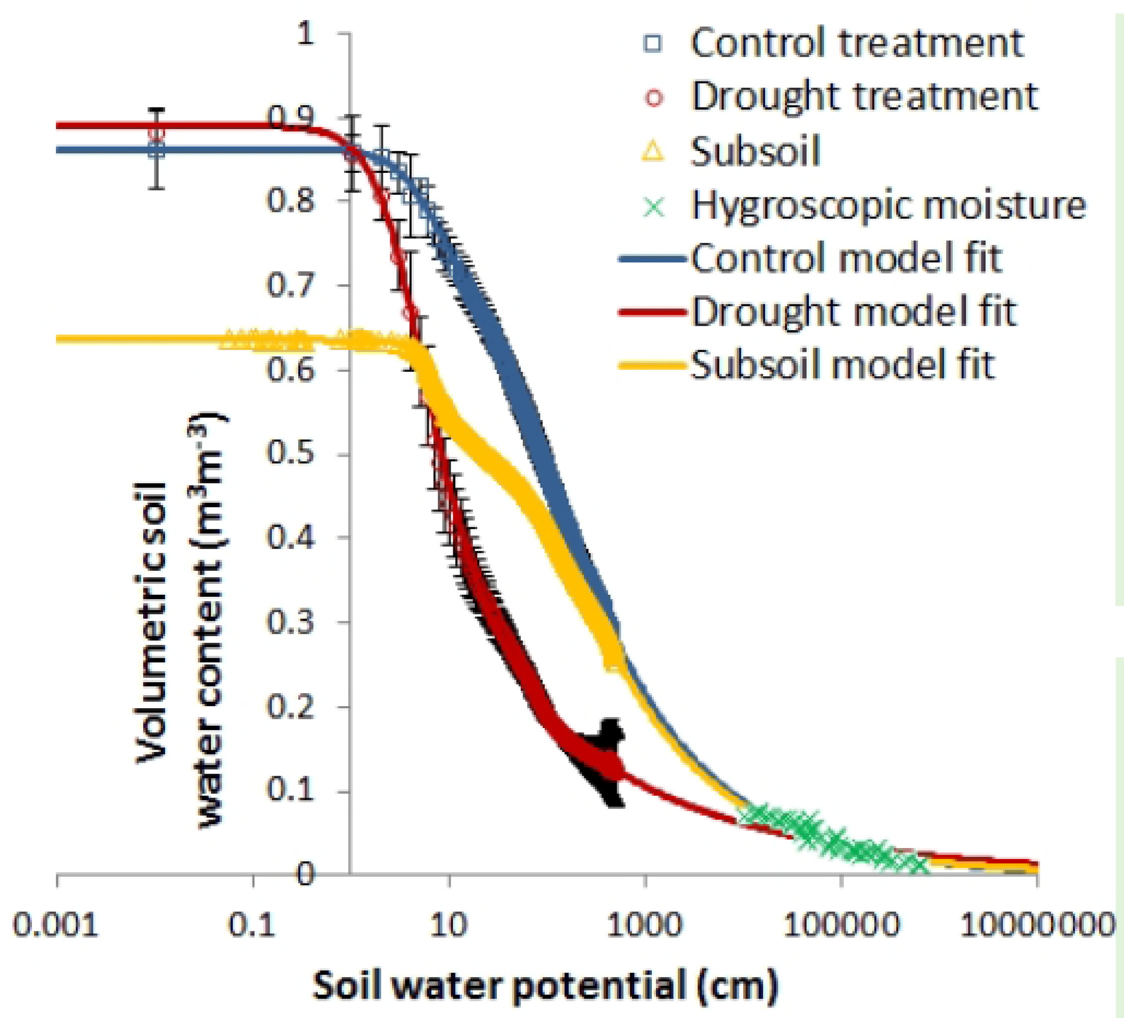

Fig.3: Soil water retention curves for control and drought plots (0-5 cm) and subsoil (10-15 cm).

Observation 1: Permanent divergence in soil moisture between control and drought treatment[3] of 0.3 m^3 m^{-3} in summer and 0.1 m^3 m^{-3} in winter (Fig.2).

Explanation: A 0.29 m^3 m^{-3} lower water retention in **drought plots** compared to **control plots** near saturation (Fig.3).

Observation 2: **State shift** in soil moisture content after **2004 drought** where soil moisture did not recover in either treatment (Fig.2).

Explanation: 3 alternative stable soil moisture states observed in the field can be simulated by accounting for drought induced soil cracking (Fig.4).

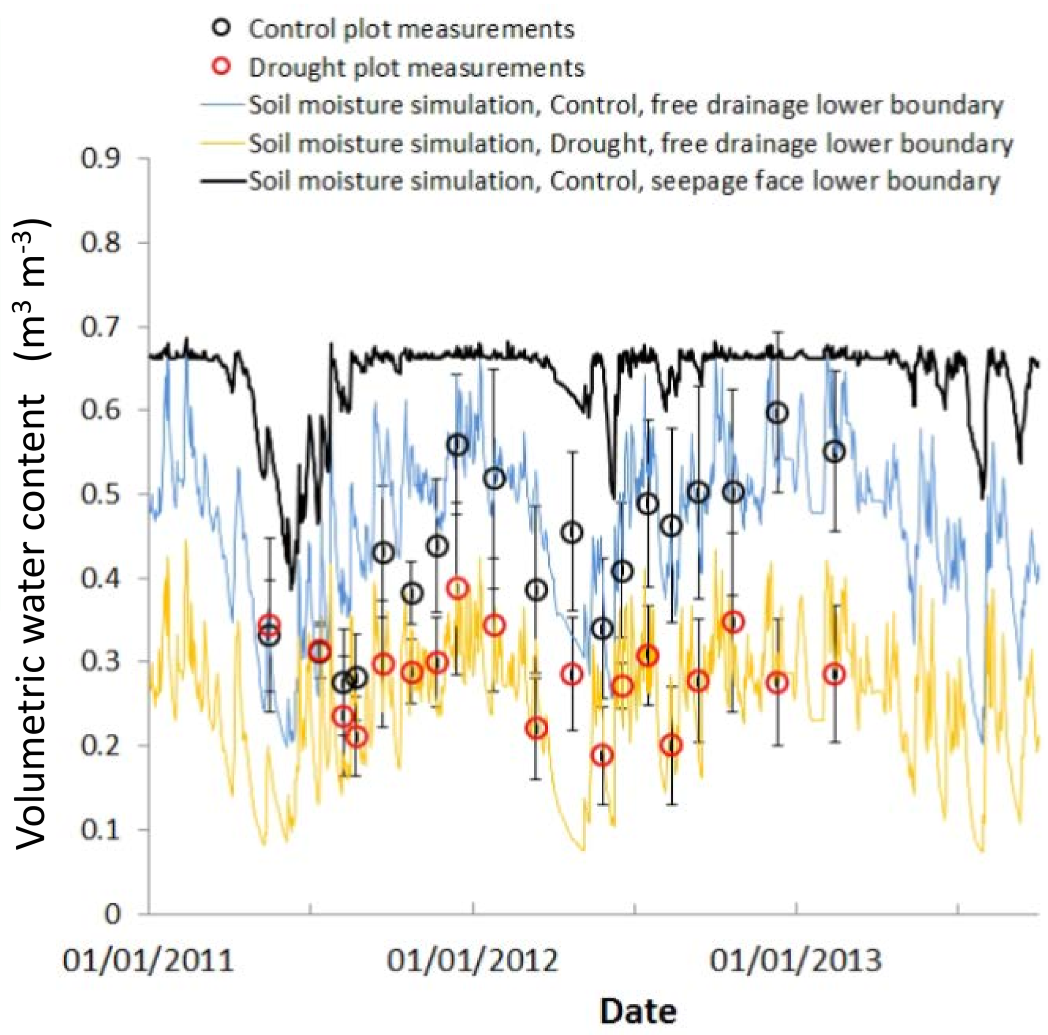

Fig. 4: Three stable soil moisture states w/varied soil moisture boundary conditions – free drainage vs. seepage face.

Conclusions and Remarks

- Lower soil water retention established due to degradation of soil carbon (oxidation of soil carbon) which substantially reduced the soils' ability to retain water.
- Soil erosion due to drought is confirmed by observation of 20-26 % increased soil respiration[6] and decreased bulk density from 0.137 g cm^{-3} in control to 0.097 g cm^{-3} in drought plots.
- Permanent alternative stable soil moisture states established due to experimental and natural droughts (Fig.5).

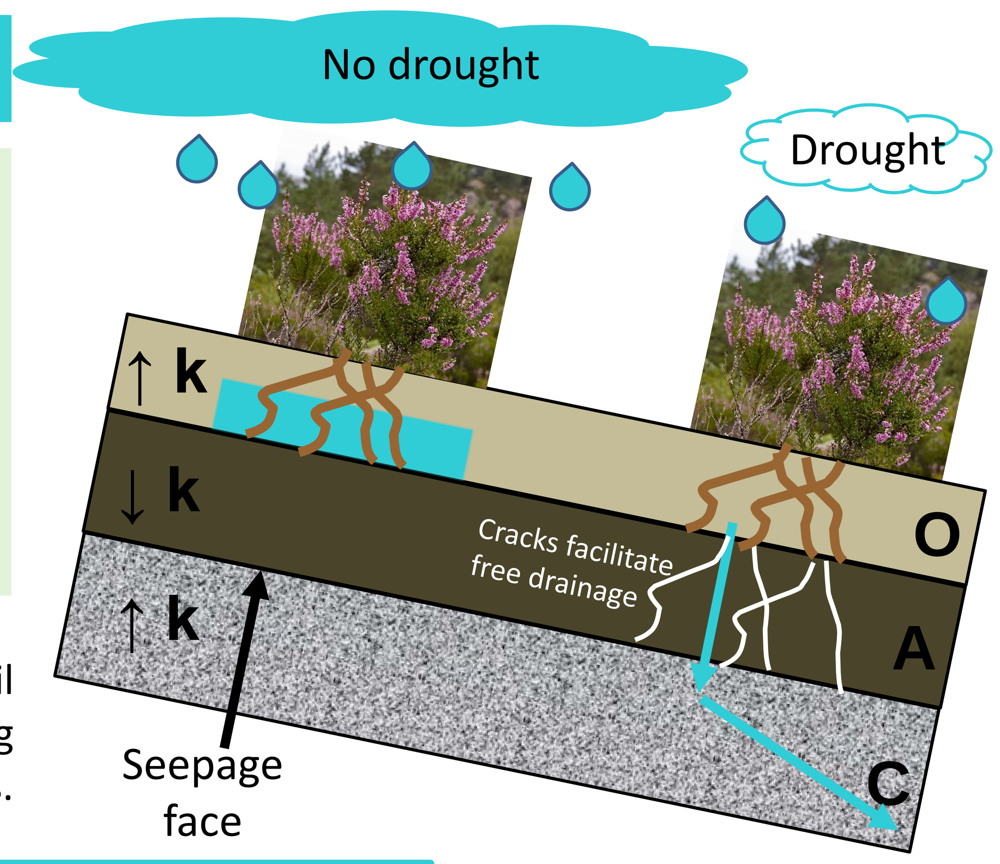

Fig. 5: Conceptual understanding of drought induced changes in soil hydraulic properties: Low hydraulic conductivity (k) of the mineral soil horizon (A) prevented water from draining. Continuous moderate experimental drought and natural drought (2003-2005) caused cracking of the mineral (A) horizon allowing free drainage; resulting in soil erosion, establishing alternative soil moisture states.

1 Holling et al. 1973 Amm Rev Ecol Syst 1-23
2 Llorens et al. 2004 Ecosystems 7: 613-624
3 Dominguez et al. 2015 Biogeochemistry 122: 151-163
4 Ciais et al. 2005 Nature 437: 529-533
5 Ciais et al. 2013 IPCC
6 Sowerby et al. 2008 GCB 14: 2388-2404
7 Robinson et al. 2016 Sci Rep 6:20018

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