Influence of small and large rainfall events on the water budget components of wheat crops

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Abstract

Power laws relating the number *N (s)* and the size *s* of events, i.e. $N(s) \sim s^{-\tau}$ are widespread in nature. We tested the following hypotheses: H1) power laws can be used to characterise rainfall patterns irrespective of the amount, seasonality and underlying mechanisms of rainfall. H2) Soil evaporation is positively associated with τ. H3) Runoff and drainage are negatively associated with τ. H1 was tested using long-term rainfall records for 114 Australian locations. Coefficients of determination of the lineal regression between log *N (s)* and log *s* ranged from 0.90 to 0.99 (P <0.0001). A single value of τ provided a good description of rainfall patterns in 50 out of the 114 locations, whereas some degree of curvilinearity suggested a multidimensional fractal approach would be more suitable in the other locations. A trade-off is proposed between the large number of parameters in multi-scaling models and the practical value of a single parameter to capture agronomically relevant features of rainfall patterns. H2&3 were tested in a simulation study including 44 seasons in 39 locations (33-36S, 134-147?E). Soil evaporation decreased whereas runoff, frequency and size of drainage events increased with increasing seasonal rainfall. For a given amount of seasonal rainfall, soil evaporation was higher and drainage and runoff lower than expected in locations with high τ indicative of high frequency of small rainfall events.

Key Words

Self-similarity, soil evaporation, runoff, drainage

Introduction

Power laws relating the number of events *N (s)* and their sizes *s,* ie. $N(s) \sim s^{-\tau}$, are widespread in nature (*1*). These laws verify general scaling relations for non-equilibrium phenomena and are, by definition, self-similar (*2*). Theoretical and empirical studies support the hypothesis of statistical self-similarity in the spatial and temporal variation of rainfall (*3, 4*). Self-similarity is a central concept in the analysis of hydrological processes, and has been successfully integrated into a range models, including channel networks and floods (*3*). In contrast, the implications of rainfall self-similarity for rain-driven agricultural processes have been largely unexplored.

Wallace's (*5*) global analysis highlights the magnitude of the water budget components that are uncoupled with crop production, i.e. runoff and drainage account for 40-55% of rainfall and soil evaporation for 30-35% in rainfed farming systems of semiarid environments. Reduction of all three unproductive components of the water budget is critical to enhance rainfall use efficiency, while reduction of runoff and drainage is also important for environmental reasons.

Rainfall and evaporative demand, topography, soil properties and management practices all influence the relative importance of the crop's water budget components. Three major features of rainfall affecting the components of the crop water budget are amount, seasonality, and frequency distribution of rainfall events of different sizes. For a given amount of rainfall, more soil evaporation and less drainage and runoff could be expected in locations or seasons with higher frequency of small rainfall events. Qualitatively, these expectations are obvious corollaries from our understanding of water dynamics in cropping systems. Quantitatively, however, attempts to assess the effects of the size of rainfall events on regional scales are scarce.

This study focused on the following hypotheses: H1) power laws can be used to characterise rainfall patterns irrespective of the amount, seasonality and underlaying mechanisms of rainfall, H2) processes that are driven by topsoil water content, including soil evaporation, are positively associated with τ, whereas H3) runoff and drainage, which are favoured by large rainfall events, are negatively associated with τ.

Method

Hypothesis 1: power laws

Empirical evidence for self-similarity was sought in long-term records of daily rainfall in 114 geographically widespread Australian locations from 12 to 43?S, and from 115 to 154?E. Median rainfall ranged from 113 to 3437 mm $year^{-1}$, and Walsh & Lawler (*6*) seasonality index from 0.07 (very equable rainfall regime) to 1.1 (most rain in 3 months or less). Sites encompassed four major climates: the arid continental centre, the Mediterranean-type climate in the southwest, the temperate climate of the southeast and the monsoon region above 25?S. Long-term (1910-2000) rainfall data was obtained from the Australian Bureau of Meteorology; locations were selected that had few missing values. Rainfall records were split in 5 mm intervals, and lineal regression was used to fit the relationship between log *N (s)* and log *s*, where *N (s)* is the number of rainfall events, and *s* is the upper limit of each interval. Significance of quadratic terms (P < 0.05) was taken as an indication of departure from linearity.

Hypotheses 2 & 3: water budget components

Two sources of variation in water budget components were combined: time, i.e. 44 years from 1957, and space, i.e. 39 locations situated in a narrow band between 33 and 36?S, and a longitudinal range from 134 to 147?E. Water budget components including runoff, soil evaporation, transpiration, and drainage beyond the root zone were simulated for each location and season using the APSIM model. Two sets of simulations were preformed. Simulations A used actual rainfall, radiation, evaporation rate, maximum and minimum temperatures for each location. Simulations B, aimed at uncoupling rainfall and other meteorological variables, used actual rainfall for each season and location, combined with actual temperatures and radiation from a single location at the centre of the region under study (Waikerie, 139?59' E). Meteorological data were obtained from the Australian Bureau of Meteorology. A sandy loam soil was assumed in the simulations. Soil hydraulic properties were derived from texture using CropSyst functions (v. 3.0.2.07, http:// bsyse.wsu.edu/cropsyst). Runoff was calculated with the USDA's curve number procedure assuming a soil in hydrological group B with good hydrologic condition, and curve number = 80. Parameters for calculation of soil evaporation were 6 mm as the upper limit of stage 1, and 3.5 mm $d^{-0.5}$ as the rate during stage 2. Sowing date was 1 May. The model was run with the non-limiting nitrogen option to restrict variation in water budget components associated with nitrogen x water interactions. Other parameters in the crop, nitrogen and water budget simulations were the model's default.

Parameter τ was calculated as explained above, using rainfall records restricted to the April-to-October period for consistency with water budget calculations. Regression analysis was used to assess the effect of seasonal rainfall on response variables, i.e. water budget components, and residuals of regressions were investigated for their association with τ.

Results

Hypothesis 1: power laws

Coefficients of determination of the lineal regression between log *N (s)* and log *s* ranged from 0.90 to 0.99 (P <0.0001), were independent on the total amount of rainfall, and decreased slightly with increasing rainfall seasonality. Scatter around the fitted models was comparable to that reported in other empirical studies of power laws (*7*). A single value of τ provided a good description of the rainfall patterns in 50 out of the 114 locations, whereas some degree of curvilinearity suggested a multidimensional fractal approach would be more suitable in the other locations (*8*). Power laws held for daily rainfall patterns analysed at monthly intervals in 1361 out of 1368 cases (114 locations x 12 months per location);

parameter τ had a normal frequency distribution with an average of 2.2. Theoretical and empirical evidence supports the concept of self-organised criticality whereby the small-scale mechanisms of the system determine its behaviour irrespective of initial conditions (*9, 10*). The consistent relationship between the number and size of rainfall events and the time persistence of rainfall patterns found in this study could be interpreted in terms self-organised criticality. Alternatively, as suggested by Lauren et al. (*11*), the scaling properties of rainfall could represent some other kind of processes, for which large-scale conditions are also important.

Hypothesis 2 & 3: water budget components

Average seasonal rainfall ranged from 176 to 381 mm and τ from 2.84 to 3.76; both variables were unrelated ($P = 0.20$). Parameter τ was unrelated to latitude in the 3? window investigated, and declined eastwards ($r = -0.75$, $P < 0.0001$; Fig. 1). There was no systematic variation of seasonal rainfall in the area under study, as indicated by its lack of association with latitude ($P > 0.70$) or longitude ($P > 0.39$). Minimum temperature ($r = -0.73$, $P < 0.0001$) and pan evaporation ($r = -0.62$, $P < 0.0001$) decreased eastwards whereas maximum temperature ($P = 0.11$) and solar radiation ($P = 0.56$) were unrelated to longitude.

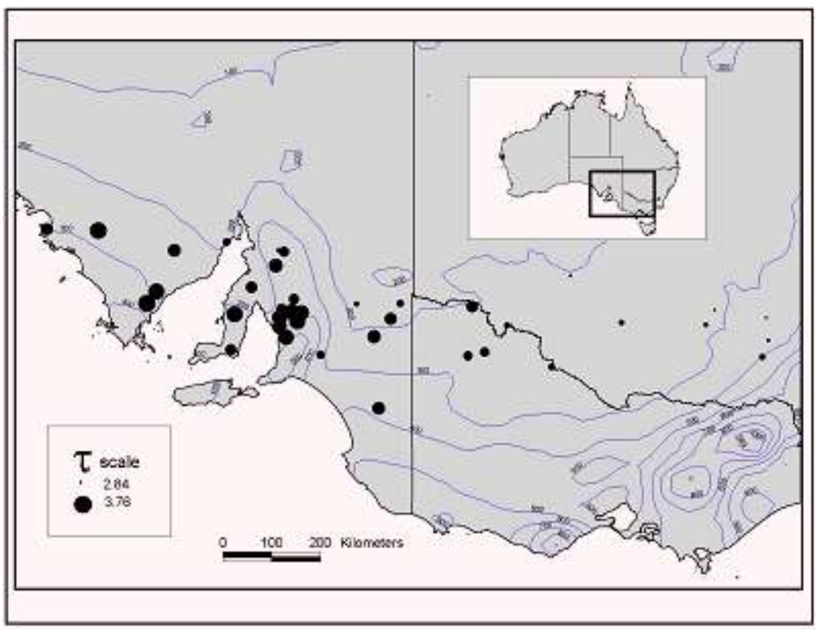

Fig. 1. Spatial variation of parameter τ (dimensionless) in south eastern Australia. Isohyets and τ both correspond to the April-October period.

Seasonal rainfall accounted for most of the variation in water budget components, as illustrated for drainage (Fig. 2a). Relationships were also significant for soil evaporation and runoff. For all three variables, τ accounted for part of the variation unaccounted for rainfall (e.g. Fig. 2b). With increasing τ - indicative of higher frequency of small rainfall events - soil evaporation was greater, whereas runoff and drainage were lower than expected from seasonal rainfall. These relationships between τ and water budget components remained or where stronger in simulations B which uncoupled rainfall effects from those of linked meteorological variables.

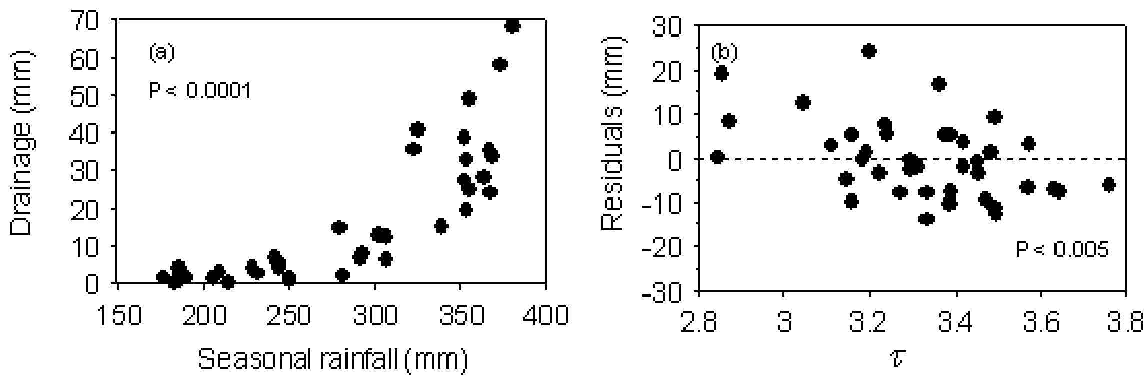

Fig. 2. Influence of amount of seasonal rainfall and relative size of rainfall events, as quantified by τ (dimensionless) on simulated drainage of wheat crops in 39 locations.

Conclusion

Despite departure from linearity in some locations, power laws provided an agronomically meaningfully description of the frequency distribution of size of rainfall events. For a given amount of rain, more drainage and runoff, and less soil evaporation can be expected in locations with low τ. In the region investigated, for a given amount of seasonal rain, management practices aimed at reducing soil evaporation would be more effective in western locations, whereas practices aimed at reducing runoff and drainage would be more effective in eastern locations.

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