



Above and below ground biomass patterns in arid lands

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ABSTRACT

Regular vegetation patterns have been observed in many arid zones around the world. This particular spontaneous arrangement of the vegetation optimizes the use of the scarce water resources and could be imitated to restore vulnerable ecosystems; at the same time, the patterns of vegetation act as an early warning signal of the fact that fragile ecosystems may suddenly undergo irreversible shifts, thus, they deserve a special attention. The formation of vegetation patterns is the object of many theoretical and experimental studies, nevertheless, in previous works, the interest that is deserved to below ground biomass allocation is minor as compared to the effort that is spent to describe the organization of vegetation above ground.

A simple model for the study of vegetation patterns in arid lands has been used here to investigate the interrelations between plant ecology and hydrology, and the interplay between above and below ground mass patterns. The results of the numerical simulations that are reported and discussed hereinafter, have been obtained by postulating different biomass growth rates and root density distributions, under water stress. By so doing, the impact of root architecture on patterns of above ground biomass with different survival strategy has been demonstrated.

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1. Introduction

Alternating bands of vegetation and bare soil favor the capture of limited rainfall in arid regions. The origin of regular vegetation patterns in arid and semiarid lands has been ascribed to a mechanism of preferential infiltration in the vegetated area. The bare soil results sealed by a soil crust, whereas the biomass growth hinders the crust formation on vegetated zones. Thanks to a mechanism of run-off run-on from bare zones toward vegetated ones the vegetation survives despite the scarce water resources (Valentin et al., 1999). Soil moisture accumulates locally in the root zone and influences the root growth and the above ground biomass organization. The soil moisture spatial distribution depends on soil properties (Rietkerk et al., 2002; Fernando and Cortina, 2002; Ursino, 2005), plant physiology (Ursino, 2007), and on rainfall seasonal and daily variability (Ursino and Contarini, 2006; Nordbotten et al., 2007; De Michele et al., 2008). Although the complexity of the soil–vegetation–atmosphere system invites a stochastic analysis to handle the common lack of knowledge in the fields of internal physical laws and external forcing (Katul et al., 2007), the deterministic modelling approach undertaken here, may better clarify the relevance and the relevant interconnections between ecological and hydrological processes.

Preferential infiltration and soil moisture redistribution have been indicated as the two major processes influencing the establishment and persistence of regular vegetation patterns in arid land (Klausmeier, 1999; HilleRisLambers et al., 2001; Rietkerk et al., 2004; Gilad et al., 2004). Furthermore, Ursino (2007) demonstrates that the plant survival strategy determines which of the above-mentioned hydrological process counts more: ecohydrological models based on different above ground biomass growth functions reproduce the macroscopic evidence of regular vegetation patterns for different reasons, depending on the biomass growth rate function that is postulated. Preferential soil moisture redistribution results to be crucial for plants that form dense biomass patterns on the soil surface and thus, require larger amount of soil moisture to sustain their growth. Vegetation that consumes less water, relies more upon preferential infiltration for surviving under scarce mean annual rainfall and leads to a scenario where more soil moisture is lost due to run-off and leakage (Ursino, 2007). Even though, in any case, the resulting soil moisture patterns are expected to influence the root growth and the above ground biomass organization, not enough effort has been spent so far in understanding below ground biomass form and functioning, as well as the interconnection between the soil moisture patterns and the below ground biomass organization.

Evapotranspiration, infiltration, lateral subsurface flow, and leakage are some building blocks of the soil water balance at the field scale, and they all are influenced (among other factors) by vegetation roots. This fact points at a substantially unexplored and

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challenging task: upscaling knowledge on preferential flow from the small scale of a single root and soil structure (see e.g., [Javaux et al., 2008](#)) to the larger field scale. The task has several implications in theoretical and applied hydrology as well as in the new interdisciplinary field of ecohydrology and geoechohydrology.

Below ground growth of biomass is especially relevant in arid areas. The coexistence of desert vegetation species as well as their above ground arrangement depends to a large extent from differences in root system morphology (see [Cody, 1986](#); and reference therein). Vegetation bands alternating with bands of bare soil can consist either of grass, trees shrubs or trees and shrubs (see [Valentin et al., 1999](#); for a review). Below ground, different vegetation species are expected to lead to very diverse root systems, even though, in general, root system in arid environment must evolve for optimal uptake of water.

The root architecture is expected to have an impact on the interrelation between relevant hydrological processes and plant survival strategy in banded landscapes. Nevertheless, previous literature models that are based on point root uptake (among them there are those cited in this section) cannot clarify the mechanisms of interaction between above and below ground biomass patterns. The possibility that the above ground biomass distribution could be influenced by the below ground root distribution has been investigated here, by ascertaining whether laterally extendible roots could gain for the plant a more favorable environment. Important interrelations between plant ecology and (subsurface) hydrology, and the interplay between above and below ground mass patterns are demonstrated and discussed in the next sections.

2. Methods

2.1. Soil moisture, biomass and vegetation balance equations

[Ursino \(2007\)](#) proposes the following dimensionless set of equations for soil moisture (w) plant biomass (n) and surface water (o) balance, defined on a one-dimensional domain indexed by x as a function of time t :

$$\begin{aligned} \frac{\partial w}{\partial t} &= l_0 \frac{n + k_2 k_3}{n + k_2} - ew - f(w, n) + v \frac{\partial w}{\partial x} + d \frac{\partial^2 w}{\partial x^2} \\ \frac{\partial n}{\partial t} &= f(w, n) - mn + d_n \frac{\partial^2 n}{\partial x^2} \\ \frac{\partial o}{\partial t} &= a - \alpha o \frac{n + k_2 k_3}{n + k_2} + v_0 \frac{\partial o}{\partial x} + d_0 \frac{\partial^2 o}{\partial x^2} \end{aligned} \quad (1)$$

Model (1) is based on the simplistic hypothesis of uniform net rainfall a . The impact of seasonality and rainfall shower frequency have been discussed by [Ursino and Contarini \(2006\)](#). A more realistic hypothesis on the distribution of the net rainfall would not change the main conclusions reported in this paper, even though it would clearly have an impact on the results. The net dimensionless rainfall a infiltrates preferentially where plants grow, inducing a feedback mechanism that is accounted for by the term $l_0((n + k_2 k_3)/(n + k_2))$, where k_2 depends on the rate at which surface water infiltration increases with biomass density, $l_0 k_3$ is the minimum infiltration rate of surface water in the absence of plants and l_0 is the maximum infiltration rate ([Rietkerk et al., 1997](#); [HilleRisLambers et al., 2001](#)). The water loss due to evaporation and leakage (ew in the first of (1)), is approximated with a linear function of the soil moisture under stress conditions. The term mn represents the plant biomass loss due to mortality; d and v are the soil moisture diffusion coefficient and transverse velocity; d_0 and v_0 are the surface water diffusion coefficient and average velocity; d_n is the diffusion coefficient of plant dispersal, and $f(w, n)$ is the plant water uptake within the soil moisture balance equation, whereas it stands for the growth rate of vegetation within the biomass balance equation.

Model (1) has been extended here in order to account for non-point root architecture and stress that is induced by persistent drought. The innovation within the set of Eq. (1) will be described in the following subsections.

2.2. Non-point root uptake

The schematic representation of the root distribution within a soil transect transverse to the bands of vegetation depends on the mean lateral root length l_r ([Gilad et al., 2004](#)), it is proportional to the above ground biomass density and is represented by the Gaussian kernel

$$K(x) = \frac{1}{l_r} \frac{1}{\sqrt{2\pi}} \exp \left[-\frac{1}{2} \left(\frac{x}{l_r} \right)^2 \right] \quad (2)$$

where $\int_{-\infty}^{\infty} K(x) dx = 1$.

In order to account for the distributed soil moisture uptake, that mimics the non-point root architecture, model (1) has been modified as follows: in the soil moisture balance (the first equation of the set (1)) the point uptake function $f(w, n)$ has been replaced by $\int_{-\infty}^{\infty} f(w(x), n(x+s)) \cdot K(s) ds$, where s is an auxiliary variable. In the biomass balance (the second of the set (1)) the term $f(w, n)$ has been replaced by $\int_{-\infty}^{\infty} f(w(x+s), n(x)) \cdot K(s) ds$.

$$\begin{aligned} \frac{\partial w}{\partial t} &= l_0 \frac{n + k_2 k_3}{n + k_2} - ew - \int_{-\infty}^{\infty} f(w(x), n(x+s)) \cdot K(s) ds + v \frac{\partial w}{\partial x} + d \frac{\partial^2 w}{\partial x^2} \\ \frac{\partial n}{\partial t} &= \int_{-\infty}^{\infty} f(w(x+s), n(x)) \cdot K(s) ds - mn + d_n \frac{\partial^2 n}{\partial x^2} \\ \frac{\partial o}{\partial t} &= a - \alpha o \frac{n + k_2 k_3}{n + k_2} + v_0 \frac{\partial o}{\partial x} + d_0 \frac{\partial^2 o}{\partial x^2} \end{aligned} \quad (3)$$

In the modified model (3), n stands for the above ground biomass as in the original model. The dimensional form of model (3) is reported in [Appendix A](#). Expressions for the dimensionless groups appearing in (3) and dimensional parameter values may be found in [Table 2](#).

2.3. Water stress

The water scarcity triggers the vegetation capacity to deal with stress. The reduced soil moisture content lowers the plant water potential and decreases transpiration ([Porporato et al., 2001](#); [Feddes et al., 1978](#)). This fact is accounted within model (3) by the dimensionless term $-ew$. The persistence of drought is expected to bring about irreversible physiological damages. To account for the loss of biomass caused by the persisting drought, vegetation mortality $m(x)$ is increased by a factor 1.5, any time the average soil moisture content $\int_{-\infty}^{\infty} w(x+s) \cdot K(s) ds$ lasts below a certain lower limit w_{lim} for a time conventionally longer than t_{lim} . If the average soil moisture increases again above the critical lower limit w_{lim} , mortality is restored to the original value m .

The newly introduced parameters: w_{lim} and t_{lim} must be considered just as *effective parameters*. They have been introduced to account for the overall impact of stress-induced damages to the biomass that are beyond repair. These effective parameters should not be interpreted as the real upper limit of the drought lag-time and the lower limit of the soil moisture that the plant can tolerate. Indeed, a proper simulation of the dynamical plant behavior, comprehending its reaction to stress, would require a more realistic reproduction of the hydrological forcing, accounting for rainfall seasonality and intermittency of showers, that is beyond the scope of this study.

2.4. Biomass growth rate

Two different biomass growth rates have been postulated and confronted. The first one is originally due to [Klausmeier \(1999\)](#)

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