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Simulating the evolution of soil solutions in irrigated rice soils in the Sahel.

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Abstract

In sahelian countries, agriculture often relies on irrigation especially for rice cropping which has been introduced these last decades. As most of the water resources used for irrigation (mainly rivers and lakes) have an alkaline composition, rice cropping is often held as responsible for soil alkalinization. In order to evaluate the probability for this process to occur, we studied 3 different sites in West Africa where numerical simulation of the geochemical interactions between soil, irrigation water and groundwater were performed with PHREEQC. It was possible to simulate the evaporation of the ponding water, the mixing between groundwater and irrigation water, the lateral drainage (flushing) and the leaching, and finally the management of the crop residues. By performing prospective simulations over 60 cropping cycles it has been shown that soil alkalinization and sodication are not inevitable in these area especially if the cropping is properly managed. Moreover, when straw is removed and the plot flushed before the new cropping season, alkaline soils can even be improved with rice cropping.

Keywords : alkalinization, sodication, PHREEQC, plant uptake, water management, West Africa

Introduction

In the Sahel, irrigated rice (*Oryza Sativa* L.) cropping has been introduced on a wide scale during the last 20 years. The construction of large (> 100 ha) and costly irrigation schemes were intended to increase food security and provide income for Sahelian farmers, whose crops and livestock were devastated during the droughts in the 1970-1980's. Irrigated rice cropping in the hot and dry Sahelian climate seems like a paradox. However, the major Sahelian rivers and some large artificial reservoirs provide more than sufficient water to support current irrigation activities throughout the year. Although most Sahelian irrigation waters contain relatively little salt, they usually show alkaline compositions, where alkalinity (Alk.) is the dominant aqueous species. It is defined as the algebraic sum of the strong base cation and strong acid anion equivalents (Stumm and Morgan, 1970), and can be expressed as : Alk. = (HCO_3^-)+ (CO_3^{2-}) +(OH^-) - (H^+) , where ( ) denote the total concentration in $mol_c\ l^{-1}$. Moreover most of the Sahelian irrigation waters, show also a positive calcite residual alkalinity ($RA_{calcite}$) which corresponds to the alkalinity of the solution after precipitation of calcite : $RA_{calcite}$ = Alk. – (Ca^{2+}), (Valles et al., 1991; Bertrand et al., 1993). $RA_{calcite}$ has also been shown to be a conservative tracer of the soil solution (Ribolzi et al., 1996; Barbiero et al., 2001; Barbiero et al., 2004). Even the residual sodium carbonate, defined as RSC = Alk. – (Ca^{2+}) - (Mg^{2+}) ; which corresponds to the alkalinity of the solution after calcite and Mg-carbonate or Mg-silicate precipitation, is positive for these solutions and is an indicator of potential alkalinization and sodication (Eaton, 1950; Hardie and Eugster, 1970; Van Beek and Van Breemen, 1973; Al Droubi et al.,1980). Continuous concentration of such waters in the soil root zone may lead to the formation of alkaline and sodic soils, showing both high pH values and high exchangeable sodium percentage : ESP = XNa^+ / CEC , where XNa^+ is the exchangeable Na^+ and CEC the total cation exchange capacity. Such soils are less productive because of the pH-induced loss or low availability of several plant nutrients (e.g. Fe, P, Zn) and poor physical properties of the

sodic horizon (Abrol et al., 1988).

Whether or not large quantities of alkaline salts will accumulate in the soil root zone depends largely on the water balance of the root zone. Evapotranspiration in the Sahelian climate can be very large and regularly exceeds rates of 10 mm day^{-1} in the dry season (November – May) when maximum temperatures reach 40 to 45 °C (Van Asten et al., 2003, Hammecker et al., 2003). In most irrigation schemes, percolation rates are very low (< 4 mm day^{-1}) (Condom, 2000 ; Hammecker et al., 2003 ; Van Asten, unpublished), due to the low hydraulic conductivity of the clayey soils and air entrapment (Hammecker et al., 2003). In the course of the cropping season, percolation rates can further decrease if groundwater levels reach the soil surface. The combination of large evapotranspiration and small percolation can lead to the excessive build up of alkaline salts in the long run.

Recent studies have shown that the current soil alkalinity and sodicity problems in Sahelian irrigation schemes are primarily caused by salts that originate from the parent material (Barbiero and Van Vliet-Lanoe, 1998, Van Asten et al., 2004), or that accumulated as a result of long-time irrigation of non-flooded crops in combination with shallow saline groundwater levels. Hence, these salts were already in the soils before irrigated rice cropping was introduced and there is little indication that the recent introduction of irrigated rice cropping contributed to a significant increase in the salt content of these soils (van Asten, 2003). Moreover, most rice soils have the capacity to buffer an increase in soil solution alkalinity through desorption of exchangeable Ca^{2+} and the subsequent precipitation of calcite. However, although this buffer capacity is large, it is not infinite. Consequently, it still remains uncertain whether current irrigation practices will not lead to soil alkalinization and sodication in the long run (i.e. some decades) in areas where salts added through irrigation can not sufficiently be leached or evacuated from the soil root zone. Given the high investment costs of irrigated agriculture and the high costs of reversing alkalinization and sodication processes, it is important to know whether current or alternative crop and water

management will lead to the degradation of one of the Sahel's most productive crop system.

In this study, we focus on three Sahelian irrigation situations, inside irrigation schemes, that differ distinctly in terms of parent material, soil water balance and irrigation water quality. All sites have earlier been subject of studies on soil and water quality (Hammecker and Maeght, 1999; Boivin et al., 2002; Van Asten, 2003). Therefore, mean values for basic crop, water and soils parameters are already available. Taking into account some of the most important chemical and hydrological features, we tried to simulate how soils and soil solutions would evolve over time, under current and alternative land management practices at the three sites. The most critical parameter; i.e. the ratio between leached and irrigated solution volume, is the leaching fraction (LF) whether with vertical drainage or lateral drainage (flushing). In order to account for spatial variability within the irrigation schemes, we calculated soil solution evolution for different leaching fractions. This approach allows for the identification of the minimum leaching fraction that is required, in order to prevent soil degradation in the long run. Proton excretion (or alkalinity uptake) by the rice plant can also contribute significantly to the alkalinity balance of the soil root zone (Van Asten et al., 2004) and was also taken into account.

The objectives of this study are: (i) to give an overview of basic soil and water parameters for a range of Sahelian irrigation schemes, (ii) to simulate soil evolution under current and alternative crop and water management practices, and (iii) to identify the minimum leaching fraction that is required to prevent soil degradation in the long term.

2. Material and methods

2.1.Study sites

This study is based on data collected in three different irrigation areas in West Africa located in the valley of River Senegal, the Gorgol noir and in the valley of river Niger, where irrigated rice cropping is the main agricultural activity.

These sites are representative of most of the conditions where rice-cropping cultivation is observed in the Sahel, and are representative of different geological, geomorphological and pedological siuations with different soil textures. They are representative of (i) silty clay loam soils, developed on crystalline bedrock (Foum Gleita), (ii) alluvial levees with loamy sand soils (Niono) and (iii) alluvial basin with clayey vertisol (Donaye).

2.1.1.Foum Gleïta

The 'Mauritanides' geological region where Foum Gleita is located, is representative of the Pan-African orogenic belt which has been folded and lifted in the Appalachian era (Carité, 1989) and is consisting of metamorphic rocks, mainly greenschists, calcshists, micaschists and quartz, and secondary intrusions of dolerite, on which pedogenesis developed alkaline soils.

The Foum Gleita irrigation scheme is located in central southern Mauritania (N16°08'; W12°46'). The scheme was constructed between 1985 and 1989, with a surface area of 1950 ha. Irrigation water originates from a large artificial lake that formed behind a dam in the Gorgol Noir river. Irrigation and drainage are gravimetric but the drainage canals are often not functional due to poor maintenance. Most soils in Foum Gleita have formed from the schist parent rock that can be found at shallow depths (< 2.5m) (Van Asten et al., 2003). Soil texture is mostly silty clay loam, with around 30% clay. Although no specific clay mineralogical studies have been done in the Foum Gleita schemes, other studies in the Gorgol basin have shown that a large proportion of the clays are illites and kaolinites (Maignien, 1961; Audry, 1961). The soils have a moderate to strong structure, varying from subangular blocky to prismatic in the more vertic soils. Biological activity in these soils is generally high. The porosity of the soils is generally medium to high, but is distinctly lower

near soil surface. Although some soils have high ESP values, up to 65%, no evidence of soil structure degradation due to sodication has been observed in Foum Gleita. (Van Asten et al., 2003). In this region the cation exchange capacity (CEC) of soils ranges from 8 to 18 $cmol_c.kg^{-1}$, and the electrical conductivity of the 1:5 paste ($EC_{1:5}$) varies from 0.12 to 1.32 $dS.cm^{-1}$. Percolation rates are generally below 4 mm day^{-1}, and decrease during the rainy season as groundwater approaches the surface. On a few soils, high percolation rates were measured (> 10 mm day^{-1}) and farmers complained about difficulties in maintaining a submersion needed for rice. After the cropping season, groundwater quickly drops to below 1.2 m, indicating that deep percolation into the vertically oriented bedrock occurs, suggesting that horizontal groundwater flow along the slopes is minimal (van Asten et al., 2003). The absence of a shallow groundwater level during fallow periods suggests that capillary rise from the ground water can generally be neglected as a source of (alkaline) salts. The irrigation water is 2 to 4 times more saline than at the other study sites (EC = 0.17 $dS.m^{-1}$), but the sodium adsorption ratio, defined as : $SAR = Na^{+} /(Ca^{2+} +Mg^{2+})^{1/2}$ where the concentration are in $mmol.l^{-1}$, is still considered as very low (0.42). The residual sodium carbonate (RSC) is low and consequently suitable for irrigation according to the Riverside's diagram (see table 1). However, as at the other sites, RSC is positive and may therefore lead to alkalinization and sodication.

2.1.2. Niono

The site of Niono, is typical of the inner Delta of river Niger, developed on three different geological units: (i) Infracambrian substratum (-500 to -480 M years) composed of fractured schists and sandstones, (ii) Continental Terminal of Post Eocene to Pre-Quaternary age (-2.5 to -2 M years) formed by alternate sedimentary deposits of clays, sandy clays and sand , (iii) recent quaternary alluvial sediments deposited by the river Niger. In the studied area, the main morphological units are sandy levees, loamy inter levee depressions and clayey settling basins.

The study is based on data obtained in the huge irrigation scheme of the Office du Niger in Mali near Ségou (14°32 N 05°59 W). The climate is semi-arid (sudano-sahelian) with an average rainfall of 460 mm/year, distributed from June to October. The annual evaporation reaches 2.5m which generates soil solution concentration and consequently alkalization processes related to the alkaline composition of irrigation water (Condom, 2000) . The distribution of the soils in this area is inherited from ancient delta deposits constituted of clayey depressions delimited by sandy levees. These soils evolved under hydrologic conditions imposed by the water management during last half century, especially related to the uprise of the groundwater level.

The soils in this study are located on a little levee. The upper soil layers are composed of 11% clay and 78% sand, and classified as loamy sand. The identified clay minerals are mainly kaolinite, smectite and traces of illite. The structure of the soil is polyhedral. The soil displays an important biological porosity in the upper part of the profile (0-70cm) due to roots and to meso-fauna activity. The CEC for this soil is 9 $cmol_c/kg$ but with large proportion of exchangeable sodium (ESP) of about 16% (table 2) ; the $EC_{1:1}$ for the soils in the area range from 0.18 to 1.09 $dS.m^{-1}$. For the last 30 years the fields have been mainly cropped in rice with market gardening as a marginal activity (Condom, 2000).

In this large irrigation scheme plots are equipped with lateral drainage canals receiving mainly water from superficial flushing. After several decades of intensive irrigation, the water table level has risen approximatively by 50 m and is now close to the surface. Condom (2000) found that during the cropping season the average infiltration was about 80 mm (i.e. 9% of the leaching fraction), whereas during the inter cropping periods an equivalent amount of water from the water table supplied capillary rise towards the surface. Lateral losses towards drains and leaks represent 26 % of the total water inputs (Condom, 2000).

The Niger River that supplies the irrigation water by gravity has very low concentration (EC) and SAR values (Table 1), whereas the groundwater is 10 times more concentrated with a very high

SAR value. According to the Riverside classification (Riverside salinity lab. staff, 1954) the quality of irrigation water does not constitute any harm to soil conservation but the composition of the groundwater typically represents a sodic hazard. Nevertheless, as illustrated by the positive $RA_{calcite}$ and RSC value (Table 1), these solutions can both become very alkaline and sodic when they concentrate, as the Ca^{2+} and Mg^{2+} might precipitate in minerals with low solubility like calcite and Mg-carbonates or Mg-silicates (e.g. sepiolite), whereas alkalinity and Na, keep concentrating in the solution (Vallès, 1991; Bethke, 2007).

2.1.3. Donaye

The third site, Donaye is representative of the irrigated soils of the river Senegal, representing a total surface area of irrigation schemes of 240,000 ha (Barbiero et al., 2001). These soils developed on marine sediments deposited during the Nouakchottian transgression (4300 BP) which extended 380 km inland, near Bogué.

The irrigation scheme is located in northern Senegal (N16°40'; W15°), in the middle valley of the Senegal River, near Podor. It is a 20-year-old irrigation scheme managed by the farmers, without drainage network. The soil which has for long time been described as formed by recent alluvial deposits is a vertisol (vertic Xerofluvent). However in a recent work Barbiero et al. (2005) have suggested that the soil distribution in lower and middle valley of river Senegal might result from the pedological transformation of a unique unripe mud, deposited during the last quaternary marine transgressions. The soils of the Senegal valley can be considered as a chronosequence, where the most recent soils can be observed downriver in the delta, and the most developed ones upriver, in the middle valley. The pedological process driven by the acidic conditions associated to the oxidation of inherited pyrite, led to the dissolution of the parental mud. The protonation and acid hydrolysis of the aluminosilicates in this material resulted in the formation of a sandy horizon, representing the quartz skeleton. In the upper part of the soil, the interaction of the river water

(through floods and irrigation) with the acidic, Al and Si rich soil solution contributed to the precipitation of clay minerals, forming vertisols. In the Delta of the river Senegal this process is still active (Barbiero et al. 2005) and the vertisol is still thin whereas in Donaye it represents a two-meter-deep soil showing a vertic structure (slickensides), and constituted by 65 to 70% clay minerals, mainly beidellite and kaolinite (Favre et al., 2002), which shows a high cation exchange capacity of 22.7 $cmol.kg^{-1}$(table 2). The soil overlays a 5 to 6 m thick sandy layer corresponding to the afore mentioned quartz skeleton.

Rice cropping is performed by surge irrigation, and flooding is maintained during the complete plant growth cycle (about 100 days). The presence of a shallow water table at 2m depth contributes to air entrapment and stops vertical infiltration (Hammecker et al. 2003). Consequently, vertical leaching is negligible, and soil solution in the upper part of the profile (above 40 cm) does not connect with the water table during the irrigation period. However, bad maintenance of bunds aimed to hold the irrigation in the paddy plots, generates important leaks contributing to non negligible loss of water, especially during the first irrigation. Irrigation water is pumped in a loop of river Senegal called Doué. This water with a very low concentration (EC = 0.07 $dS.m^{-1}$) and a low SAR value (Table 1), is suitable for irrigation according to Riverside's diagram. Nevertheless, like in the former situations, the $RA_{calcite}$ and RSC of the irrigation water are positive, and the concentration of this solution may lead to sodication.

2.2. Numerical simulation.

2.2.1. The model and its main parameters.

The evolution of the soil solution and its interactions with the solid phase (precipitation-dissolution and exchange processes) were evaluated with the computer model PHREEQC v2. (Parkhurst and Appelo, 1999). This model, based on aqueous thermodynamics, computes equilibrium chemistry of aqueous solutions interacting with minerals, gases, solid solutions, exchangers, and sorption

surfaces, providing a full speciation of an aqueous system. The different databases provided with the model give a very wide possibility for computing the activities of most of the aqueous species present in natural solutions, especially for the CO_3-HCO_3 solutions. This model is especially useful as, in addition to the calculation of the chemical equilibria, it allows for the simulation of mixing different solutions, for concentrating solution due to evaporation, and for adding or taking out aqueous species from the soil solution. Using these options, it is possible to simulate solution changes due to flooded irrigation combined with concentration of the soil solution and evaporation. In surge flooding conditions, successive water inputs are usually performed to maintain a constant ponding level.

Considering the duration of the rice cycle, the average evapotranspiration and the soil porosity, Hammecker et al. 2003 found that about 17 irrigations were necessary during one growing cycle. Considering that in the PHREEQC model all the calculations are performed for a given volume of solution, the Cation Exchange Capacity (CEC) and exchangeable cations were expressed per volume of liquid phase, depending on the soil porosity. The mass balance for water and solutes was calculated in the root zone, i.e. the first 20 centimeters of the soil profile (Slaton et al., 1990; Sharma et al., 1994; Boivin et al.2002). The irrigation water management during the cropping season, was simulated for one liter of soil solution in the root zone and the corresponding water volume for the superficial ponding water. As depicted in figure 2, during the first irrigation of the season 3 liters are introduced into the system : 1 liter for the soil solutions, and two liters for superficial ponding. During the cropping season, the superficial water level can almost disappear completely, but farmers usually irrigate before the complete drying-up of the plot.

Different hydrological conditions, typical of field situations, were considered to simulate the geochemical evolution taking into account different leaching fractions, presence or absence of capillary rise from an aquifer with different composition, and the influence of plant uptake of nutriments. The actual leaching fraction (LF) being considered is the fraction of applied irrigation

water that drains below the root zone :

$$LF = \frac{D_d}{D_a} \qquad [1]$$

Where D_d [L] is the amount of water drained below the root zone and D_a [L] the amount of irrigation water applied.

2.2.2. Chemical equilibria

Ionic activities in the soil solution were computed according to Debye-Hückel expression, based on the ionic strength of the solution. The soil solution was equilibrated with exchange sites on clay minerals and organic matter following Gaines and Thomas (1953) convention and mass conservation. Equilibrium with gas and minerals were considered for those initially present in soil, and those likely to crystallize or to affect the evolution of soil solution. The minerals usually found in arid soils like Mg-calcite, gypsum, quartz, kaolinite and sepiolite, were allowed to precipitate and dissolve, consequently to modify the composition of the solution. As quartz is initially present in the soil, this mineral has been chosen rather than amorphous silica, though the two options were tested and no differences in the major results of these simulations were found. When Al in solution analysis was not available it was computed considering equilibrium with kaolinite at the pH of the soil solution. The main solid and gaseous phases used in these simulations are reported in table 3, with their dissociation equation, and solubility products (K). Partial CO_2 pressure was considered to be equal to atmospheric value (log pCO2 = -3.5 atm) whereas in the soil solution it was considered to be higher and constant, with log pCO2 = -1.8 atm, like in most of the tropical soils (Brook et al. 1983). The crystallization of the different minerals was considered to take place when the solution reached equilibrium, regardless of any eventual super-saturation or kinetics phenomenon. However as the simulation is performed over a very long term, with different water contents, these processes will scarcely affect the final result.

2.2.3 The hydrological parameters

The adopted procedure for calculation was first, to equilibrate the irrigation solution with the soil solution, the mineral phases, and the partial CO_2 pressure in soil ($10^{-1.8}$ atm). The resulting solution was then concentrated to 5% of its original volume, as the farmers don't let the plot dry out completely. This value has been estimated from experimental observations (Hammecker, non published), though it has been verified that the choice of this value has little influence on the final result. During this procedure equilibria with the solid phase were computed considering the soils being initially formed by quartz, kaolinite, beidelite and by their respective exchangeable cations (table 2).

Finally, depending on the leaching fraction (LF), the remaining water content after evaporation (Q_0) was added to a new amount of irrigation water (Q_1), in order to start a new simulation with the same amount of water (one liter), following this relation :

$$Q_0 = (1\text{-}LF) \times 0.05 \qquad [2a]$$

$$Q_1 = 1\text{-}Q_0 \qquad [2b]$$

This procedure was performed 17 times for one cropping cycle, and 60 cropping cycles were simulated. In order to take into account the capillary rise in these geochemical processes, we estimated the quantity of solution possibly risen from the water table towards the root zone with water flows derived from hydraulic gradients measured during the dry period (Condom, 2000). As capillary rise occurs only during the inter-cropping period, we treated both periods together, by mixing the two solutions (irrigation and water table) in their respective proportions (90% and 10%) in the root zone.

In addition to vertical drainage, superficial lateral drainage (flushing) is performed intentionally or accidentally by the farmers in some situations. During this type of water management all salts and concentrated soils solutions present in the superficial layers of soil are dissolved and partially evacuated with the first water input at the beginning of the cropping period. As the soil profile dried

out during the inter-cropping season most of the soluble salts have accumulated in surface. Superficial lateral drainage experiment performed in Donaye showed that just with natural leakage from the bunds, an average of 15% of the total salinity (0-1m) could be removed (Hammecker et al. 1999). In Niono the flushing (lateral drainage) is performed intentionally, at the beginning of each new cropping season whereas in Donaye it occurs accidentally as, the margins of the plots leak after the inter cropping period when the soil shrinks and the margins crack. Consequently, we simulated an input of irrigation before each cropping period. This water was equilibrated with the soil solution, the minerals and the exchangeable cations, and was then partially evacuated from the system (Fig. 3). This numerical treatment, simulates the exportation of elements during a flush (lateral drainage), where flushing rates were defined as the proportion of water exported from the system, after the first water input had equilibrated with soil. Equilibrium during this procedure is conditioned by different physico-chemical processes like : (i) the competition between convective downward flow during infiltration and upward molecular diffusion towards the superficial water layer, (ii) the kinetics of minerals dissolution , (iii) the lateral losses in the plot. These processes were not considered individually but integrated into a bulk value of flushing rate. Different theoretical flushing rates were tested (5%, 10%, 30% and 50%) as no precise measurements for actual superficial lateral drainage were available in the three conditions. However they are in concordance with the flushing rate measured by Hammecker et al.1999 and with those determined in the experiment performed by Haefele et al. (1999) in the same area, who that showed superficial lateral drainage after submersed ploughing (puddling) at the beginning of the cropping season, could increase this salt exportation four folds.

2.2.4. Plant uptake

The geochemical budget was considered with and without the incidence of the plant uptake, in order to quantify the contribution of the plant uptake to soil degradation or conservation processes. The

main threat being alkalization due to carbonate concentration (pH increase), the focus has been set on the ability for rice to export alkalinity, and the main related cations (Ca and Mg) possibly affecting the carbonate balance and ESP. Data of Dobermann and Fairhurst (2000) on the average final composition of rice were used (Table 4). We considered an average yield of 5t/ha, which corresponds to 10t/ha of dry biomass(DB), a soil depth (z) of 0.2 m, an average bulk density (ρ_b) of 1750 kg.m^{-3} and a mineral density (ρ_s) of 2650 kg.m^{-3}.

The average ratio between the dry biomass (DB) and the volume of the soil solution (V_{soil}) has been calculated to be 14.7 kg.m^{-3} as follows :

$$\frac{DB}{V_{soil}} = \frac{DB \cdot 10^3}{z \cdot 10^4 \cdot \theta_s}$$

where θs is the porosity. As the soil profile is saturated porosity is defined as:

$$\theta_s = 1 - \frac{\rho_b}{\rho_s}$$

Plants export alkalinity because they absorb more cations than anions. In order to maintain electrical neutrality both inside and outside of the roots they have to produce organic anions and excrete protons (Pinton et al.,2001 ; Rengel, 2003). The average plant alkalinity was calculated as the difference between the cations and anions absorbed by the plant (Table 4). It was considered that all plant alkalinity was removed from the field, as farmers export the entire plant for threshing.

Moreover, when a crop is considered in the geochemical system , it is also necessary to take into account the N cycle. In paddy fields the plant absorb N as NH_4^+ originating from the deamination of the organic matter and the hydrolysis of the urea used as N fertilizer:

$R(NH_2)_2 + H^+ + H_2O = NH_4^+ + ROH$ Helyar and Porter, 1989

$CO(NH_2)_2 + 2H^+ + H_2O = 2NH_4^+ + CO_2$ Bolan and Hedley, 2003

In both cases for each mole of $NH4^+$ produced one mole of protons is removed from soil solution.

Part of the ammonium produced is also adsorbed on the exchangeable complex or lost as ammonia. Therefore we only took into account the ammonium ions absorbed by the plant, by using the total N content of the plant (Table 4), irrespectively of the actual urea management in these sites. The net acidification due to plant uptake and the N cycle was calculated as:

proton produced = plant alkalinity– N uptake.

In order to simulate the exportation of alkalinity, hence the acidification of the soil solution due to proton excretion, potassium bicarbonate ($KHCO_3$), magnesium and calcium carbonate ($MgCO_3$, $CaCO_3$) and potassium chloride (KCl) were numerically removed from the irrigation solution in proportions, calculated to meet the corresponding alkalinity uptake (Table 4). The total uptake for the different ions was divided by 17 (i.e. the number of irrigation events during a cropping cycle) and distributed evenly over the entire cropping season.

3.Results and discussion.

3.1.Evolution of the irrigation solutions with increasing concentration.

Results displayed in Figure 4 show the evolution of the solution composition versus the concentration rate defined as : concentration rate = $(V_i – V) / V_i$, where V_i is the initial volume of solution and V the volume of solution reached after concentration.

These results showed an important increase in pH with concentration, up to values around 9, and clearly superior to 8.3 the pK of calcite. Irrigation water of Foum Gleïta, rapidly reached saturation with calcite for its large initial Ca concentration. Consequently Ca concentration in solution decreased constantly whereas Alkalinity, Na and Mg concentrations increased, despite a slight depletion in Mg when sepiolite crystallization started. At the same time pH increased drastically despite sepiolite precipitation involving a release of protons into the solution (Table 3). Finally even for very high concentration rates, Mg increased noticeably in the solution because of its high initial

content, as sepiolite crystallization is controlled by Si, which is less abundant.

During this simulation, the irrigation water of Niono rapidly reached saturation with quartz and while it is the only mineral precipitating, alkalinity and concentrations in all the cations increased regularly with concentration rate. The solution reached saturation with calcite for a high concentration rate (0.75) then Ca concentration decreased. For higher concentration rates, Mg concentration dropped when sepiolite crystallized whereas Na kept concentrating. A similar behavior was observed in Donaye, when water of river Senegal concentrated. In the three cases the pH of irrigation water increased and Na became the dominant cation in solution, enhancing the risk of sodication. Considering the SAR and the Electrical Conductivity of the irrigation water of the different situations, they can be considered as suitable for irrigation according to the Riverside diagram (1954). However this static view does not reflect the evolution of the solutions that may occur when concentrating. Numerical simulation of the concentration of these solutions (Figure 5), show that their SAR increased drastically with concentration, whereas the total salinity (EC) didn't increase as much, mainly because of the precipitation of calcite. Barbiero et al. (2004) showed some results for experimental concentration of irrigation water from River Niger, in the Republic of Niger, which have similar initial composition as the irrigation water of Niono, where the SAR of the solutions also increased but with much higher EC values until reaching the C4S4 domain, instead of C2S4 as in the numerical simulation (Fig. 5). This discrepancy should mainly be explained by the fact that in the simulation the kinetics of precipitations have not been taken into account, and especially the retardation induced by the presence of Mg in the same proportions as Ca (House et al. 1988). However, in both cases the simulation shows that resulting solutions are extremely hazardous for soil conservation as they tend to promote sodication.

3.2. Evolution of the soil solutions over 60 simulated cropping cycles.

The previous simulations described the evolution of the irrigation solution without taking into

account the interactions with soils, especially with the exchange complex and the minerals. Moreover, in order to get an overall idea of the geochemical processes involved in field conditions, the vertical drainage and capillary rise was taken into account, following the simulation procedures described previously for the three situations.

The first set of simulation was aimed at quantifying the influence of the presence of a soil with a reactive adsorption complex and minerals, as well as the influence of the vertical leaching towards the water table. As the concentration of the soil varies constantly between two irrigations, the results displayed in the following figures corresponds to the composition of the soil solution and the exchange complex, immediately after the irrigation i.e. when the plots are full of water, in order to represent the actual solution infiltrating into the soil.

In the case of Foum Gleita (Fig. 6) where irrigation water tends to become very alkaline with concentration, an equivalent trend was observed in presence of soil and vertical drainage. However this trend appeared in lesser proportions, as pH reached only a value of 7.8 after 60 cropping cycles. The major ions in solution were Na^+ and alkalinity. Both increased regularly with the number of cropping cycles whereas Ca^{2+} decreased as calcite precipitated. The complex reacted to compensate this trend, providing Ca^{2+} to the soil solution. Consequently, the proportion of exchangeable Ca decreased and exchangeable Mg became dominant. At the same time, exchangeable Na increased and consequently ESP rose to 15% after 10 cropping cycles and finally reached 30% after 60 cropping cycles. The evolution of the pH and alkalinity is still positive, but at a noticeably lower rate than for the concentration of the irrigation water alone. In fact, the large CEC of the soil buffered the effects of irrigation solution composition, especially as it imposed the geochemical composition of the soil solution, and supplied sufficient Ca^{2+} ions necessary to precipitate calcite and so prevented the accumulation of excessive alkalinity. According to the Residual Alkalinity (RA), which is still positive, the general trend of the system is to evolve continuously, but slowly, towards alkaline conditions.

In the case of Niono (Fig. 7), the simulation showed a continuous increase in pH during the first 35 cropping cycles followed by a stabilization at around pH=8.1. Alkalinity and Na^+ in soil solution and in the soil displayed a similar evolution, namely increasing until reaching saturation towards sepiolite. $RA_{calcite}$ followed the same increasing trend as alkalinity, witnessing an alkaline evolution. Exchangeable sodium increased drastically during the first cropping cycles and reached a maximum of 53% of the exchangeable complex after 50 cropping cycles, until sepiolite started to crystallize. Although extreme values for ESP have not actually been observed in this region, they are indicative of the type of degradation the soils might undergo in these conditions : high pH and ESP values are typical of alkalization and sodication processes. Although the irrigation solution is potentially less alkaline than in Foum Gleita, its use for irrigation is more hazardous, because the adsorption complex is very vulnerable to soil solution composition due to low CEC ; the exchange between the adsorbed Ca^{2+} and Na^+ in solution will therefore lead to a rapid increase in ESP.

Finally, in the case of Donaye (Fig. 8), the pH of the soil solution did not change much with the number of cropping cycles and mainly remained near neutrality. Sodium and magnesium were the major cations in the soil solution, and both concentrations increased with the number of cropping cycles. Alkalinity was the main anion, but both chloride and sulphate increased drastically with time, as there was no leaching towards the water table in this site. The soil solution temporarily reached equilibrium with gypsum during the dry season when all the irrigation water was evaporated, and especially during the inter cropping periods, according field observations (Boivin et al., 2002; Barbiero et al., 2005).

In the first instance $RA_{calcite}$ dropped slightly but increased again progressively when calcite and later gypsum started to precipitate. As the soil is very clayey with high CEC, the composition of the soil solution was determined by the buffering property of the soil. Exchangeable calcium was

progressively desorbed and precipitated, exchangeable magnesium increased and became the first exchangeable cation. At the same time ESP increased linearly up to 9% after 60 cycles. These extreme values for adsorbed magnesium were not observed yet, but still represent the values potentially reached for these conditions. Sixty cropping cycles were not sufficient to lead to alkaline conditions. However these confined conditions promote a very slow alkalization and sodication process.

3.3. Importance of plant uptake

Results displayed in figure 9 to 11 showed clearly that the ionic plant uptake in the soil solution, decreased systematically the pH of soil solution in the three sites. Nevertheless, the plant effect was moderate for the most alkaline conditions, namely Niono where pH still increased with time, up to 7.75 after sixty cropping cycles. In the case of Foum Gleita and Donaye pH decreased until reaching a final value of 7.2 as plant uptake counterbalanced the alkaline input of irrigation water. The total concentration of the soil solution, as indicated by EC, decreased by at least 30% , almost 50% for Foum Gleita and Niono. In Donaye, plant uptake played a major role for it is the only process exporting elements out of the system, as there was no vertical drainage. The same trend was observed for ESP in the cases of Foum Gleita and Donaye, where plant uptake contributed to a reduction by 50% of exchangeable sodium and consequently reduced the sodic risk. In Niono, unlike the former cases, plant uptake had a moderate effect on ESP. In fact, as K^+, Ca^{2+} and Mg^{2+} were preferentially absorbed by rice to Na^+, its concentration increased relatively in soil solution and exchangeable position. In all cases, $RA_{calcite}$ of the soil solution was significantly reduced, and even showing a serious decrease for Donaye until reaching 0.0015 $mol.l^{-1}$, though still remaining positive.

This simulation showed that in alkaline geochemical conditions, total exportation of rice (grains +

straw) improved generally the composition of the soil solution and tended to reduce the risks of salinisation, alkalization and generally sodication except in the case of Niono where the low CEC was very sensitive to a relative Na increase in the soil solution. This situation is illustrated by Barbiero et al. 2001 who carried out an experiment in Niger (Lossa) where the cultivation of a local fodder grass (Echinochloa stagnina) and its exportation out of the field contributed to noticeable de-alkalization of a highly alkaline soil.

3.4. Effects of superficial lateral drainage (flushing).

Results displayed in figures 12 to 14 showed distinctly that even for low rates, superficial flushing reduced significantly EC (i.e. the total salinity) of the soil solution, as well as ESP. The incidence of lateral drainage on pH and on RAC was less clear, especially for the case of Donaye as both parameters used to decrease without superficial lateral drainage and whereas they tended to increase slightly or stay constant when lateral drainage was simulated. However, in the case of Foum Gleita (Figure 12) the processes of sodication and alkalization were thoroughly reduced even for the smallest lateral drainage rate, as pH, EC, ESP and $RA_{calcite}$ decrease with increasing flushing rate. For flushing rates greater than 30% the simulation shows that all these parameters reach constant low values, namely pH = 7.3, EC = 0.6 $dS.m^{-1}$, ESP =2%, $AR_{calcite}$ = 0.03 $mol.l^{-1}$, witnessing stable geochemical conditions, harmless for the quality of soil and solution.

In the case of Niono (figure 13), superficial flushing was as effective as in the previous example, for its incidence was clearly noticeable, even for low flushing rates. The simulation showed that a flushing rate of 30% was sufficient to control and maintain EC at a constant level, with only a slight increase in ESP. The incidence of lateral drainage on pH and $AR_{Calcite}$ was very important for the low rates (5% and 10%) during 20 first cropping cycles, as these parameters decreased slightly, until $AR_{calcite}$ becoming negative for 5% flushing rate, and finally increased constantly. For the higher flushing rates (30 % and 50 %) the incidence on pH and $AR_{calcite}$ was less important for the

first simulated cropping cycles, but remained constant over the entire period. This special behavior is probably related to the difference in pCO_2 between the soil solution ($10^{-1.8}$ atm) and the supplementary irrigation water ($10^{-3.5}$ atm) added to compensate lateral drainage, and their relative proportions when mixed, promoting whether calcite precipitation or dilution of the soil solution. In any cases the superficial flushing reduced significantly the risk of alkalisation and sodication, though ESP values still reached relatively high values (17%).

An equivalent behavior was noticed in the simulation for the case of Donaye (figure 14), although no vertical drainage was considered; EC and ESP showed a significant decrease even for low flushing rates and reached a low constant value all along the cropping cycles when higher superficial lateral drainage rates were achieved (EC = 0.7 $dS.m^{-1}$; ESP =1.5 % for 30% flushing rate and EC = 0.6 $dS.m^{-1}$; ESP = 0.8 % for a flushing rate of 50 %). Consequently the soil solution and soil quality increased. On the other hand, pH and $AR_{calcite}$ showed a significant decrease when no lateral drainage was simulated whereas they showed a similar behavior for the different flushing rates as described for the case of Niono. However these variations of pH and $AR_{calcite}$ can be considered as negligible considering alkalization because for the worst condition (flushing rate of 10 %), pH reached 7.33 and ARcalcite reached 0.004 $mol_c.l^{-1}$ after 60 cropping cycles .

Moreover these results also show that $AR_{calcite}$, which is considered as a conservative tracer (Ribolzi et al. 1996;Barbiero et al. 2001; Barbiero et al. 2004), varies along the simulation, and probably also in field conditions, as solutions with different pCO_2 are mixed.

In Donaye, mineralogical and chemical experimental studies of the soil have been performed to assess the modifications of the soil quality after 15 years of intensive irrigation. When compared inside an irrigated plot and outside the irrigation scheme, the evolution of the soil exchangeable complex, especially the ESP, has been found not significantly different (Charolais and Weber, 1994). Equally, when the pH of the soil, the EC and the content of accumulated carbonates in the topsoil have been measured on a 1/50 aqueous extract, (Schiess, 1995; Boivin et al. 1998) only a

slight increase in the soil between the two situations was noticeable, though the difference isn't really statistically different between the two groups (figure 15). These experimental results show that in 15 years of irrigation the soil quality has not changed noticeably. In Donaye the rice straw is usually not exported from the field, but left to graze for cattle or burned. However, “natural” leakage throughout the bunds of the plot, due to a lack of maintenance is almost systematically observed. In fact, this disorder actually contributes to the superficial flushing, especially during the first irrigation when the soil shrinkage cracks are still open in bunds, and helps to preserve the soil quality despite the improper quality of irrigation water.

Although the quantitative effect of superficial flushing is difficult to model accurately because of the lack of information, this study demonstrates clearly the crucial role of superficial flushing for soil conservation, and attests the general conclusions of the numerical simulation results.

3.5. Effect of soil reduction.

Although this process has not been modelled specifically in this work for the lack of Eh information in some cases, it is still possible to evaluate its effect on the proton balance. In the case of prolongated submersion conditions, like in paddy fields, the soil undergoes reduction as microbial activity consumes the dissolved oxygen, and finally reduces the iron oxi-hydroxides (the most commonly found). The oxidation of organic matter by reducing Fe(III) to Fe(II) produces alkalinity and consequently an increase in pH :

$$FeOOH + ½\ COOH^- + 5/2\ H^+ \leftrightarrow Fe^{2+} + ½\ CO_2 + 2H_2O$$

When the system oxides at the end of the submersion period an equivalent amount of acidity is produced and the general proton balance is null in confined conditions. However in case of a leaching fraction during reduced conditions, reoxidation leads generally to ferrolysis phenomenon which is a soil transformation involving a protonation of the complex, an attack of the clay crystalline structure, where H^+ is penetrating the octahedral layers and taking the place of Al^{3+} as

described by Brinkman (1979) and revisited by van Ranst and De Coninck (2002). Consequently, soil reduction has either no effect on alkalinity or, on contrary, consumes alkalinity and reduces pH in the studied situations.

Conclusion

In this study we used PHREEQC to predict the evolution of the soil and soil solution over several years, with different soil and water management. Although the use of Riversides' diagram, $RA_{calcite}$ and the RSC index, can be informative about the potential risks, they cannot predict the evolution of the soil nor of the soil solution. Especially as they don't take into account the buffer capacity of soil, the water management involving dilutions and variations in pCO_2, and the effect of the plants uptake. We demonstrated that despite the high risk of alkalinisation and sodication according to these indicators, in three west African situations of irrigation, soil degradation is not a fate. Considering the buffer effect of the soil (very high in Senegal), the possibilities of removing alkalinity from the plots by straw management, and finally the use of superficial flushing whether naturally (Foum Gleita), artificially with an effective drainage network (Niono) or accidentally with leaks in the bunds (Donaye), alkalinisation or sodication is not jeopardizing soil properties in well-conducted rice cropping system. These results using geochemical numerical modelling, attest that in Sahel, although the main rivers (river Senegal, Niger, Gorgol Noir) show an alkaline composition with positive $RA_{calcite}$ and RSC values, their use for irrigation in paddy fields cannot be considered as directly responsible for soil alkalinisation. Barbiero et al. (1998), in the Republic of Niger, or van Asten et al. (2004) in Foum Gleita, found similar conclusions based on experimental results. The presence of alkaline soils is more probably due to the alteration of an alkaline bed rock (in Foum Gleita) or to the presence of groundwater leaching through a deeper alkaline bed rock (in Niono).

Unlike the usual assumptions,where rice cropping is held responsible for soil salinization or alkalinisation, this study show that in these cases, rice cropping can improve the soil quality when irrigation and residue management are performed properly. Namely a superficial lateral drainage performed once, at the beginning of the cropping season, although being sometimes seen as a waste of water by the local farmers, improves noticeably the sustainability of the system despite adverse composition of the irrigation water. More over, in the situation of alkalinisation risk, the exportation of the straw out of the plots contributes significantly to the control of the average alkalinity of soil, especially in the cases of Niono and Donaye.

Table 1: Composition of irrigation water (I) and groundwater (GW) in the different locations

	Ca	Mg	Na	K	Alk.	Cl	SO_4	RSC	pH	SAR	EC
				$\times 10^{-3}$	$mol_c.l^{-1}$						$dS.m^{-1}$
Foum[I]	0.78	0.38	0.32	0.12	1.4	0.11	0.09	0.24	7.54	0.42	0.17
Niono[I]	0.11	0.1	0.17	0.05	0.38	0.08	0	0.17	6.52	0.62	0.04
Niono[GW]	0.62	0.36	6.05	0.09	6.91	0.13	0.08	5.93	7.69	8.62	0.58
Donaye[I]	0.23	0.12	0.1	0.06	0.61	0.06	0.07	0.26	7.28	0.25	0.07

Table 2: Adsorbed cations of the different soils. ESP : exchangeable sodium percentage.

	XCa	XMg	XNa	XK	Σcat	ESP
		$cmol_{c}.kg^{-1}$				%
Foum Gleita	11.8	4.8	0.3	0.6	17,5	1.71
Niono	5.5	2	1.5	0.1	9.1	16.48
Donaye	13	9	0.4	0.3	22.7	1.76

Table 3 : Minerals dissociation equations and solubility product values at 10^5 Pa and 298.15K (1) : PHREEQC data base, (2) : estimated as a solid solution with data from PHREEQC data base, (3) : Kindis data base (Made, 1991) , (4) : fixed (Brooks et al. 1983)

Minerals	**equations**	**log K (25 °C)**
CO_2		-1.8 (4)
Mg-Calcite	$Ca_{.98}Mg_{.02}CO_3 = .98\ Ca^{2+} + .02Mg^{2+} + CO_3^{-2}$	-8.46608 (2)
Sepiolite	$Mg_2Si_3O_{7.5}OH{:}3H_2O + 4\ H^+ + 0.5H_2O = 2\ Mg^{2+} + 3\ H_4SiO_4$	15.76 (1)
Kaolinite	$Al_2Si_2O_5(OH)_4 + 6\ H^+ = H_2O + 2\ H_4SiO_4 + 2\ Al^{3+}$	7.44 (1)
Gypsum	$CaSO_4{:}2H_2O = Ca^{2+} + SO_4^{-2} + 2\ H_2O$	-4.58 (1)
quartz	$SiO_2 + 2\ H_2O = H_4SiO_4$	-3.98 (1)
beidellite	$Si_{3.8}Al_{1.7}Fe_{.3}Mg_{.2}O_{10}(OH)_2Ca_{.2} + 6.8H^+ + 3.2\ H_2O =$ $3.8H_4SiO_4 + 1.7Al^{3+} + .3Fe^{3+} + .2Mg^{2+} + .2Ca^{2+}$	-33.98 (3)

Table 4 : Average paddy uptake (grain + straw) and equivalent uptake in soil solution (average yield of 5t/ha, and average bulk density of 1750kg.m^{-3})

	Dobermann & Fairhurst, 2000	equivalent ionic	
	%	species	mmol/l
N	0.65	NH_4^+	6.62
K	1.4	K^+	5.1
Mg	0.2	Mg^{2+}	2.35
Ca	0.3	Ca^{2+}	2.13
Na	0.2	Na^+	1.24
Σc			18.01
P	0.1	$H_2PO_4^-$	0.46
Cl	0.5	Cl^-	2.01
S	0.075	SO_4^{2-}	0.66
Σa			3.24
Σc - Σa		Alkalinity	14.3

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Figure 1 : Location of the studied sites

Figure 2 : Schematic representation water use dynamics in simulation : **a.** after irrigation, 2 liters of superficial ponding water + 1 liter soil solution in the root zone, **b.** : after evaporation and just before the next irrigation, 1 liter of soil solution in the root zone.

Figure 3: Schematic representation of the procedure adopted to simulate the effects of the leaching fraction (**L.F.**) and of the superficial flushing (**S.F.**). **a. -1**: the soil is saturated, 2 : at the end of the concentration period, part of the remaining solution is evacuated from the system (LF). **b. -1** : at the end of an inter-cropping period precipitated minerals and concentrated solutions are close to the soil surface, **2**: addition of a superficial layer of irrigation water, dissolving the minerals and equilibrating with soil solution and and exchangeable cations, **3**: part of the superficial layer is evacuated.

Figure 4 : Evolution of irrigation water composition during concentration for $pCO_2 = 10^{1.5}$ Pa and possibility for common minerals (calcite, quartz, sepiolite, kaolinite, gypsum) to precipitate.

Figure 5 : Evolution of irrigation water composition during concentration in the Riverside diagram.

Figure 6 : Evolution of soil solution and adsorption complex for Foum Gleita. RAC : $RA_{calcite}$, the straight horizontal solid line states for the precipitation of calcite.

Figure 7 : Evolution of soil solution and adsorption complex for Niono. RAC : $RA_{calcite}$, the straight horizontal solid line states for the precipitation of calcite and the dotted line for the precipitation of sepiolite.

Figure 8 : Evolution of soil solution and adsorption complex for Donaye, RAC : $RA_{calcite}$, the straight horizontal solid line states for the precipitation of calcite and the dotted line for the precipitation of gypsum.

Figure 9 : Evolution of pH, EC of soil solution, ESP and $RA_{calcite}$ of the soil solution for Foum Gleïta considering presence (solid line) and absence (dotted line) of plant uptake.

Figure 10 : Evolution of pH, EC of soil solution, ESP and $RA_{calcite}$ of the soil solution for Niono considering presence (solid line) and absence (dotted line) of plant uptake.

Figure 11 : Evolution of pH, EC of soil solution, ESP and $RA_{calcite}$ of the soil solution for Donaye considering presence (solid line) and absence (dotted line) of plant uptake.

Figure 12 : Evolution of pH, EC of soil solution, ESP and $RA_{calcite}$ of the soil solution for Foum Gleïta, considering different superficial flushing rates, vertical drainage and plant uptake.

Figure 13 : Evolution of pH, EC of soil solution, ESP and $RA_{calcite}$ of the soil solution for Niono, considering different superficial flushing rates, vertical drainage and plant uptake.

Figure 14 : Evolution of pH, EC of soil solution, ESP and $RA_{calcite}$ of the soil solution for Donaye, considering different superficial flushing rates and plant uptake.

Figure 15 : Comparison of soil quality between irrigated rice cropped plots and uncultivated soil in Donaye. The diagrams were obtained with superficial (0-10cm) soil samples, n=130 in irrigated plots and n=95 in uncultivated soils.

* Revision Notes
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Revision notes for the manuscript GEODER 4246 :

Simulating the evolution of soil solutions in irrigated rice soils in the Sahel.

By
Claude Hammecker[a], Piet van Asten[b e], Serge Marlet[c], Jean-Luc Maeght[a] and Roland Poss[d].

The comments and corrections suggested by the reviewers have been taken into account in the new version of the manuscript. Considering the numerous items listed by the reviewers, they will not be commented individually.

Reviewer 1 :

- The different sites studied in this paper have been put into a regional context demonstrating their relevance according to specific geological, geomorphological, pedological, and textural conditions. Moreover their specific water management and hydrological conditions have been highlighted.
- The evolution of the Residual Alkalinity Calcite has been introduced into the new version of the manuscript, according to the reviewers recommendations. However this simulation study showed that $AR_{calcite}$ is dependent on the mixing of solutions where pCO2 is different, and therefore partially fails to its conservative tracer property.
- The typos and missing references have been corrected.
- As during the simulated process, the volume of solution varies between two consecutive irrigations, the results presented for the soil solution compositions and the exchangeable cations are those computed for the situation where the water level in the plot is at the maximum, that is just before evaporation starts. Therefore the results presented in the manuscript are not exactly thoses for which the most soluble minerals like sepiolite or gypsum precipitate, though they do precipitate just before the next irrigation.

- The authors chose to keep the results and the discussion in the same section, in order to avoid repeating the same statements. However as recommended by the reviewer, the results have been discussed more thoroughly and documented.
- Extreme ESP values or Mg concentrations in soil solution and on the exchangeable complex, computed by the model in absence of plant or drainage have not been observed in field conditions, attesting that these processes have an important influence on the evolution of the soil and soil solution. When taken into account in the simulations they contribute in mitigating the influence of adverse irrigation water quality, displaying results closer to reality.
- The functioning of the model PHREEQC has been described more clearly in the revised version.
- The units for pCO2 have been homogenized and the choice of pCO2 in tropical soils has been documented.
- The reference to soil reduction and specially to ferrolysis had been precised according to the reviewers recommendations.
- In the conclusion we drew recommendations for a long lasting management of irrigation schemes according to the specificity of each site.

Reviewer 2 :

- As suggested, it has been stated more precisely that the results presented in the manuscript are simulations and not experimental results. However each it was possible the simulated results were validated by field data or references.
- The different precisions about the the definitions of alkalinity, ESP, SAR, EC, Ece, SARe required by the reviewer have been introduced in the revised version, when available.
- Supersaturation of the soil solution has not been taken into account in these study as it is usually governed by kinetic processes. Considering that the simulations are aimed to describe long term evolutions, we felt that the it would not have improved the simulation and the final results.
- The use of abbreviations has been improved and homogenized in the new version of the manuscript.
- Few data were available about the irrigation efficiencies in the different sites. Therefore this subject has not been discussed in the paper, though we understand it's importance.

* Marked Manuscript
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Simulating the evolution of soil solutions in irrigated rice soils in the Sahel.

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Abstract

In sahelian countries, agriculture often relies on irrigation especially for rice cropping which has been introduced these last decades. As most of the water resources used for irrigation (mainly rivers and lakes) have an alkaline composition, rice cropping is often held as responsible for soil alkalinization. In order to evaluate the probability for this process to occur, we studied 3 different sites in West Africa where numerical simulation of the geochemical interactions between soil, irrigation water and groundwater were performed with PHREEQC. It was possible to simulate the evaporation of the ponding water, the mixing between groundwater and irrigation water, the lateral drainage (flushing) and the leaching, and finally the management of the crop residues. By performing prospective simulations over 60 cropping cycles it has been shown that soil alkalinization and sodication are not inevitable in these area especially if the cropping is properly managed. Moreover, when straw is removed and the plot flushed before the new cropping season, alkaline soils can even be improved with rice cropping.

Keywords : alkalinization, sodication, PHREEQC, plant uptake, water management, West Africa

Introduction

In the Sahel, irrigated rice (*Oryza Sativa* L.) cropping has been introduced on a wide scale during the last 20 years. The construction of large (> 100 ha) and costly irrigation schemes were intended to increase food security and provide income for Sahelian farmers, whose crops and livestock were devastated during the droughts in the 1970-1980's. Irrigated rice cropping in the hot and dry Sahelian climate seems like a paradox. However, the major Sahelian rivers and some large artificial reservoirs provide more than sufficient water to support current irrigation activities throughout the year. Although most Sahelian irrigation waters contain relatively little salt, they usually show alkaline compositions, where alkalinity (Alk.) is the dominant aqueous species. It is defined as the algebraic sum of the strong base cation and strong acid anion equivalents (Stumm and Morgan, 1970), and can be expressed as : $Alk. = (HCO_3^-) + (CO_3^{2-}) + (OH^-) - (H^+)$, where ( ) denote the total concentration in $mol_c\ l^{-1}$. Moreover most of the Sahelian irrigation waters, show also a positive calcite residual alkalinity ($RA_{calcite}$) which corresponds to the alkalinity of the solution after precipitation of calcite : $RA_{calcite} = Alk. - (Ca^{2+})$, (Valles et al., 1991; Bertrand et al., 1993). $RA_{calcite}$ has also been shown to be a conservative tracer of the soil solution (Ribolzi et al., 1996; Barbiero et al., 2001; Barbiero et al., 2004). Even the residual sodium carbonate, defined as $RSC = Alk. - (Ca^{2+}) - (Mg^{2+})$; which corresponds to the alkalinity of the solution after calcite and Mg-carbonate or Mg-silicate precipitation, is positive for these solutions and is an indicator of potential alkalinization and sodication (Eaton, 1950; Hardie and Eugster, 1970; Van Beek and Van Breemen, 1973; Al Droubi et al.,1980). Continuous concentration of such waters in the soil root zone may lead to the formation of alkaline and sodic soils, showing both high pH values and high exchangeable sodium percentage : $ESP = XNa^+ / CEC$, where XNa^+ is the

exchangeable Na^+ and CEC the total cation exchange capacity. Such soils are less productive because of the pH-induced loss or low availability of several plant nutrients (e.g. Fe, P, Zn) and poor physical properties of the sodic horizon (Abrol et al., 1988).

Whether or not large quantities of alkaline salts will accumulate in the soil root zone depends largely on the water balance of the root zone. Evapotranspiration in the Sahelian climate can be very large and regularly exceeds rates of 10 mm day^{-1} in the dry season (November – May) when maximum temperatures reach 40 to 45 °C (Van Asten et al., 2003, Hammecker et al., 2003). In most irrigation schemes, percolation rates are very low (< 4 mm day^{-1}) (Condom, 2000 ; Hammecker et al., 2003 ; Van Asten, unpublished), due to the low hydraulic conductivity of the clayey soils and air entrapment (Hammecker et al., 2003). In the course of the cropping season, percolation rates can further decrease if groundwater levels reach the soil surface. The combination of large evapotranspiration and small percolation can lead to the excessive build up of alkaline salts in the long run.

Recent studies have shown that the current soil alkalinity and sodicity problems in Sahelian irrigation schemes are primarily caused by salts that originate from the parent material (Barbiero and Van Vliet-Lanoe, 1998, Van Asten et al., 2004), or that accumulated as a result of long-time irrigation of non-flooded crops in combination with shallow saline groundwater levels. Hence, these salts were already in the soils before irrigated rice cropping was introduced and there is little indication that the recent introduction of irrigated rice cropping contributed to a significant increase in the salt content of these soils (van Asten, 2003). Moreover, most rice soils have the capacity to buffer an increase in soil solution alkalinity through desorption of exchangeable Ca^{2+} and the subsequent precipitation of calcite. However, although this buffer capacity is large, it is not infinite. Consequently, it still remains uncertain whether current irrigation practices will not lead to soil alkalinization and

sodication in the long run (i.e. some decades) in areas where salts added through irrigation can not sufficiently be leached or evacuated from the soil root zone. Given the high investment costs of irrigated agriculture and the high costs of reversing alkalinization and sodication processes, it is important to know whether current or alternative crop and water management will lead to the degradation of one of the Sahel's most productive crop system.

In this study, we focus on three Sahelian irrigation situations, inside irrigation schemes, that differ distinctly in terms of parent material, soil water balance and irrigation water quality. All sites have earlier been subject of studies on soil and water quality (Hammecker and Maeght, 1999; Boivin et al., 2002; Van Asten, 2003). Therefore, mean values for basic crop, water and soils parameters are already available. Taking into account some of the most important chemical and hydrological features, we tried to simulate how soils and soil solutions would evolve over time, under current and alternative land management practices at the three sites. The most critical parameter; i.e. the ratio between leached and irrigated solution volume, is the leaching fraction (LF) whether with vertical drainage or lateral drainage (flushing). In order to account for spatial variability within the irrigation schemes, we calculated soil solution evolution for different leaching fractions. This approach allows for the identification of the minimum leaching fraction that is required, in order to prevent soil degradation in the long run. Proton excretion (or alkalinity uptake) by the rice plant can also contribute significantly to the alkalinity balance of the soil root zone (Van Asten et al., 2004) and was also taken into account.

The objectives of this study are: (i) to give an overview of basic soil and water parameters for a range of Sahelian irrigation schemes, (ii) to simulate soil evolution under current and

alternative crop and water management practices, and (iii) to identify the minimum leaching fraction that is required to prevent soil degradation in the long term.

2. Material and methods

2.1.Study sites

This study is based on data collected in three different irrigation areas in West Africa located in the valley of River Senegal, the Gorgol noir and in the valley of river Niger, where irrigated rice cropping is the main agricultural activity.

These sites are representative of most of the conditions where rice-cropping cultivation is observed in the Sahel, and are representative of different geological, geomorphological and pedological siuations with different soil textures. They are representative of (i) silty clay loam soils, developed on crystalline bedrock (Foum Gleita), (ii) alluvial levees with loamy sand soils (Niono) and (iii) alluvial basin with clayey vertisol (Donaye).

2.1.1.Foum Gleïta

The 'Mauritanides' geological region where Foum Gleita is located, is representative of the Pan-African orogenic belt which has been folded and lifted in the Appalachian era (Carité, 1989) and is consisting of metamorphic rocks, mainly greenschists, calcshists, micaschists and quartz, and secondary intrusions of dolerite, on which pedogenesis developed alkaline soils. The Foum Gleita irrigation scheme is located in central southern Mauritania (N16°08'; W12°46'). The scheme was constructed between 1985 and 1989, with a surface area of 1950 ha. Irrigation water originates from a large artificial lake that formed behind a dam in the Gorgol Noir river. Irrigation and drainage are gravimetric but the drainage canals are often

not functional due to poor maintenance. Most soils in Foum Gleita have formed from the schist parent rock that can be found at shallow depths (< 2.5m) (Van Asten et al., 2003). Soil texture is mostly silty clay loam, with around 30% clay. Although no specific clay mineralogical studies have been done in the Foum Gleita schemes, other studies in the Gorgol basin have shown that a large proportion of the clays are illites and kaolinites (Maignien, 1961; Audry, 1961). The soils have a moderate to strong structure, varying from subangular blocky to prismatic in the more vertic soils. Biological activity in these soils is generally high. The porosity of the soils is generally medium to high, but is distinctly lower near soil surface. Although some soils have high ESP values, up to 65%, no evidence of soil structure degradation due to sodication has been observed in Foum Gleita. (Van Asten et al., 2003). In this region the cation exchange capacity (CEC) of soils ranges from 8 to 18 $cmol_c.kg^{-1}$, and the electrical conductivity of the 1:5 paste ($EC_{1:5}$) varies from 0.12 to 1.32 $dS.cm^{-1}$. Percolation rates are generally below 4 mm day^{-1}, and decrease during the rainy season as groundwater approaches the surface. On a few soils, high percolation rates were measured (> 10 mm day^{-1}) and farmers complained about difficulties in maintaining a submersion needed for rice. After the cropping season, groundwater quickly drops to below 1.2 m, indicating that deep percolation into the vertically oriented bedrock occurs, suggesting that horizontal groundwater flow along the slopes is minimal (van Asten et al., 2003). The absence of a shallow groundwater level during fallow periods suggests that capillary rise from the ground water can generally be neglected as a source of (alkaline) salts. The irrigation water is 2 to 4 times more saline than at the other study sites (EC = 0.17 $dS.m^{-1}$), but the sodium adsorption ratio, defined as : $SAR = Na^{+} /(Ca^{2+} + Mg^{2+})^{1/2}$ where the concentration are in $mmol.l^{-1}$, is still considered as very low (0.42). The residual sodium carbonate (RSC) is low and consequently suitable for irrigation according to the Riverside's diagram (see table

1). However, as at the other sites, RSC is positive and may therefore lead to alkalinization and sodication.

2.1.2. Niono

The site of Niono, is typical of the inner Delta of river Niger, developed on three different geological units: (i) Infracambrian substratum (-500 to -480 M years) composed of fractured schists and sandstones, (ii) Continental Terminal of Post Eocene to Pre-Quaternary age (-2.5 to -2 M years) formed by alternate sedimentary deposits of clays, sandy clays and sand , (iii) recent quaternary alluvial sediments deposited by the river Niger. In the studied area, the main morphological units are sandy levees, loamy inter levee depressions and clayey settling basins.

The study is based on data obtained in the huge irrigation scheme of the Office du Niger in Mali near Ségou (14°32 N 05°59 W). The climate is semi-arid (sudano-sahelian) with an average rainfall of 460 mm/year, distributed from June to October. The annual evaporation reaches 2.5m which generates soil solution concentration and consequently alkalization processes related to the alkaline composition of irrigation water (Condom, 2000) . The distribution of the soils in this area is inherited from ancient delta deposits constituted of clayey depressions delimited by sandy levees. These soils evolved under hydrologic conditions imposed by the water management during last half century, especially related to the uprise of the groundwater level.

The soils in this study are located on a little levee. The upper soil layers are composed of 11% clay and 78% sand, and classified as loamy sand. The identified clay minerals are mainly kaolinite, smectite and traces of illite. The structure of the soil is polyhedral. The soil displays an important biological porosity in the upper part of the profile (0-70cm) due to roots and to

meso-fauna activity. The CEC for this soil is 9 $cmol_c/kg$ but with large proportion of exchangeable sodium (ESP) of about 16% (table 2) ; the $EC_{1:1}$ for the soils in the area range from 0.18 to 1.09 $dS.m^{-1}$. For the last 30 years the fields have been mainly cropped in rice with market gardening as a marginal activity (Condom, 2000).

In this large irrigation scheme plots are equipped with lateral drainage canals receiving mainly water from superficial flushing. After several decades of intensive irrigation, the water table level has risen approximatively by 50 m and is now close to the surface. Condom (2000) found that during the cropping season the average infiltration was about 80 mm (i.e. 9% of the leaching fraction), whereas during the inter cropping periods an equivalent amount of water from the water table supplied capillary rise towards the surface. Lateral losses towards drains and leaks represent 26 % of the total water inputs (Condom, 2000).

The Niger River that supplies the irrigation water by gravity has very low concentration (EC) and SAR values (Table 1), whereas the groundwater is 10 times more concentrated with a very high SAR value. According to the Riverside classification (Riverside salinity lab. staff, 1954) the quality of irrigation water does not constitute any harm to soil conservation but the composition of the groundwater typically represents a sodic hazard. Nevertheless, as illustrated by the positive $RA_{calcite}$ and RSC value (Table 1), these solutions can both become very alkaline and sodic when they concentrate, as the Ca^{2+} and Mg^{2+} might precipitate in minerals with low solubility like calcite and Mg-carbonates or Mg-silicates (e.g. sepiolite), whereas alkalinity and Na, keep concentrating in the solution (Vallès, 1991; Bethke, 2007).

2.1.3. Donaye

The third site, Donaye is representative of the irrigated soils of the river Senegal, representing

a total surface area of irrigation schemes of 240,000 ha (Barbiero et al., 2001). These soils developed on marine sediments deposited during the Nouakchottian transgression (4300 BP) which extended 380 km inland, near Bogué.

The irrigation scheme is located in northern Senegal (N16°40'; W15°), in the middle valley of the Senegal River, near Podor. It is a 20-year-old irrigation scheme managed by the farmers, without drainage network. The soil which has for long time been described as formed by recent alluvial deposits is a vertisol (vertic Xerofluvent). However in a recent work Barbiero et al. (2005) have suggested that the soil distribution in lower and middle valley of river Senegal might result from the pedological transformation of a unique unripe mud, deposited during the last quaternary marine transgressions. The soils of the Senegal valley can be considered as a chronosequence, where the most recent soils can be observed downriver in the delta, and the most developed ones upriver, in the middle valley. The pedological process driven by the acidic conditions associated to the oxidation of inherited pyrite, led to the dissolution of the parental mud. The protonation and acid hydrolysis of the aluminosilicates in this material resulted in the formation of a sandy horizon, representing the quartz skeleton. In the upper part of the soil, the interaction of the river water (through floods and irrigation) with the acidic, Al and Si rich soil solution contributed to the precipitation of clay minerals, forming vertisols. In the Delta of the river Senegal this process is still active (Barbiero et al. 2005) and the vertisol is still thin whereas in Donaye it represents a two-meter-deep soil showing a vertic structure (slickensides), and constituted by 65 to 70% clay minerals, mainly beidellite and kaolinite (Favre et al., 2002), which shows a high cation exchange capacity of 22.7 cmol.kg^{-1}(table 2). The soil overlays a 5 to 6 m thick sandy layer corresponding to the afore mentioned quartz skeleton.

Rice cropping is performed by surge irrigation, and flooding is maintained during the

complete plant growth cycle (about 100 days). The presence of a shallow water table at 2m depth contributes to air entrapment and stops vertical infiltration (Hammecker et al. 2003). Consequently, vertical leaching is negligible, and soil solution in the upper part of the profile (above 40 cm) does not connect with the water table during the irrigation period. However, bad maintenance of bunds aimed to hold the irrigation in the paddy plots, generates important leaks contributing to non negligible loss of water, especially during the first irrigation. Irrigation water is pumped in a loop of river Senegal called Doué. This water with a very low concentration (EC = 0.07 $dS.m^{-1}$) and a low SAR value (Table 1), is suitable for irrigation according to Riverside's diagram. Nevertheless, like in the former situations, the $RA_{calcite}$ and RSC of the irrigation water are positive, and the concentration of this solution may lead to sodication.

2.2. Numerical simulation.

2.2.1. The model and its main parameters.

The evolution of the soil solution and its interactions with the solid phase (precipitation-dissolution and exchange processes) were evaluated with the computer model PHREEQC v2. (Parkhurst and Appelo, 1999). This model, based on aqueous thermodynamics, computes equilibrium chemistry of aqueous solutions interacting with minerals, gases, solid solutions, exchangers, and sorption surfaces, providing a full speciation of an aqueous system. The different databases provided with the model give a very wide possibility for computing the activities of most of the aqueous species present in natural solutions, especially for the CO_3-HCO_3 solutions. This model is especially useful as, in addition to the calculation of the chemical equilibria, it allows for the simulation of mixing different solutions, for concentrating solution due to evaporation, and for adding or taking out aqueous species from

the soil solution. Using these options, it is possible to simulate solution changes due to flooded irrigation combined with concentration of the soil solution and evaporation. In surge flooding conditions, successive water inputs are usually performed to maintain a constant ponding level.

Considering the duration of the rice cycle, the average evapotranspiration and the soil porosity, Hammecker et al. 2003 found that about 17 irrigations were necessary during one growing cycle. Considering that in the PHREEQC model all the calculations are performed for a given volume of solution, the Cation Exchange Capacity (CEC) and exchangeable cations were expressed per volume of liquid phase, depending on the soil porosity. The mass balance for water and solutes was calculated in the root zone, i.e. the first 20 centimeters of the soil profile (Slaton et al., 1990; Sharma et al., 1994; Boivin et al.2002). The irrigation water management during the cropping season, was simulated for one liter of soil solution in the root zone and the corresponding water volume for the superficial ponding water. As depicted in figure 2, during the first irrigation of the season 3 liters are introduced into the system : 1 liter for the soil solutions, and two liters for superficial ponding. During the cropping season, the superficial water level can almost disappear completely, but farmers usually irrigate before the complete drying-up of the plot.

Different hydrological conditions, typical of field situations, were considered to simulate the geochemical evolution taking into account different leaching fractions, presence or absence of capillary rise from an aquifer with different composition, and the influence of plant uptake of nutriments. The actual leaching fraction (LF) being considered is the fraction of applied irrigation water that drains below the root zone :

$$LF = \frac{D_d}{D_a} \qquad [1]$$

Where D_d [L] is the amount of water drained below the root zone and D_a [L] the amount of

irrigation water applied.

2.2.2. Chemical equilibria

Ionic activities in the soil solution were computed according to Debye-Hückel expression, based on the ionic strength of the solution. The soil solution was equilibrated with exchange sites on clay minerals and organic matter following Gaines and Thomas (1953) convention and mass conservation. Equilibrium with gas and minerals were considered for those initially present in soil, and those likely to crystallize or to affect the evolution of soil solution. The minerals usually found in arid soils like Mg-calcite, gypsum, quartz, kaolinite and sepiolite, were allowed to precipitate and dissolve, consequently to modify the composition of the solution. As quartz is initially present in the soil, this mineral has been chosen rather than amorphous silica, though the two options were tested and no differences in the major results of these simulations were found. When Al in solution analysis was not available it was computed considering equilibrium with kaolinite at the pH of the soil solution. The main solid and gaseous phases used in these simulations are reported in table 3, with their dissociation equation, and solubility products (K). Partial CO_2 pressure was considered to be equal to atmospheric value (log pCO2 = -3.5 atm) whereas in the soil solution it was considered to be higher and constant, with log pCO2 = -1.8 atm, like in most of the tropical soils (Brook et al. 1983). The crystallization of the different minerals was considered to take place when the solution reached equilibrium, regardless of any eventual super-saturation or kinetics phenomenon. However as the simulation is performed over a very long term, with different water contents, these processes will scarcely affect the final result.

2.2.3 The hydrological parameters

The adopted procedure for calculation was first, to equilibrate the irrigation solution with the soil solution, the mineral phases, and the partial CO_2 pressure in soil ($10^{-1.8}$ atm). The resulting solution was then concentrated to 5% of its original volume, as the farmers don't let the plot dry out completely. This value has been estimated from experimental observations (Hammecker, non published), though it has been verified that the choice of this value has little influence on the final result. During this procedure equilibria with the solid phase were computed considering the soils being initially formed by quartz, kaolinite, beidelite and by their respective exchangeable cations (table 2).

Finally, depending on the leaching fraction (LF), the remaining water content after evaporation (Q_0) was added to a new amount of irrigation water (Q_1), in order to start a new simulation with the same amount of water (one liter), following this relation :

$$Q_0 = (1\text{-}LF) \times 0.05 \qquad [2a]$$

$$Q_1 = 1\text{-}Q_0 \qquad [2b]$$

This procedure was performed 17 times for one cropping cycle, and 60 cropping cycles were simulated. In order to take into account the capillary rise in these geochemical processes, we estimated the quantity of solution possibly risen from the water table towards the root zone with water flows derived from hydraulic gradients measured during the dry period (Condom, 2000). As capillary rise occurs only during the inter-cropping period, we treated both periods together, by mixing the two solutions (irrigation and water table) in their respective proportions (90% and 10%) in the root zone.

In addition to vertical drainage, superficial lateral drainage (flushing) is performed intentionally or accidentally by the farmers in some situations. During this type of water management all salts and concentrated soils solutions present in the superficial layers of soil are dissolved and partially evacuated with the first water input at the beginning of the

cropping period. As the soil profile dried out during the inter-cropping season most of the soluble salts have accumulated in surface. Superficial lateral drainage experiment performed in Donaye showed that just with natural leakage from the bunds, an average of 15% of the total salinity (0-1m) could be removed (Hammecker et al. 1999). In Niono the flushing (lateral drainage) is performed intentionally, at the beginning of each new cropping season whereas in Donaye it occurs accidentally as, the margins of the plots leak after the inter cropping period when the soil shrinks and the margins crack. Consequently, we simulated an input of irrigation before each cropping period. This water was equilibrated with the soil solution, the minerals and the exchangeable cations, and was then partially evacuated from the system (Fig. 3). This numerical treatment, simulates the exportation of elements during a flush (lateral drainage), where flushing rates were defined as the proportion of water exported from the system, after the first water input had equilibrated with soil. Equilibrium during this procedure is conditioned by different physico-chemical processes like : (i) the competition between convective downward flow during infiltration and upward molecular diffusion towards the superficial water layer, (ii) the kinetics of minerals dissolution , (iii) the lateral losses in the plot. These processes were not considered individually but integrated into a bulk value of flushing rate. Different theoretical flushing rates were tested (5%, 10%, 30% and 50%) as no precise measurements for actual superficial lateral drainage were available in the three conditions. However they are in concordance with the flushing rate measured by Hammecker et al.1999 and with those determined in the experiment performed by Haefele et al. (1999) in the same area, who that showed superficial lateral drainage after submersed ploughing (puddling) at the beginning of the cropping season, could increase this salt exportation four folds.

2.2.3

2.2.4. Plant uptake

The geochemical budget was considered with and without the incidence of the plant uptake, in order to quantify the contribution of the plant uptake to soil degradation or conservation processes. The main threat being alkalization due to carbonate concentration (pH increase), the focus has been set on the ability for rice to export alkalinity, and the main related cations (Ca and Mg) possibly affecting the carbonate balance and ESP. Data of Dobermann and Fairhurst (2000) on the average final composition of rice were used (Table 4). We considered an average yield of 5t/ha, which corresponds to 10t/ha of dry biomass(DB), a soil depth (z) of 0.2 m, an average bulk density (ρ_b) of 1750 kg.m^{-3} and a mineral density (ρ_s) of 2650 kg.m^{-3}.

The average ratio between the dry biomass (DB) and the volume of the soil solution (V_{soil}) has been calculated to be 14.7 kg.m^{-3} as follows :

$$\frac{DB}{V_{soil}} = \frac{DB \cdot 10^3}{z \cdot 10^4 \cdot \theta_s}$$

where θs is the porosity. As the soil profile is saturated porosity is defined as:

$$\theta_s = 1 - \frac{\rho_b}{\rho_s}$$

Plants export alkalinity because they absorb more cations than anions. In order to maintain electrical neutrality both inside and outside of the roots they have to produce organic anions and excrete protons (Pinton et al.,2001 ; Rengel, 2003). The average plant alkalinity was calculated as the difference between the cations and anions absorbed by the plant (Table 4). It was considered that all plant alkalinity was removed from the field, as farmers export the entire plant for threshing.

Moreover, when a crop is considered in the geochemical system , it is also necessary to take

into account the N cycle. In paddy fields the plant absorb N as NH_4^+ originating from the deamination of the organic matter and the hydrolysis of the urea used as N fertilizer:

$$R(NH_2)_2 + H^+ + H_2O = NH_4^+ + ROH \quad \text{Helyar and Porter, 1989}$$
$$CO(NH_2)_2 + 2H^+ + H_2O = 2NH_4^+ + CO_2 \quad \text{Bolan and Hedley, 2003}$$

In both cases for each mole of $NH4^+$ produced one mole of protons is removed from soil solution. Part of the ammonium produced is also adsorbed on the exchangeable complex or lost as ammonia. Therefore we only took into account the ammonium ions absorbed by the plant, by using the total N content of the plant (Table 4), irrespectively of the actual urea management in these sites. The net acidification due to plant uptake and the N cycle was calculated as:

proton produced = plant alkalinity– N uptake.

In order to simulate the exportation of alkalinity, hence the acidification of the soil solution due to proton excretion, potassium bicarbonate ($KHCO_3$), magnesium and calcium carbonate ($MgCO_3$, $CaCO_3$) and potassium chloride (KCl) were numerically removed from the irrigation solution in proportions, calculated to meet the corresponding alkalinity uptake (Table 4). The total uptake for the different ions was divided by 17 (i.e. the number of irrigation events during a cropping cycle) and distributed evenly over the entire cropping season.

3.Results and discussion.

3.1.Evolution of the irrigation solutions with increasing concentration.

Results displayed in Figure 4 show the evolution of the solution composition versus the concentration rate defined as : concentration rate = $(V_i - V) / V_i$, where V_i is the initial volume of solution and V the volume of solution reached after concentration.

These results showed an important increase in pH with concentration, up to values around 9, and clearly superior to 8.3 the pK of calcite. Irrigation water of Foum Gleïta, rapidly reached saturation with calcite for its large initial Ca concentration. Consequently Ca concentration in solution decreased constantly whereas Alkalinity, Na and Mg concentrations increased, despite a slight depletion in Mg when sepiolite crystallization started. At the same time pH increased drastically despite sepiolite precipitation involving a release of protons into the solution (Table 3). Finally even for very high concentration rates, Mg increased noticeably in the solution because of its high initial content, as sepiolite crystallization is controlled by Si, which is less abundant.

During this simulation, the irrigation water of Niono rapidly reached saturation with quartz and while it is the only mineral precipitating, alkalinity and concentrations in all the cations increased regularly with concentration rate. The solution reached saturation with calcite for a high concentration rate (0.75) then Ca concentration decreased. For higher concentration rates, Mg concentration dropped when sepiolite crystallized whereas Na kept concentrating. A similar behavior was observed in Donaye, when water of river Senegal concentrated. In the three cases the pH of irrigation water increased and Na became the dominant cation in solution, enhancing the risk of sodication. Considering the SAR and the Electrical Conductivity of the irrigation water of the different situations, they can be considered as suitable for irrigation according to the Riverside diagram (1954). However this static view does not reflect the evolution of the solutions that may occur when concentrating. Numerical simulation of the concentration of these solutions (Figure 5), show that their SAR increased drastically with concentration, whereas the total salinity (EC) didn't increase as much, mainly because of the precipitation of calcite. Barbiero et al. (2004) showed some results for experimental concentration of irrigation water from River Niger, in the Republic of Niger,

which have similar initial composition as the irrigation water of Niono, where the SAR of the solutions also increased but with much higher EC values until reaching the C4S4 domain, instead of C2S4 as in the numerical simulation (Fig. 5). This discrepancy should mainly be explained by the fact that in the simulation the kinetics of precipitations have not been taken into account, and especially the retardation induced by the presence of Mg in the same proportions as Ca (House et al. 1988). However, in both cases the simulation shows that resulting solutions are extremely hazardous for soil conservation as they tend to promote sodication.

3.2. Evolution of the soil solutions over 60 simulated cropping cycles.

The previous simulations described the evolution of the irrigation solution without taking into account the interactions with soils, especially with the exchange complex and the minerals. Moreover, in order to get an overall idea of the geochemical processes involved in field conditions, the vertical drainage and capillary rise was taken into account, following the simulation procedures described previously for the three situations.

The first set of simulation was aimed at quantifying the influence of the presence of a soil with a reactive adsorption complex and minerals, as well as the influence of the vertical leaching towards the water table. As the concentration of the soil varies constantly between two irrigations, the results displayed in the following figures corresponds to the composition of the soil solution and the exchange complex, immediately after the irrigation i.e. when the plots are full of water, in order to represent the actual solution infiltrating into the soil.

In the case of Foum Gleita (Fig. 6) where irrigation water tends to become very alkaline with concentration, an equivalent trend was observed in presence of soil and vertical drainage. However this trend appeared in lesser proportions, as pH reached only a value of 7.8 after 60

cropping cycles. The major ions in solution were Na^+ and alkalinity. Both increased regularly with the number of cropping cycles whereas Ca^{2+} decreased as calcite precipitated. The complex reacted to compensate this trend, providing Ca^{2+} to the soil solution. Consequently, the proportion of exchangeable Ca decreased and exchangeable Mg became dominant. At the same time, exchangeable Na increased and consequently ESP rose to 15% after 10 cropping cycles and finally reached 30% after 60 cropping cycles. The evolution of the pH and alkalinity is still positive, but at a noticeably lower rate than for the concentration of the irrigation water alone. In fact, the large CEC of the soil buffered the effects of irrigation solution composition, especially as it imposed the geochemical composition of the soil solution, and supplied sufficient Ca^{2+} ions necessary to precipitate calcite and so prevented the accumulation of excessive alkalinity. According to the Residual Alkalinity (RA), which is still positive, the general trend of the system is to evolve continuously, but slowly, towards alkaline conditions.

In the case of Niono (Fig. 7), the simulation showed a continuous increase in pH during the first 35 cropping cycles followed by a stabilization at around pH=8.1. Alkalinity and Na^+ in soil solution and in the soil displayed a similar evolution, namely increasing until reaching saturation towards sepiolite. $RA_{calcite}$ followed the same increasing trend as alkalinity, witnessing an alkaline evolution. Exchangeable sodium increased drastically during the first cropping cycles and reached a maximum of 53% of the exchangeable complex after 50 cropping cycles, until sepiolite started to crystallize. Although extreme values for ESP have not actually been observed in this region, they are indicative of the type of degradation the soils might undergo in these conditions : high pH and ESP values are typical of alkalization and sodication processes. Although the irrigation solution is potentially less alkaline than in Foum Gleita, its use for irrigation is more hazardous, because the adsorption complex is very

vulnerable to soil solution composition due to low CEC ; the exchange between the adsorbed Ca^{2+} and Na^{+} in solution will therefore lead to a rapid increase in ESP.

Finally, in the case of Donaye (Fig. 8), the pH of the soil solution did not change much with the number of cropping cycles and mainly remained near neutrality. Sodium and magnesium were the major cations in the soil solution, and both concentrations increased with the number of cropping cycles. Alkalinity was the main anion, but both chloride and sulphate increased drastically with time, as there was no leaching towards the water table in this site. The soil solution temporarily reached equilibrium with gypsum during the dry season when all the irrigation water was evaporated, and especially during the inter cropping periods, according field observations (Boivin et al., 2002; Barbiero et al., 2005).

In the first instance $RA_{calcite}$ dropped slightly but increased again progressively when calcite and later gypsum started to precipitate. As the soil is very clayey with high CEC, the composition of the soil solution was determined by the buffering property of the soil. Exchangeable calcium was progressively desorbed and precipitated, exchangeable magnesium increased and became the first exchangeable cation. At the same time ESP increased linearly up to 9% after 60 cycles. These extreme values for adsorbed magnesium were not observed yet, but still represent the values potentially reached for these conditions. Sixty cropping cycles were not sufficient to lead to alkaline conditions. However these confined conditions promote a very slow alkalization and sodication process.

3.3. Importance of plant uptake

Results displayed in figure 9 to 11 showed clearly that the ionic plant uptake in the soil solution, decreased systematically the pH of soil solution in the three sites. Nevertheless, the

plant effect was moderate for the most alkaline conditions, namely Niono where pH still increased with time, up to 7.75 after sixty cropping cycles. In the case of Foum Gleita and Donaye pH decreased until reaching a final value of 7.2 as plant uptake counterbalanced the alkaline input of irrigation water. The total concentration of the soil solution, as indicated by EC, decreased by at least 30% , almost 50% for Foum Gleita and Niono. In Donaye, plant uptake played a major role for it is the only process exporting elements out of the system, as there was no vertical drainage. The same trend was observed for ESP in the cases of Foum Gleita and Donaye, where plant uptake contributed to a reduction by 50% of exchangeable sodium and consequently reduced the sodic risk. In Niono, unlike the former cases, plant uptake had a moderate effect on ESP. In fact, as K^+, Ca^{2+} and Mg^{2+} were preferentially absorbed by rice to Na^+, its concentration increased relatively in soil solution and exchangeable position. In all cases, $RA_{calcite}$ of the soil solution was significantly reduced, and even showing a serious decrease for Donaye until reaching 0.0015 $mol.l^{-1}$, though still remaining positive.

This simulation showed that in alkaline geochemical conditions, total exportation of rice (grains + straw) improved generally the composition of the soil solution and tended to reduce the risks of salinisation, alkalization and generally sodication except in the case of Niono where the low CEC was very sensitive to a relative Na increase in the soil solution. This situation is illustrated by Barbiero et al. 2001 who carried out an experiment in Niger (Lossa) where the cultivation of a local fodder grass (Echinochloa stagnina) and its exportation out of the field contributed to noticeable de-alkalization of a highly alkaline soil.

3.4. Effects of superficial lateral drainage (flushing).

Results displayed in figures 12 to 14 showed distinctly that even for low rates, superficial flushing reduced significantly EC (i.e. the total salinity) of the soil solution, as well as ESP. The incidence of lateral drainage on pH and on RAC was less clear, especially for the case of Donaye as both parameters used to decrease without superficial lateral drainage and whereas they tended to increase slightly or stay constant when lateral drainage was simulated. However, in the case of Foum Gleita (Figure 12) the processes of sodication and alkalization were thoroughly reduced even for the smallest lateral drainage rate, as pH, EC, ESP and $RA_{calcite}$ decrease with increasing flushing rate. For flushing rates greater than 30% the simulation shows that all these parameters reach constant low values, namely pH = 7.3, EC = 0.6 $dS.m^{-1}$, ESP =2%, $AR_{calcite}$ = 0.03 $mol.l^{-1}$, witnessing stable geochemical conditions, harmless for the quality of soil and solution.

In the case of Niono (figure 13), superficial flushing was as effective as in the previous example, for its incidence was clearly noticeable, even for low flushing rates. The simulation showed that a flushing rate of 30% was sufficient to control and maintain EC at a constant level, with only a slight increase in ESP. The incidence of lateral drainage on pH and $AR_{Calcite}$ was very important for the low rates (5% and 10%) during 20 first cropping cycles, as these parameters decreased slightly, until $AR_{calcite}$ becoming negative for 5% flushing rate, and finally increased constantly. For the higher flushing rates (30 % and 50 %) the incidence on pH and $AR_{calcite}$ was less important for the first simulated cropping cycles, but remained constant over the entire period. This special behavior is probably related to the difference in pCO_2 between the soil solution ($10^{-1.8}$ atm) and the supplementary irrigation water ($10^{-3.5}$ atm) added to compensate lateral drainage, and their relative proportions when mixed, promoting whether calcite precipitation or dilution of the soil solution. In any cases the superficial flushing reduced significantly the risk of alkalisation and sodication, though ESP

values still reached relatively high values (17%).

An equivalent behavior was noticed in the simulation for the case of Donaye (figure 14), although no vertical drainage was considered; EC and ESP showed a significant decrease even for low flushing rates and reached a low constant value all along the cropping cycles when higher superficial lateral drainage rates were achieved (EC = 0.7 $dS.m^{-1}$; ESP =1.5 % for 30% flushing rate and EC = 0.6 $dS.m^{-1}$; ESP = 0.8 % for a flushing rate of 50 %). Consequently the soil solution and soil quality increased. On the other hand, pH and $AR_{calcite}$ showed a significant decrease when no lateral drainage was simulated whereas they showed a similar behavior for the different flushing rates as described for the case of Niono. However these variations of pH and $AR_{calcite}$ can be considered as negligible considering alkalization because for the worst condition (flushing rate of 10 %), pH reached 7.33 and ARcalcite reached 0.004 $mol_c.l^{-1}$ after 60 cropping cycles .

Moreover these results also show that $AR_{calcite}$, which is considered as a conservative tracer (Ribolzi et al. 1996;Barbiero et al. 2001; Barbiero et al. 2004), varies along the simulation, and probably also in field conditions, as solutions with different pCO_2 are mixed.

In Donaye, mineralogical and chemical experimental studies of the soil have been performed to assess the modifications of the soil quality after 15 years of intensive irrigation. When compared inside an irrigated plot and outside the irrigation scheme, the evolution of the soil exchangeable complex, especially the ESP, has been found not significantly different (Charolais and Weber, 1994). Equally, when the pH of the soil, the EC and the content of accumulated carbonates in the topsoil have been measured on a 1/50 aqueous extract, (Schiess, 1995; Boivin et al. 1998) only a slight increase in the soil between the two situations was noticeable, though the difference isn't really statistically different between the two groups (figure 15). These experimental results show that in 15 years of irrigation the soil

quality has not changed noticeably. In Donaye the rice straw is usually not exported from the field, but left to graze for cattle or burned. However, “natural” leakage throughout the bunds of the plot, due to a lack of maintenance is almost systematically observed. In fact, this disorder actually contributes to the superficial flushing, especially during the first irrigation when the soil shrinkage cracks are still open in bunds, and helps to preserve the soil quality despite the improper quality of irrigation water.

Although the quantitative effect of superficial flushing is difficult to model accurately because of the lack of information, this study demonstrates clearly the crucial role of superficial flushing for soil conservation, and attests the general conclusions of the numerical simulation results.

3.5. Effect of soil reduction.

Although this process has not been modelled specifically in this work for the lack of Eh information in some cases, it is still possible to evaluate its effect on the proton balance. In the case of prolongated submersion conditions, like in paddy fields, the soil undergoes reduction as microbial activity consumes the dissolved oxygen, and finally reduces the iron oxi-hydroxides (the most commonly found). The oxidation of organic matter by reducing Fe(III) to Fe(II) produces alkalinity and consequently an increase in pH :

$$FeOOH + ½\ COOH^- + 5/2\ H^+ \leftrightarrow Fe^{2+} + ½\ CO_2 + 2H_2O$$

When the system oxides at the end of the submersion period an equivalent amount of acidity is produced and the general proton balance is null in confined conditions. However in case of a leaching fraction during reduced conditions, reoxidation leads generally to ferrolysis phenomenon which is a soil transformation involving a protonation of the complex, an attack of the clay crystalline structure, where H^+ is penetrating the octahedral layers and

taking the place of Al^{3+} as described by Brinkman (1979) and revisited by van Ranst and De Coninck (2002). Consequently, soil reduction has either no effect on alkalinity or, on contrary, consumes alkalinity and reduces pH in the studied situations.

Conclusion

In this study we used PHREEQC to predict the evolution of the soil and soil solution over several years, with different soil and water management. Although the use of Riversides' diagram, $RA_{calcite}$ and the RSC index, can be informative about the potential risks, they cannot predict the evolution of the soil nor of the soil solution. Especially as they don't take into account the buffer capacity of soil, the water management involving dilutions and variations in pCO_2, and the effect of the plants uptake. We demonstrated that despite the high risk of alkalinisation and sodication according to these indicators, in three west African situations of irrigation, soil degradation is not a fate. Considering the buffer effect of the soil (very high in Senegal), the possibilities of removing alkalinity from the plots by straw management, and finally the use of superficial flushing whether naturally (Foum Gleita), artificially with an effective drainage network (Niono) or accidentally with leaks in the bunds (Donaye), alkalinisation or sodication is not jeopardizing soil properties in well-conducted rice cropping system. These results using geochemical numerical modelling, attest that in Sahel, although the main rivers (river Senegal, Niger, Gorgol Noir) show an alkaline composition with positive $RA_{calcite}$ and RSC values, their use for irrigation in paddy fields cannot be considered as directly responsible for soil alkalinisation. Barbiero et al. (1998), in the Republic of Niger, or van Asten et al. (2004) in Foum Gleita, found similar conclusions based on experimental

results. The presence of alkaline soils is more probably due to the alteration of an alkaline bed rock (in Foum Gleita) or to the presence of groundwater leaching through a deeper alkaline bed rock (in Niono). Unlike the usual assumptions,where rice cropping is held responsible for soil salinization or alkalinisation, this study show that in these cases, rice cropping can improve the soil quality when irrigation and residue management are performed properly. Namely a superficial lateral drainage performed once, at the beginning of the cropping season, although being sometimes seen as a waste of water by the local farmers, improves noticeably the sustainability of the system despite adverse composition of the irrigation water. More over, in the situation of alkalinisation risk, the exportation of the straw out of the plots contributes significantly to the control of the average alkalinity of soil, especially in the cases of Niono and Donaye.

Table 1: Composition of irrigation water (I) and groundwater (GW) in the different locations

	Ca	Mg	Na	K	Alk.	Cl	SO_4	RSC	pH	SAR	EC
				$\times 10^{-3}$	$mol_c.l^{-1}$						$dS.m^{-1}$
Foum^{I}	0.78	0.38	0.32	0.12	1.4	0.11	0.09	0.24	7.54	0.42	0.17
Niono^{I}	0.11	0.1	0.17	0.05	0.38	0.08	0	0.17	6.52	0.62	0.04
Niono^{GW}	0.62	0.36	6.05	0.09	6.91	0.13	0.08	5.93	7.69	8.62	0.58
Donaye^{I}	0.23	0.12	0.1	0.06	0.61	0.06	0.07	0.26	7.28	0.25	0.07

Table 2: Adsorbed cations of the different soils. ESP : exchangeable sodium percentage.

	XCa	**XMg**	**XNa**	**XK**	**Σcat**	**ESP**
		$cmol_c.kg^{-1}$				**%**
Foum Gleita	11.8	4.8	0.3	0.6	17,5	1.71
Niono	5.5	2	1.5	0.1	9.1	16.48
Donaye	13	9	0.4	0.3	22.7	1.76

Table 3 : Minerals dissociation equations and solubility product values at 10^5 Pa and 298.15K

(1) : PHREEQC data base, (2) : estimated as a solid solution with data from PHREEQC data base, (3) : Kindis data base (Made, 1991) , (4) : fixed (Brooks et al. 1983)

Minerals	**equations**	**log K (25 °C)**
CO_2		-1.8 (4)
Mg-Calcite	$Ca_{.98}Mg_{.02}CO_3 = .98\ Ca^{2+} + .02Mg^{2+} + CO_3^{-2}$	-8.46608 (2)
Sepiolite	$Mg_2Si_3O_{7.5}OH{:}3H_2O + 4\ H^+ + 0.5H_2O = 2\ Mg^{2+} + 3\ H_4SiO_4$	15.76 (1)
Kaolinite	$Al_2Si_2O_5(OH)_4 + 6\ H^+ = H_2O + 2\ H_4SiO_4 + 2\ Al^{3+}$	7.44 (1)
Gypsum	$CaSO_4{:}2H_2O = Ca^{2+} + SO_4^{-2} + 2\ H_2O$	-4.58 (1)
quartz	$SiO_2 + 2\ H_2O = H_4SiO_4$	-3.98 (1)
beidellite	$Si_{3.8}Al_{1.7}Fe_{.3}Mg_{.2}O_{10}(OH)_2Ca_{.2} + 6.8H^+ + 3.2\ H_2O =$	-33.98 (3)
	$3.8H_4SiO_4 + 1.7Al^{3+} + .3Fe^{3+} + .2Mg^{2+} + .2Ca^{2+}$	

Table 4 : Average paddy uptake (grain + straw) and equivalent uptake in soil solution (average yield of 5t/ha, and average bulk density of 1750kg.m^{-3})

	Dobermann & Fairhurst, 2000	equivalent ionic	
	%	species	mmol/l
N	0.65	NH_4^+	6.62
K	1.4	K^+	5.1
Mg	0.2	Mg^{2+}	2.35
Ca	0.3	Ca^{2+}	2.13
Na	0.2	Na^+	1.24
Σc			18.01
P	0.1	$H_2PO_4^-$	0.46
Cl	0.5	Cl^-	2.01
S	0.075	SO_4^{2-}	0.66
Σa			3.24
Σc - Σa		Alkalinity	14.3

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Figure 1 : Location of the studied sites

Figure 2 : Schematic representation water use dynamics in simulation : **a.** after irrigation, 2 liters of superficial ponding water + 1 liter soil solution in the root zone, **b.** : after evaporation and just before the next irrigation, 1 liter of soil solution in the root zone.

Figure 3: Schematic representation of the procedure adopted to simulate the effects of the leaching fraction (**L.F.**) and of the superficial flushing (**S.F.**). **a. -1**: the soil is saturated, 2 : at the end of the concentration period, part of the remaining solution is evacuated from the system (LF). **b. -1** : at the end of an inter-cropping period precipitated minerals and concentrated solutions are close to the soil surface, **2**: addition of a superficial layer of irrigation water, dissolving the minerals and equilibrating with soil solution and and exchangeable cations, **3**: part of the superficial layer is evacuated.

Figure 4 : Evolution of irrigation water composition during concentration for $pCO_2 = 10^{1.5}$ Pa and possibility for common minerals (calcite, quartz, sepiolite, kaolinite, gypsum) to precipitate.

Figure 5 : Evolution of irrigation water composition during concentration in the Riverside diagram.

Figure 6 : Evolution of soil solution and adsorption complex for Foum Gleita. RAC : $RA_{calcite}$, the straight horizontal solid line states for the precipitation of calcite.

Figure 7 : Evolution of soil solution and adsorption complex for Niono. RAC : $RA_{calcite}$, the

straight horizontal solid line states for the precipitation of calcite and the dotted line for the precipitation of sepiolite.

Figure 8 : Evolution of soil solution and adsorption complex for Donaye, RAC : $RA_{calcite}$, the straight horizontal solid line states for the precipitation of calcite and the dotted line for the precipitation of gypsum.

Figure 9 : Evolution of pH, EC of soil solution, ESP and $RA_{calcite}$ of the soil solution for Foum Gleïta considering presence (solid line) and absence (dotted line) of plant uptake.

Figure 10 : Evolution of pH, EC of soil solution, ESP and $RA_{calcite}$ of the soil solution for Niono considering presence (solid line) and absence (dotted line) of plant uptake.

Figure 11 : Evolution of pH, EC of soil solution, ESP and $RA_{calcite}$ of the soil solution for Donaye considering presence (solid line) and absence (dotted line) of plant uptake.

Figure 12 : Evolution of pH, EC of soil solution, ESP and $RA_{calcite}$ of the soil solution for Foum Gleïta, considering different superficial flushing rates, vertical drainage and plant uptake.

Figure 13 : Evolution of pH, EC of soil solution, ESP and $RA_{calcite}$ of the soil solution for Niono, considering different superficial flushing rates, vertical drainage and plant uptake.

Figure 14 : Evolution of pH, EC of soil solution, ESP and $RA_{calcite}$ of the soil solution for Donaye, considering different superficial flushing rates and plant uptake.

Figure 15 : Comparison of soil quality between irrigated rice cropped plots and uncultivated

soil in Donaye. The diagrams were obtained with superficial (0-10cm) soil samples, n=130 in irrigated plots and n=95 in uncultivated soils.

Figure1

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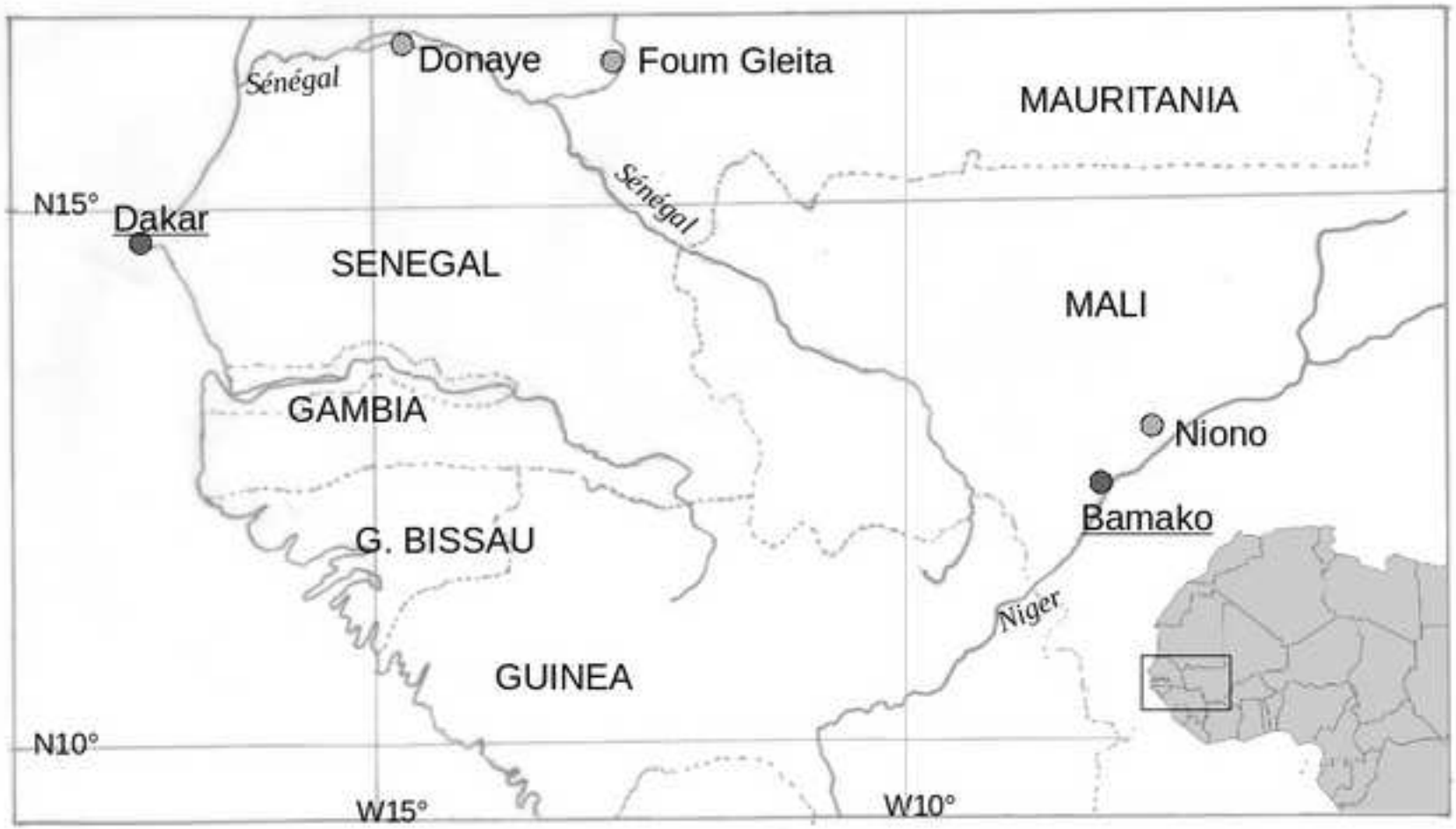


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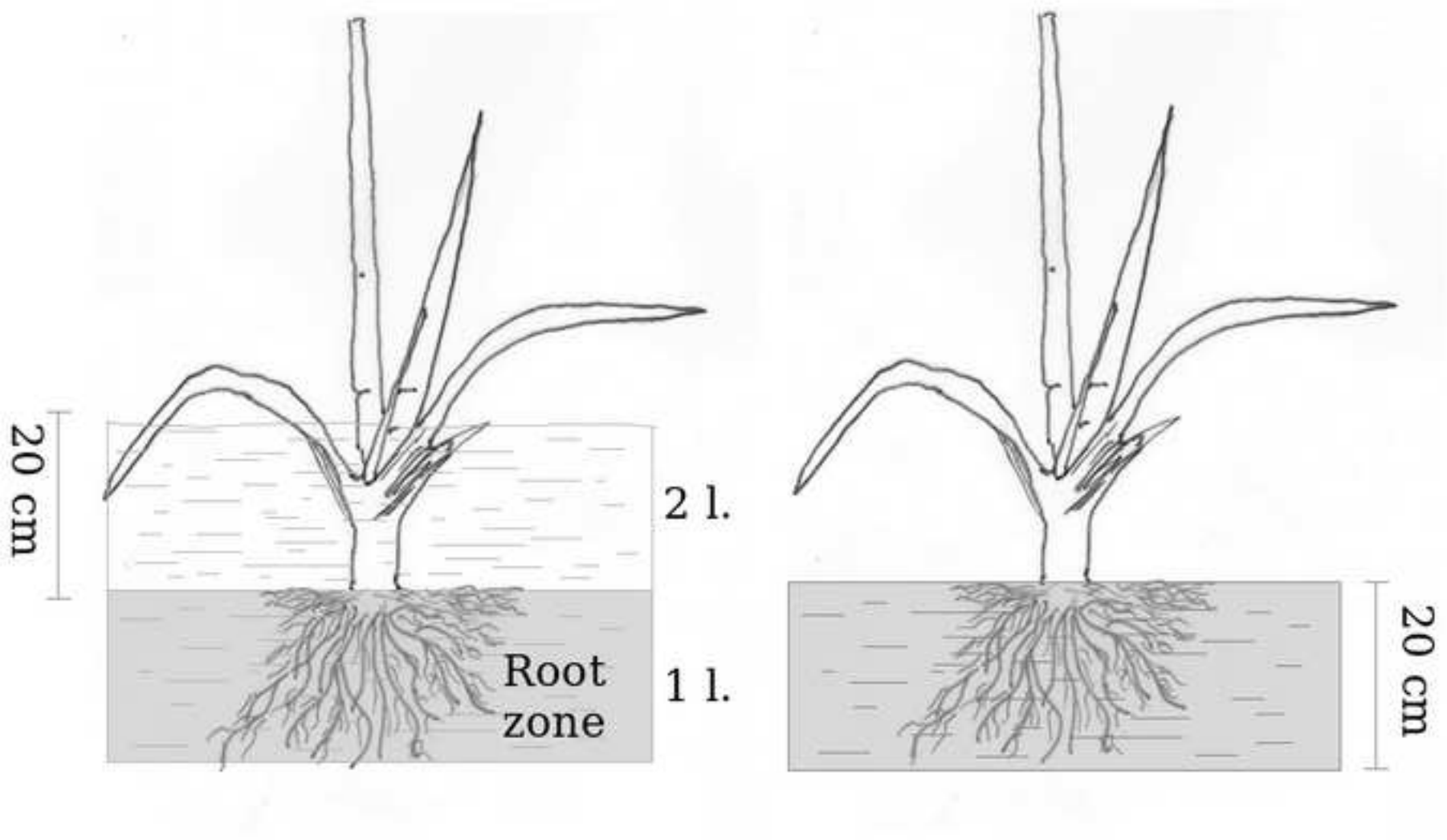


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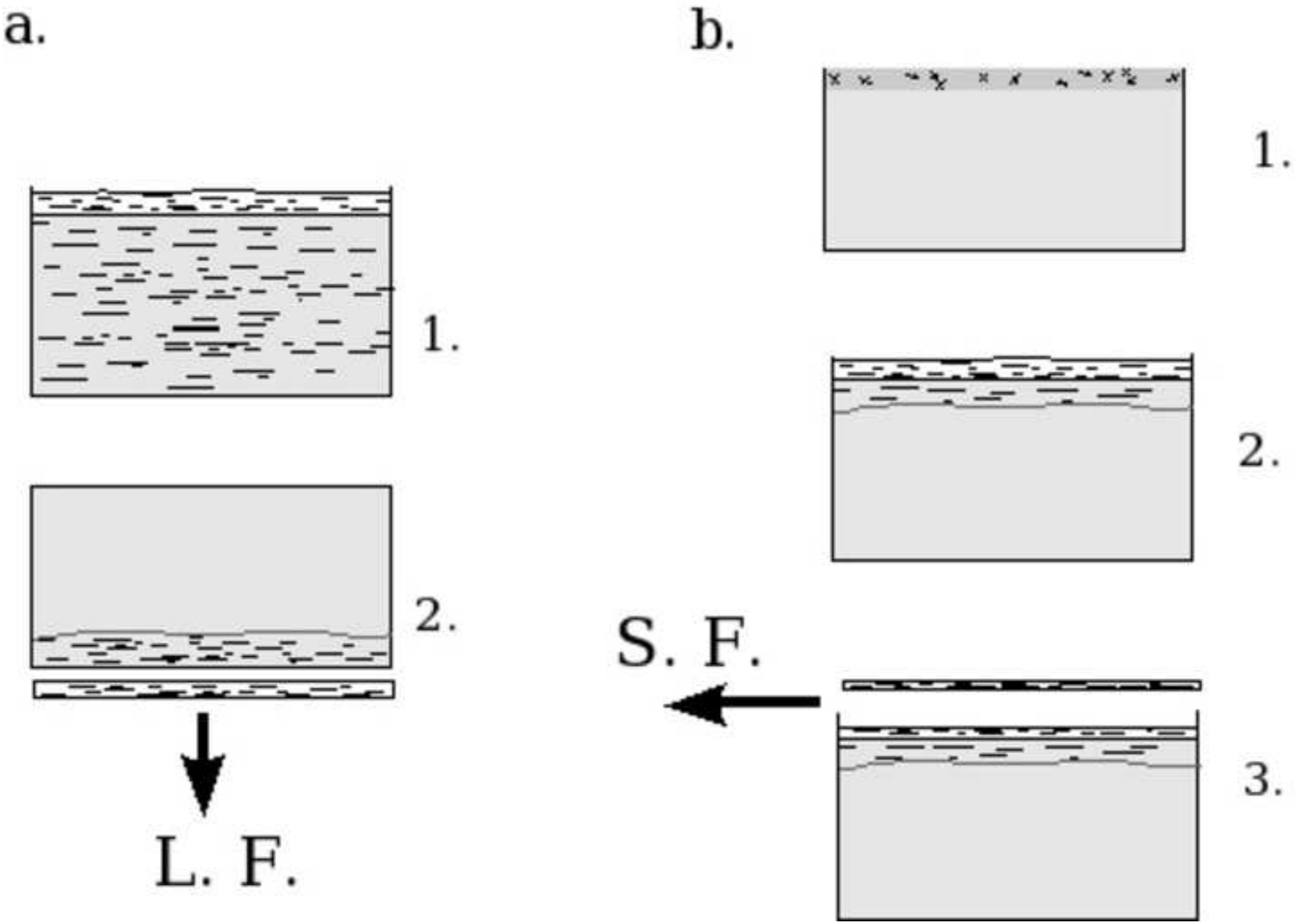


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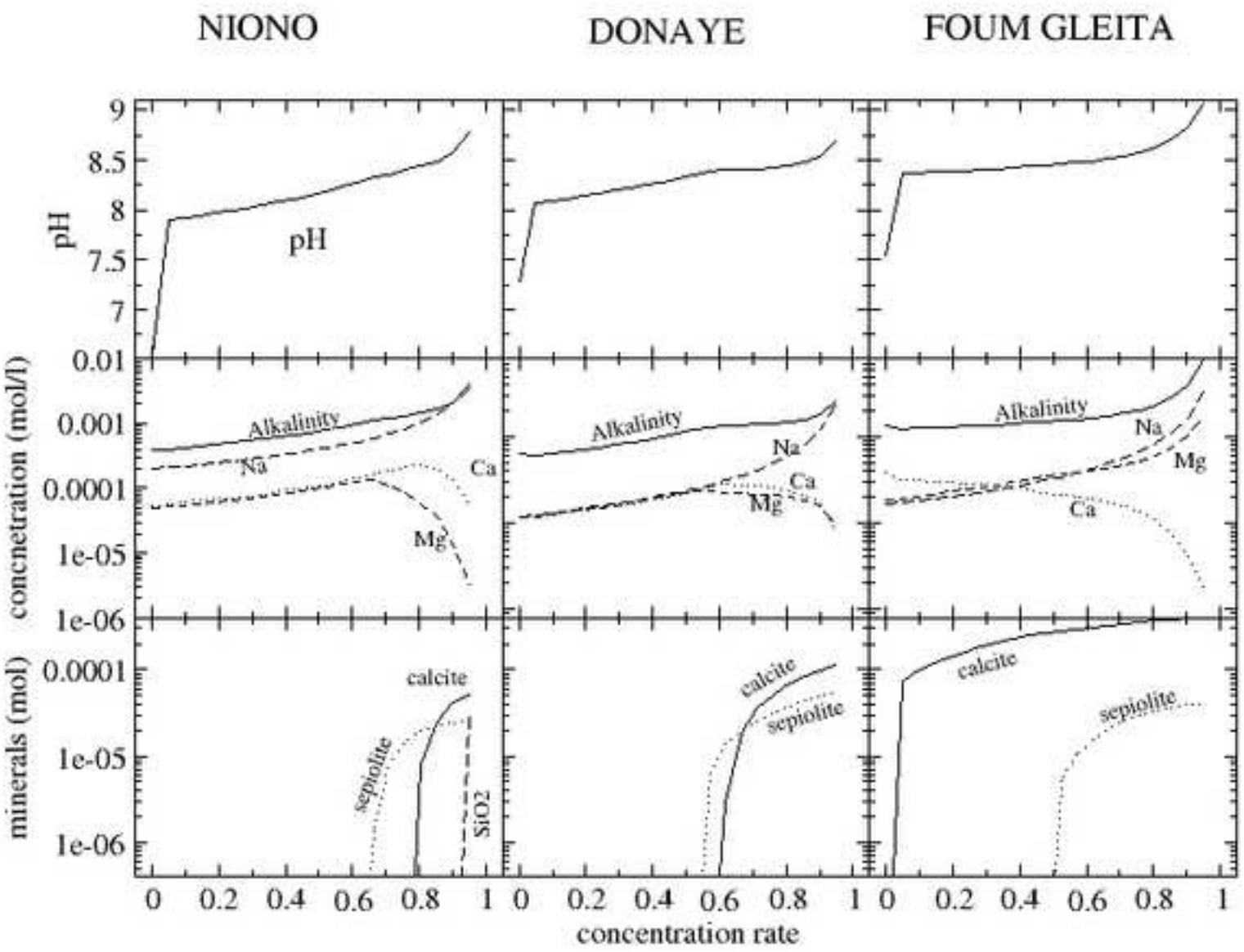


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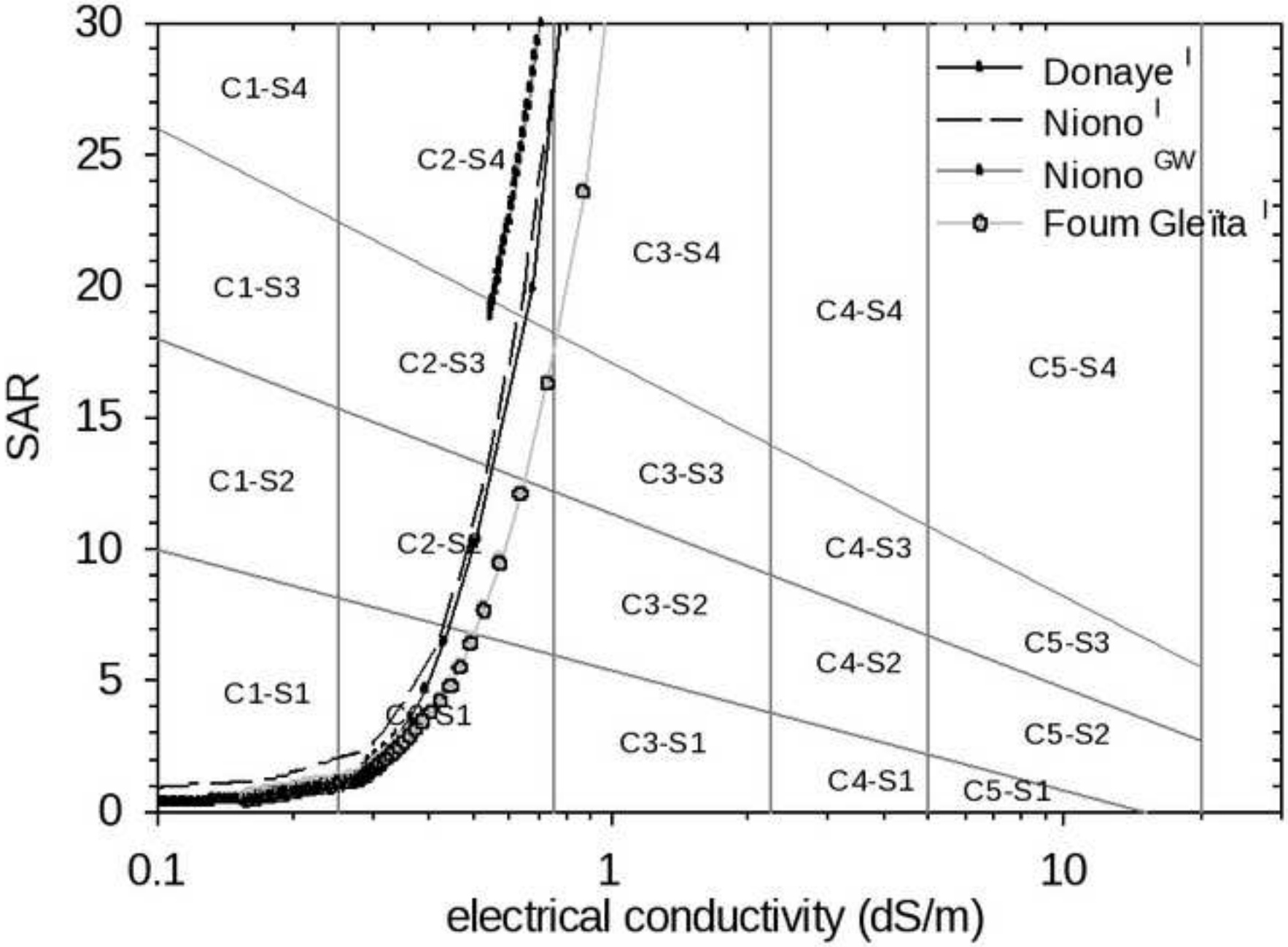


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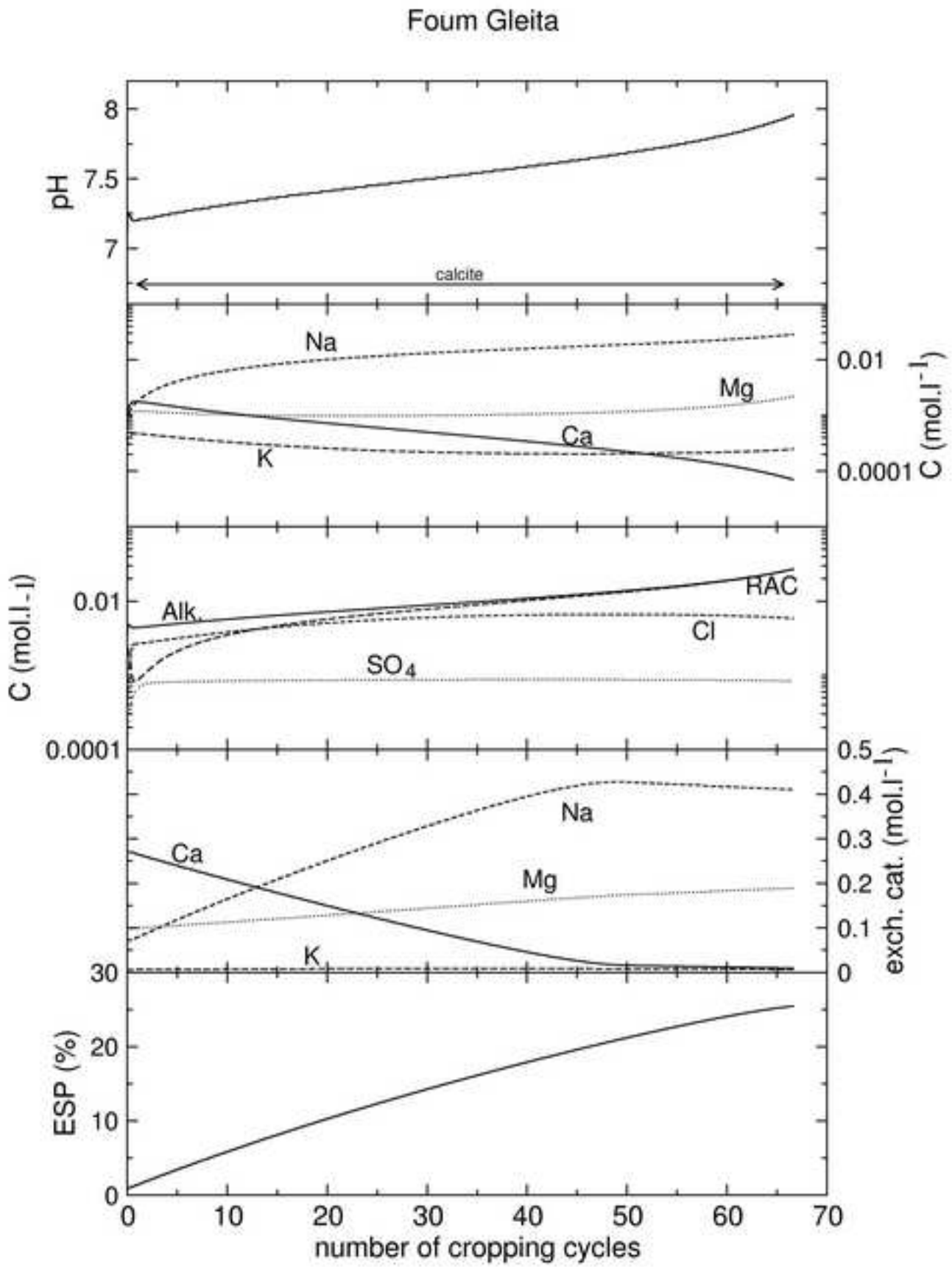


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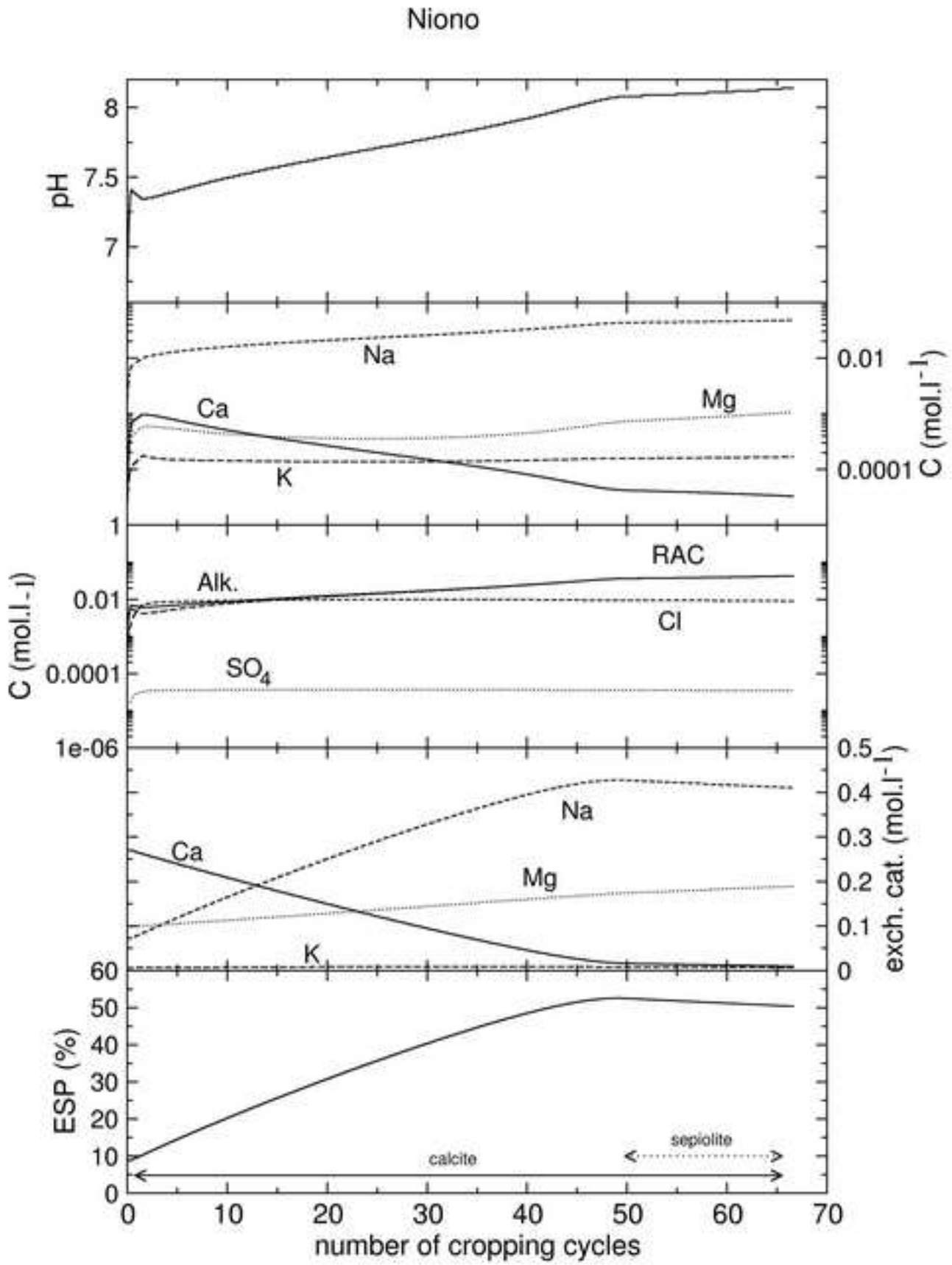


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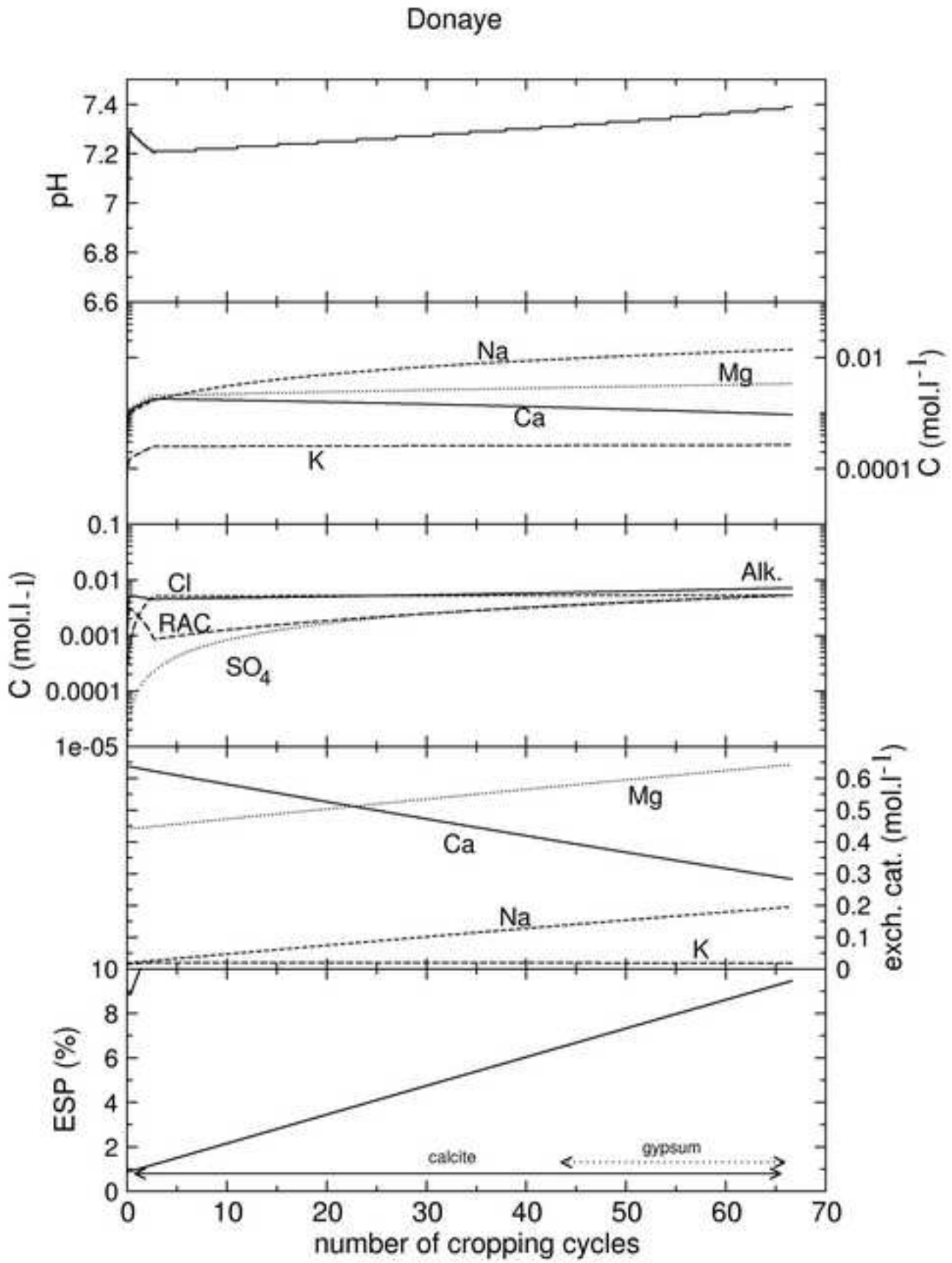


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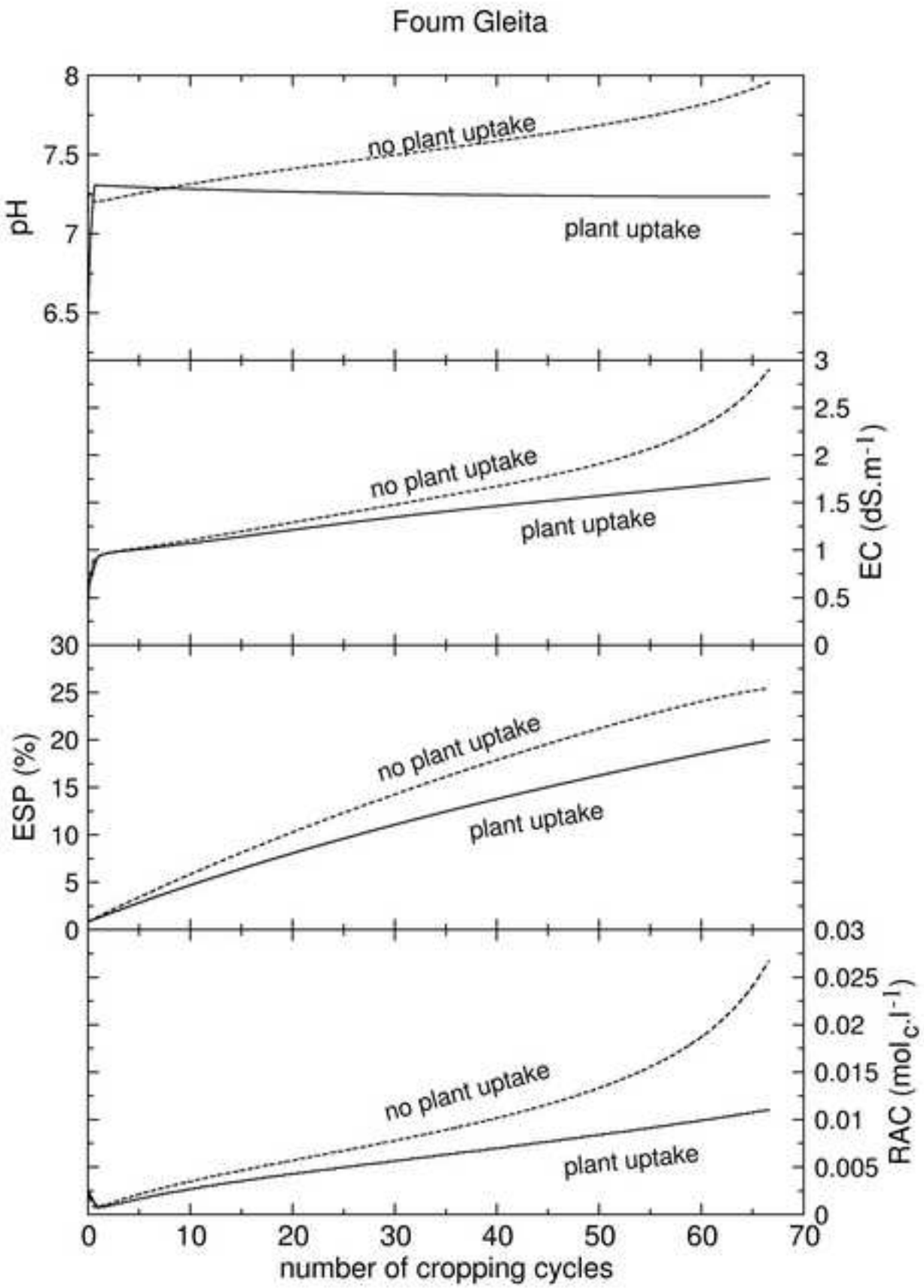


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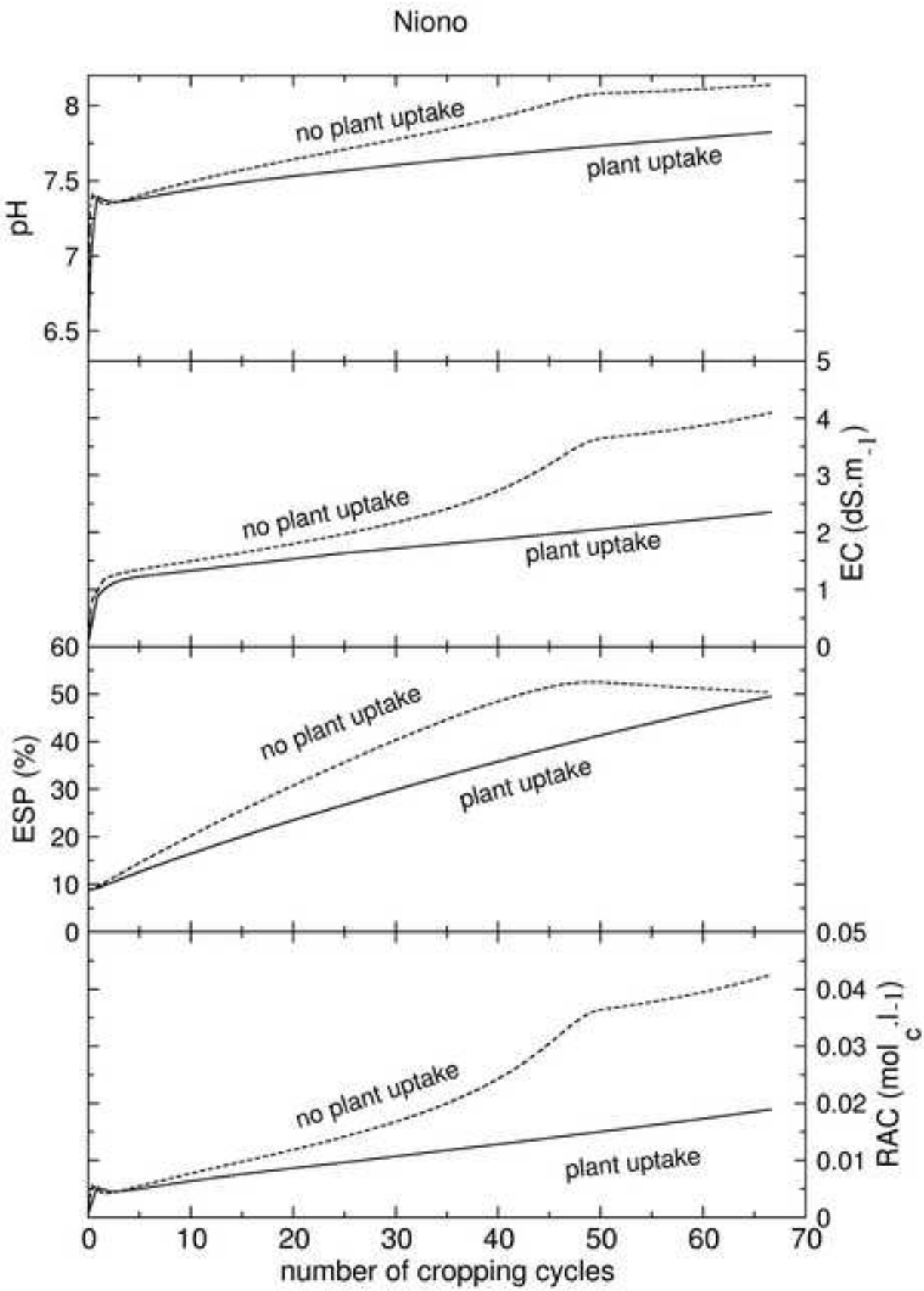


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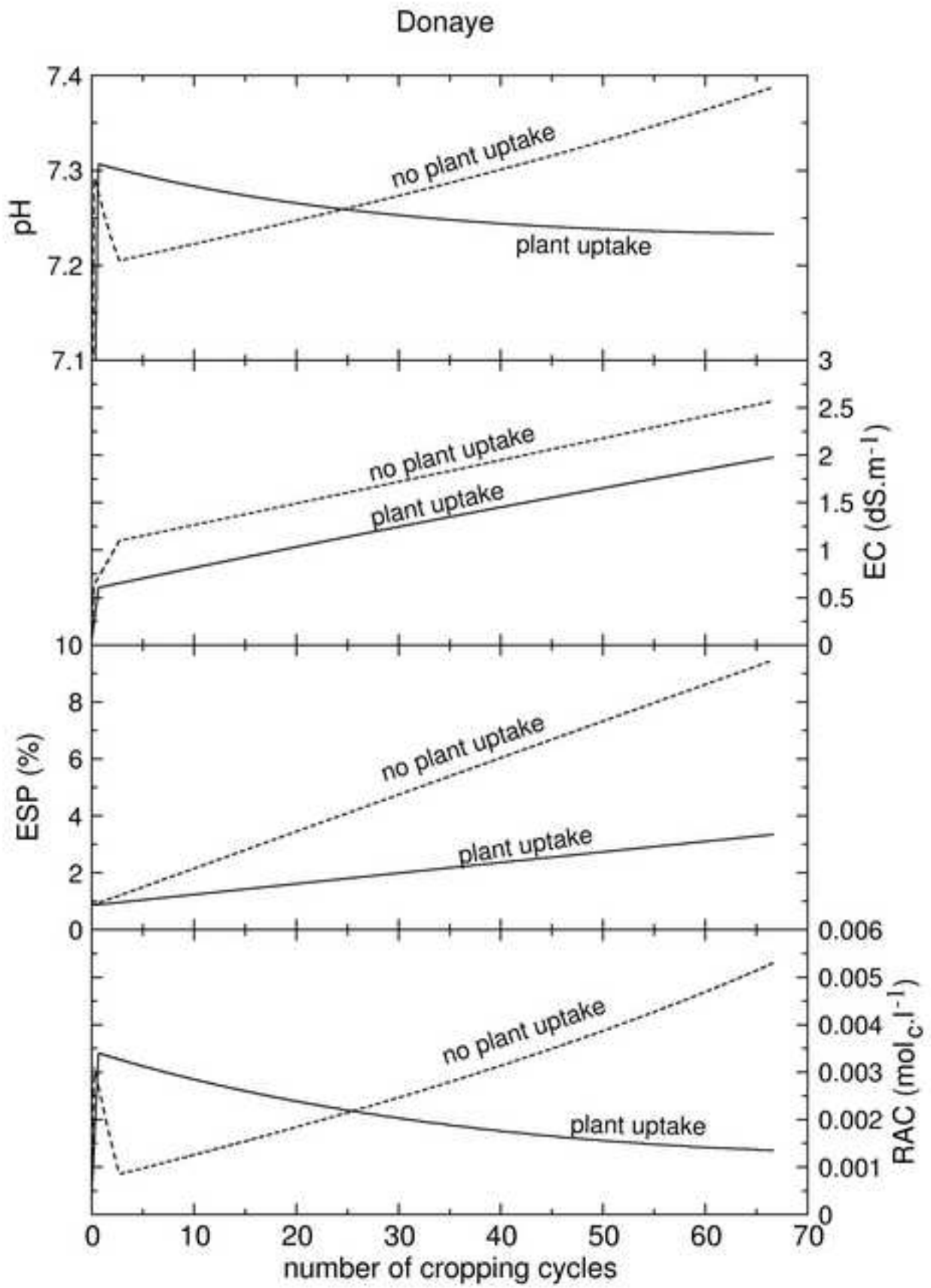


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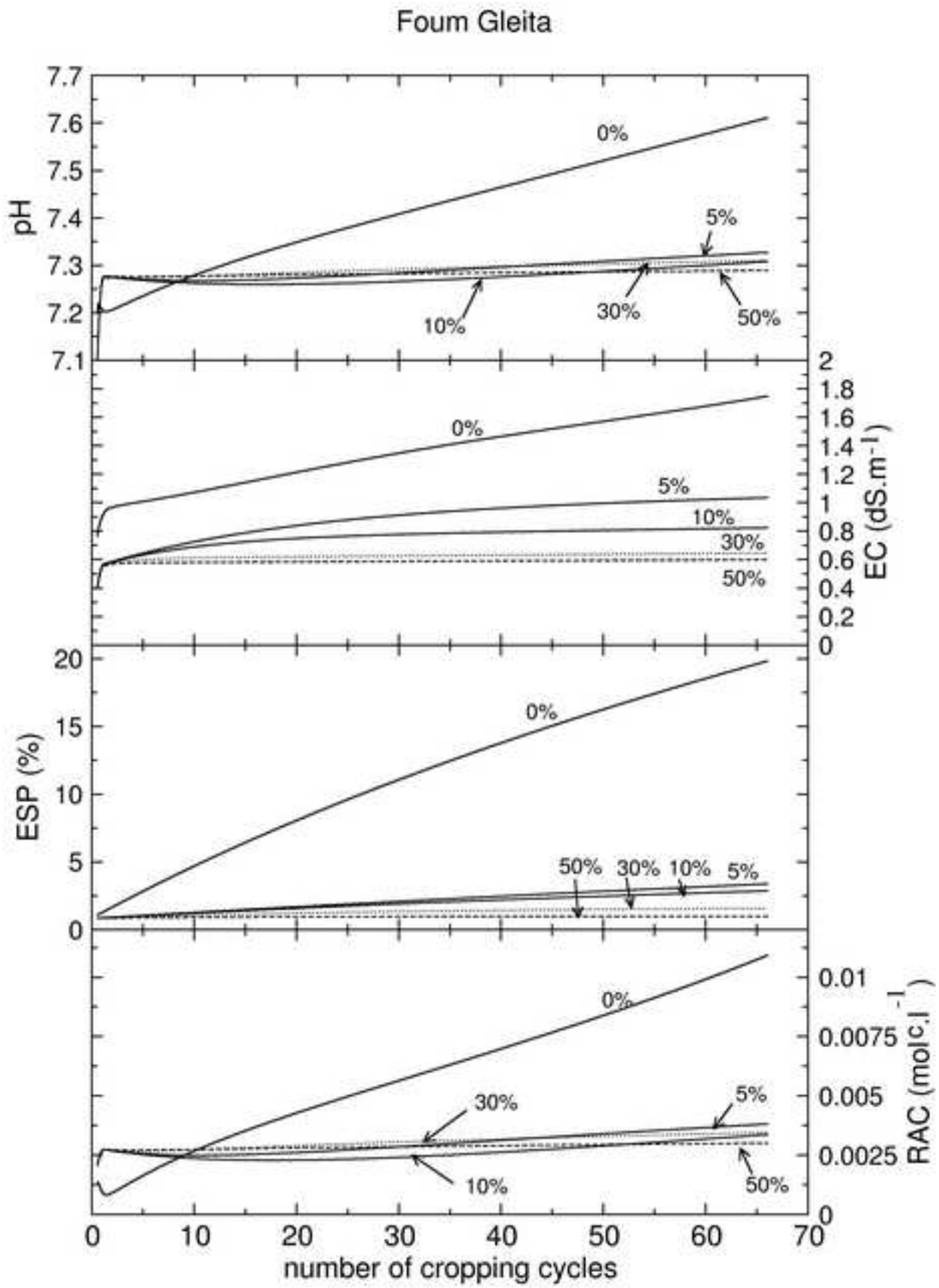


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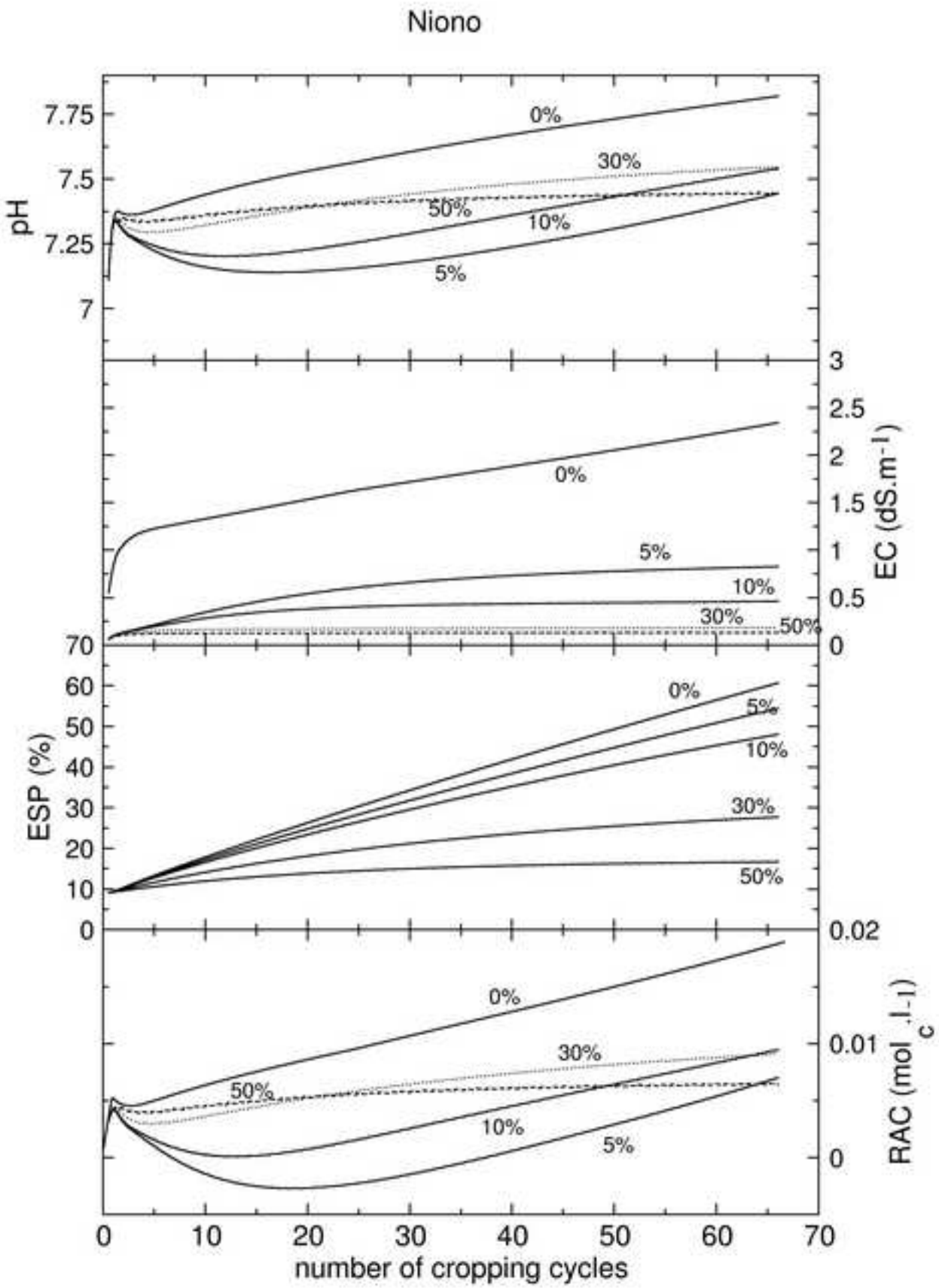


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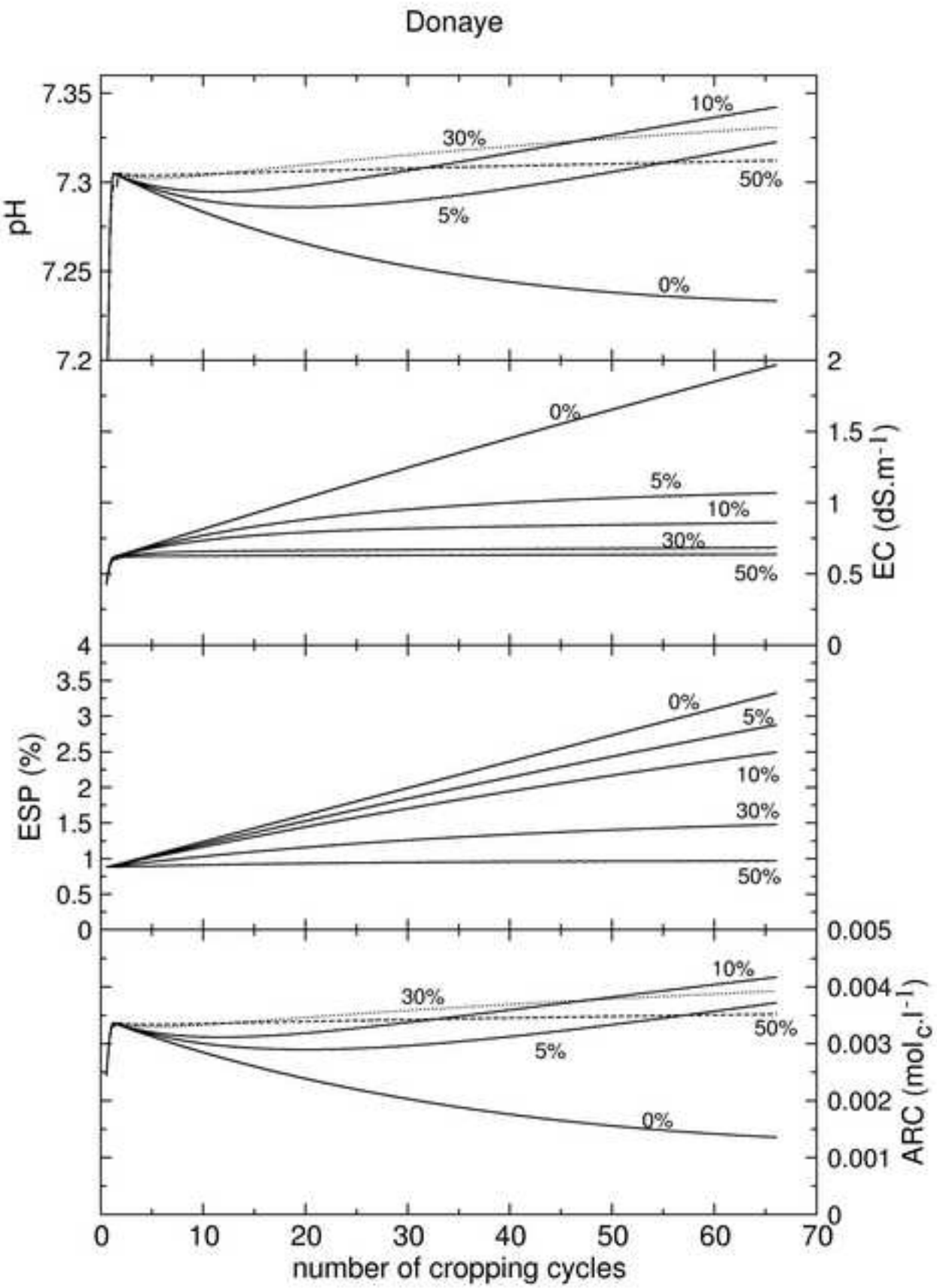


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