Modeling Water and Nitrogen Fate from Sweet Sorghum Irrigated with Fresh and Blended Saline Waters using HYDRUS-2D

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Abstract

The Alentejo region in southern Portugal faces water scarcity and environmental problems as a result of high atmospheric demands and irregular rainfall. The HYDRUS software package has been calibrated and validated in the last few years in order to minimize human-induced salinization and sodification, and non-point source pollution from agricultural fertilization in the region. This paper describes results from an experiment where HYDRUS-2D was used to assess the fate of nitrogen in a plot planted with sweet sorghum, while considering drip irrigation scenarios with different levels of nitrogen and salty waters. HYDRUS-2D simulated water contents, EC_{sw}, and N-NH_4^+ and N-NO_3^- concentrations continuously between 2007 and 2010, while producing RMSE between simulated and measured data of 0.030 cm^3 cm^{-3}, 1.764 dS m^{-1}, 0.042 $mmol_c$ L^{-1}, and 3.078 $mmol_c$ L^{-1}, respectively. Actual transpiration varied between 264 and 334 mm depending upon the crop season and the irrigation treatment. Sweet sorghum showed to be tolerant to saline waters only during one crop season. After that, the continuous use of saline waters led to soil salinization, and to root water uptake reductions due to the increasing salinity stress. N uptake and leaching were dependent on the amount of water flowing through the root zone, the amount of N applied, the form of N in the fertilizer, and the timing and number of fertigation events. The effect of the osmotic stress on nitrogen leaching was only minimal. The yield function developed from N-NO_3^- uptake and dry biomass yield (R^2 = 0.71) estimated N needs between 130 and 180 kg/ha. The simulations with HYDRUS-2D were thus useful to understand the best strategies toward increasing nutrient uptake and reducing nutrient leaching.

1. Introduction

The Alentejo region of southern Portugal normally exhibits high summer temperatures and very low rainfall that limit crop production. In this water scarce region, irrigation plays a fundamental economical and social role but has enhanced several environmental problems as a result of poor irrigation and water management practices. Human-induced salinization and sodification, and non-point source pollution from agricultural fertilization are among the recognized problems. Therefore, a sound irrigation policy must be established to avoid and mitigate these risks. Such policy may include the adoption of less water and nutrient demanding crops, as well as be based on a quantitative understanding of the subsurface movement of water and dissolved chemicals.

Modeling of subsurface water flow and the transport of major soluble ions in and below the root zone is essential for predicting groundwater quality, implementing better irrigation and fertilization practices (Cameira et al., 2003), and quantifying salinization and alkalization hazards. Thus, the HYDRUS software package (Šimůnek et al., 2008) has been used in the last few years to better understand the main physical and chemical processes involved when irrigating with waters of different quality and help establishing sound irrigation practices for the soils in the region.

Gonçalves et al. (2006) first started by analysing transient water flow and solute transport in three soil lysimeters with waters of different quality over a period of 3 years using the UNSATCHEM module implemented in HYDRUS-1D. In this study, HYDRUS-1D successfully described water contents, overall salinity, concentration of major soluble cations (Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}), sodium adsorption ration, and exchangeable sodium percentage.

Later, Ramos et al. (2011) addressed the transport and reactions of salts and nitrogen species in the soil profile in an integrated way. The UNSATCHEM module was again used to simulate the overall salinity and major cations in two soils with coarse and medium textures during a long term experiment, while the general solute transport module of HYDRUS-1D was used to model nutrient fate ($N\text{-}NO_3^-$ and $N\text{-}NH_4^+$). This study allowed a better understanding of solute interactions between the solid and liquid phases and the complex reactions involved in solute transport. The study further allowed understanding the basic relations between the salinity stress caused by the use of saline waters and nutrient uptake and leaching.

Although the modeling approaches carried out were successful in modeling soil water dynamics and solute transport in field conditions, those two studies were only one-dimensional and neglected water and solute fluxes, and pressure head and concentration gradients in the horizontal direction. Additionally, one-dimensional models fail to adequately simulate micro-irrigation systems (such as drip emitters, drip tape, and micro-sprinklers), which can efficiently apply water and nutrients in the right amounts and precise locations throughout a field (e.g., Gärdenäs et al., 2005). Since drip irrigation is often used in Portugal it seemed more adequate to find modeling approaches that are more able to represent complex physical and chemical processes that take place in the soil profile under this irrigation system.

The main objective of this study was to use the HYDRUS-2D software package to model nitrogen fate in a field with sweet sorghum while considering different drip fertigation and water quality scenarios. Field data was used to calibrate and validate HYDRUS-2D for predicting (i) soil water contents and fluxes, (ii) the electrical conductivity of the soil solution (EC_{sw}), (iii) water uptake reductions due to the use of saline waters, and (iv) $N\text{-}NH_4^+$ and $N\text{-}NO_3^-$ concentrations in the soil and leaching. Water and nutrient balances were calculated based on model predictions. A complete description of this study is reported by Ramos et al. (2012b).

2. Material and Methods

2.1. Field Experiment

The field experiment was conducted at the Alvalade Experimental Station (37º 56’ 48’’ N and 8º 23’ 40’’ W), southern Portugal, from May, 2007 to April, 2010. The field experiment involved irrigation of sweet sorghum (*Sorghum bicolor* (L.) Moench) with synthetic saline waters blended with fresh irrigation waters and waters with nitrogen (NH_4NO_3) during three crop seasons. The blended amounts varied between the 12 experimental plots, while the total amount of water applied per irrigation event and per crop season, as well as the quality of the irrigation waters before blending, remained identical in all plots.

The total amount of water applied was 425, 522, and 546 mm in 2007, 2008, and 2009, respectively. Application amounts averaged 15, 16, and 17 mm per irrigation event in 2007, 2008, and 2009, respectively. Nitrogen fertilization was applied in 4 (2007), 6 (2008), and 3 (2009) irrigation events during the vegetative stage (July). The EC of the fresh waters, saline waters, and waters with fertilizer was 0.8, 7.6-10.6, and 6.8-9.5 dS m^{-1}, respectively. $N\text{-}NH_4^+$ and $N\text{-}NO_3^-$ concentrations in the waters with fertilizer varied between 67.7-95.0 $mmol_c\ L^{-1}$.

In the plots with the highest application of synthetic saline waters, and in those irrigated only with the locally available fresh water, TDR probes with waveguides from the Trase System (Soil Moisture Equipment Corp., Goleta, CA) and ceramic cups were installed at depths of 20, 40, and 60 cm to measure soil water contents and collect soil solutions, respectively. The soil solution was monitored for EC_{sw} and the concentrations of $N\text{-}NH_4^+$ and $N\text{-}NO_3^-$. The dry biomass of sweet sorghum was determined at the end of each crop season by harvesting all sorghum plants in each experimental plot and oven drying at 70 ºC to a constant weight.

2.2. Modeling approach

Modeling of water flow and solute transport was carried out for all experimental plots irrigated with the highest application of synthetic saline waters, and irrigated only with the water available in the region. The HYDRUS-2D software package (Šimůnek et al., 2008) was used to simulate the transient axisymmetrical (or radially symmetrical) three-dimensional movement of water and nutrients in the soil. The transport domain was set as a rectangle with a width of 37.5 cm (half the lateral spacing, i.e., the half-distance between triple joint laterals placed along the sorghum rows) and a depth of 100 cm (Figure 1). The flux boundary condition with the flux q was defined as:

$$q = \frac{volume\ of\ \ water\ applied}{surface\ wetted\ area \times duration} \tag{1}$$

where the volume of water applied [L^3] varied for different irrigation events, the surface wetted area [L^2] was approximately 1,256 cm^2 (i.e., 3.14 x 20^2), and the irrigation duration was adjusted to permit water to infiltrate into the soil without producing positive surface pressure heads and allow for the application of irrigation waters of different qualities within a particular irrigation event.

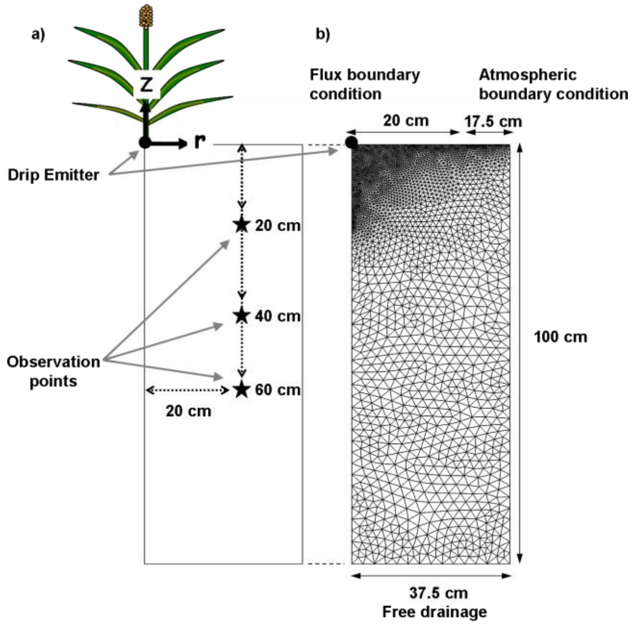

Figure 1. Location of observation points within the soil profile (a) and an axisymmetrical domain geometry with the finite element discretization used in HYDRUS-2D simulations (b).

HYDRUS-2D numerically solved the Richards equation for describing the variably saturated water flow in a radially symmetric domain and the convection-dispersion equation for solute transport. The soil hydraulic properties were described using the van Genuchten-Mualem model (van Genuchten, 1980). Since the fertilizer used in our study was NH_4NO_3, nitrification ϕ [$ML^{-3}T^{-1}$] of the $N\text{-}NH_4^+$ species to $N\text{-}NO_3^-$ was assumed to be the main N process occurring in the soil. This process was described by means of a sequential first-order decay chain as follows:

$$\phi_{N-NH_4^+} = -\phi_{N-NO_3^-} = -\mu_{w,N-NH_4^+}\theta c_{N-NH_4^+} - \mu_{s,N-NH_4^+}\rho \bar{c}_{N-NH_4^+} \tag{2}$$

where c, and $\bar{c}$ are solute concentrations in the liquid phase [ML^{-3}] and solid phase [MM^{-1}], respectively, μ_w and μ_s (set to 0.2 d^{-1}) are the first-order rate constants for solutes in the liquid and solid phases [T^{-1}], respectively, θ is the volumetric water content [L^3L^{-3}], and ρ is the soil bulk density [ML^{-3}]. The first-order reaction terms, representing nitrification of $N\text{-}N\text{-}NH_4^+$ to $N\text{-}NO_3^-$, thus act as a sink for $N\text{-}NH_4^+$ and as a source for $N\text{-}NO_3^-$. The distribution of solutes between the solid and liquid phases was described by means of a linear adsorption isotherm. Only $N\text{-}NH_4^+$ was assumed to adsorb to the solid phase (K_d of 3.5 cm^3g^{-1}).

The Richards and the CDE equations incorporate a sink term to account for water uptake by roots. Water and salinity stresses were defined according to the functions proposed by Feddes et al. (1978) and the Maas (1990) salinity threshold and slope function, respectively. Soil evaporation and plant transpiration rates were obtained by combining the daily values of reference evapotranspiration (ET_0), determined with the FAO Penman-Monteith method and the dual crop coefficient approach (Allen et al., 1998). Nutrient uptake was simulated by considering unlimited passive uptake for nitrogen species (Šimůnek and Hopmans, 2009). Model validation was carried out by comparing field measured values with HYDRUS-2D simulations using the root mean square error (*RMSE*) for quantifying model uncertainty.

3. Results and Discussion

Figure 2 compares the measured and simulated water contents at 40 cm depth in plots with the highest application of the saline and fresh waters. Water contents increased to full saturation near the emitter after an irrigation or rain event, and then decreased gradually during the following hours and days, until the next irrigation or rain event took place. Deeper depths showed smaller water content variations since root water uptake and soil evaporation were more pronounced at shallower depths. A *RMSE* of 0.030 $cm^3\ cm^{-3}$ were found between measured and simulated values.

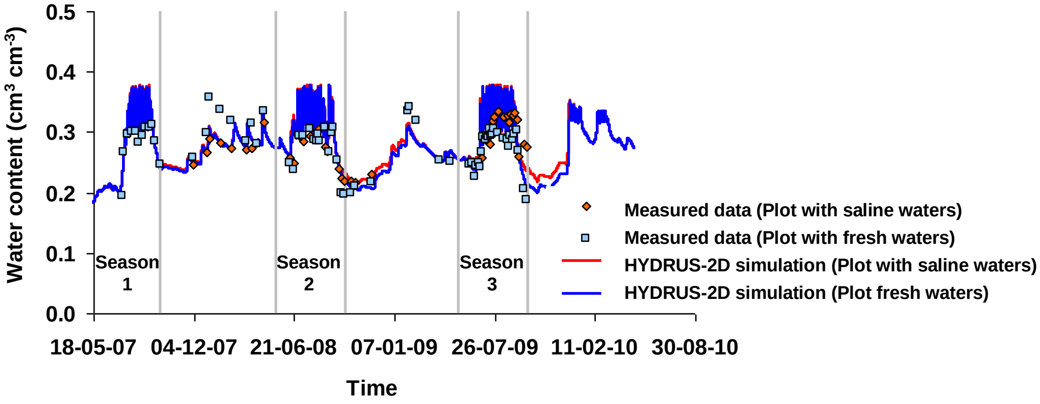

Figure 2. Measured and simulated water content at 40 cm.

Potential transpiration (T_p) varied between 360 and 457 mm. T_p values obtained in plots irrigated with saline waters were generally lower that those obtained in plots irrigated with fresh waters. However, the differences were found to be very small since sweet sorghum is moderately to highly tolerant to salinity (Maas, 1990). Actual transpiration (T_a) varied between 264 and 334 mm. T_p reductions due to water stress (21.9-27.4%) were a function of the adopted irrigation schedule. In plots irrigated with saline waters, T_p was further reduced by 2.3-7.0% due to salinity stress. The salinity stress became increasingly higher as a result of soil salinization and the continuous and increasing amount of synthetic saline waters being applied in each experimental plot (Figure 3). The *RMSE* obtained between measured and simulated EC_{sw} was 1.764 dS m^{-1}.

Nitrogen leaching was directly related to water flow through the bottom boundary of the soil domain. The movement of N out of the root zone also depended on the amount of applied N, the form of N in the fertilizer, and the time and number of fertigation events. Based on model simulations, most N-NH_4^+ was rapidly nitrified into N-NO_3^-, not reaching depths deeper than 20 cm (Figure 4). Leaching of nitrogen occurred mainly in the N-NO_3^- form (Figure 5). The higher the number of fertigation events, the lower the amount of N applied per event, and thus the lower the amount of leached N-NO_3^-. Nutrient uptake by plant roots occurred mainly in the N-NO_3^- form as well. The number of fertigation events also significantly influenced the amount of N-NO_3^- taken up by plant roots. The effects of the salinity stress on nutrient uptake (and inversely on nutrient leaching) was relatively small since sweet sorghum has a medium to high tolerance to salinity, and consequently there were only small reductions in transpiration due to the increase of the osmotic stress.

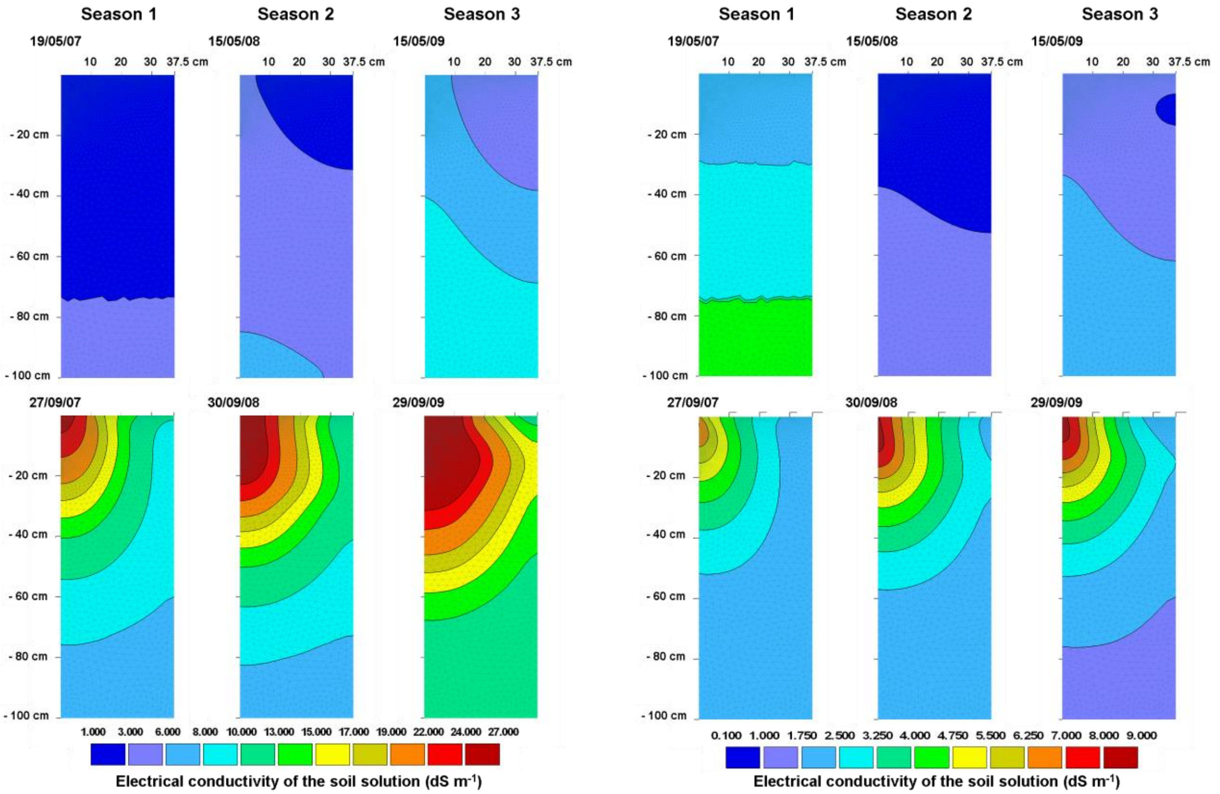

Figure 3. Simulated distributions of the electrical conductivity of the soil solution in plots irrigated with saline (left) and fresh (right) waters during sowing (top) and harvest (bottom) of each crop season. The drip emitter was located in the top left corner of each contour plot.

The *RMSE* obtained while comparing measured and simulated N-NH_4^+ and N-NO_3^- concentrations were 0.042 and 3.078 $mmol_c$ L^{-1}, respectively. Deviations between measured data and simulated variables were related to field measurements, model input and model structure errors. Here we would like to refer that the approach followed for modeling the transport of the N species (eq. 2) is relatively simple but can only consider N processes that are involved in a sequential-first order decay chain, such as nitrification, denitrification, and volatilization. Other

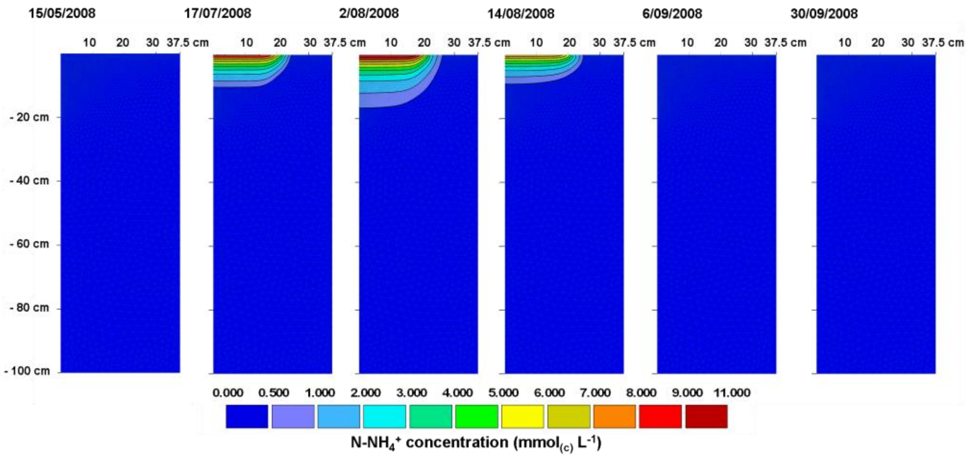

Figure 4. Simulated distributions of N-NH_4^+ concentrations in plot irrigated with saline waters during crop season 2. The dripper was located in the top left corner the contour plots.

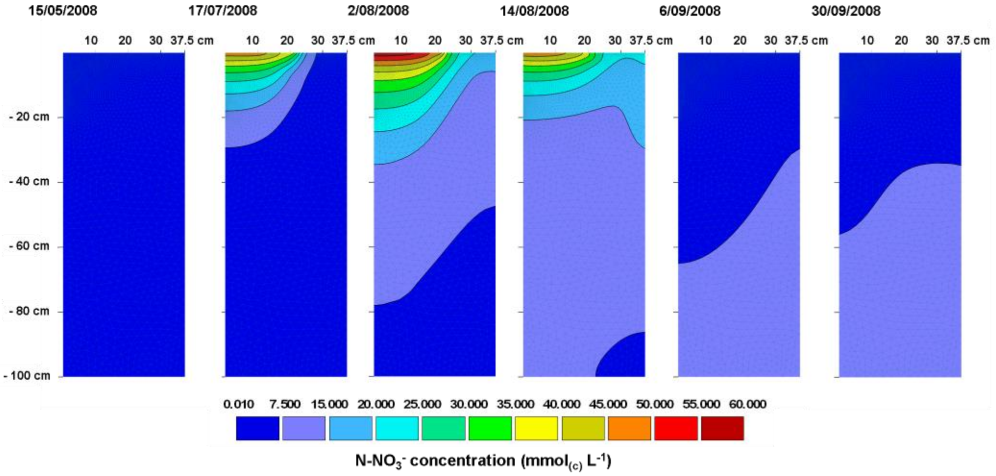

Figure 5. Simulated distributions of N-NO$_3^-$concentrations in plot irrigated with saline waters during crop season 2. The dripper was located in the top left corner the contour plots.

nitrogen reactions, with probable relevance for long-term applications such as ours, simply cannot be accounted for using this approach. However, from an agronomical perspective where the efficient use of the fertilizer applied is one of the main objectives to achieve, the approach is adequate.

Figure 6 shows the relationship between the N-NO$_3^-$ plant uptake calculated using HYDRUS-2D and the experimentally determined dry biomass yield expressed using a logarithmic function with a R^2 of 0.71. This logarithmic function fitted to experimental data shows that an additional incremental increase of N-NO$_3^-$ uptake produced diminishing returns in the total dry biomass response with optimum levels being reached at 130-180 kg/ha (Ramos et al., 2012a).

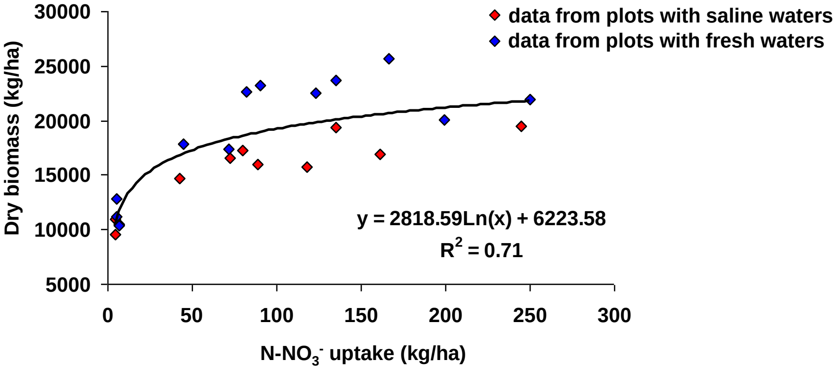

Figure 6. Relationship between N-NO$_3^-$ uptake, as simulated by HYDRUS-2D, and dry biomass yield (*Y*).

4. Conclusions

HYDRUS-2D successfully estimated the fate of nitrogen in field plots grown with sweet sorghum in Alentejo. In this water-scarce region, where even saline waters can be viewed as an important source of irrigation water during drought seasons, the use of marginal waters showed viability for irrigating sweet sorghum during a limited time period (one crop season).

Furthermore, the relatively low water needs (360-457 mm) and N requirements (130-180 kg/ha) of sweet sorghum makes it a good alternative when compared to other traditional crops grown in the region. The leaching of N out of the root zone depended closely on drainage, the amount of N applied, the form of N in the fertilizer, and the time and number of fertigation events. The modeling approach helped us understand the best irrigation and fertigation management practices to be adopted in future practical applications for increasing nutrient uptake and reducing nutrient leaching.

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